Astronomy

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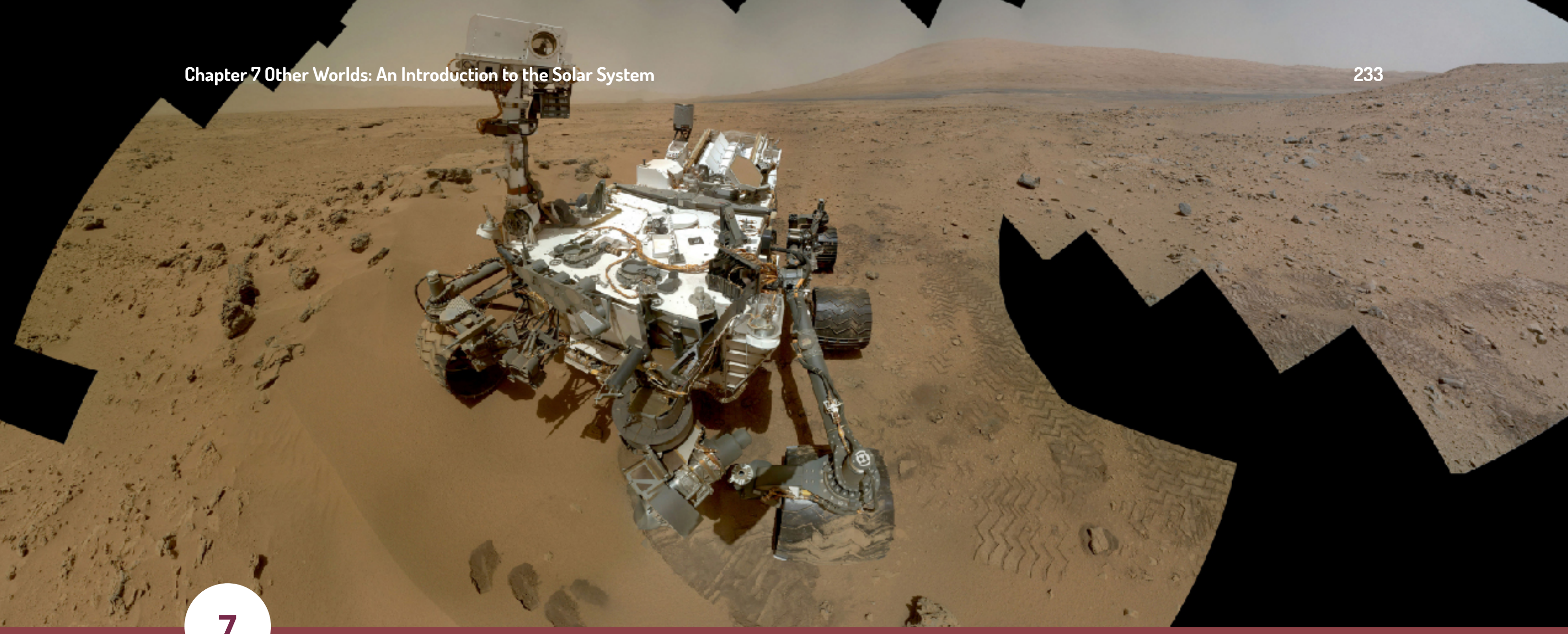


7

OTHER WORLDS: AN INTRODUCTION TO THE SOLAR SYSTEM

Figure 7.1 "Self-Portrait" of Mars. This picture was taken by the *Curiosity* Rover on Mars in 2012. The image is reconstructed digitally from 55 different images taken by a camera on the rover's extended mast, so that the many positions of the mast (which acted like a selfie stick) are edited out. (credit: modification of work by NASA/JPL-Caltech/MSSS)

Chapter Outline

Thinking Ahead

Surrounding the Sun is a complex system of worlds with a wide range of conditions: eight major planets, many dwarf planets, hundreds of moons, and countless smaller objects. Thanks largely to visits by spacecraft, we can now envision the members of the solar system as other worlds like our own, each with its own chemical and geological history, and unique sights that interplanetary tourists may someday visit. Some have called these past few decades the "golden age of planetary exploration," comparable to the golden age of exploration in the fifteenth century, when great sailing ships plied Earth's oceans and humanity became familiar with our own planet's surface.

In this chapter, we discuss our planetary system and introduce the idea of comparative planetology—studying how the planets work by comparing them with one another. We want to get to know the planets not only for what we can learn about them, but also to see what they can tell us about the origin and evolution of the entire solar system. In the upcoming chapters, we describe the better-known members of the solar system and begin to compare them to the thousands of planets that have been discovered recently, orbiting other stars.

7.1 OVERVIEW OF OUR PLANETARY SYSTEM

Learning Objectives

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

- Describe how the objects in our solar system are identified, explored, and characterized
- Describe the types of small bodies in our solar system, their locations, and how they formed
- Model the solar system with distances from everyday life to better comprehend distances in space

The solar system[1] consists of the Sun and many smaller objects: the planets, their moons and rings, and such “debris” as asteroids, comets, and dust. Decades of observation and spacecraft exploration have revealed that most of these objects formed together with the Sun about 4.5 billion years ago. They represent clumps of material that condensed from an enormous cloud of gas and dust. The central part of this cloud became the Sun, and a small fraction of the material in the outer parts eventually formed the other objects.

During the past 50 years, we have learned more about the solar system than anyone imagined before the space age. In addition to gathering information with powerful new telescopes, we have sent spacecraft directly to many members of the planetary system. (Planetary astronomy is the only branch of our science in which we can, at least vicariously, travel to the objects we want to study.) With evocative names such as Voyager, Pioneer, *Curiosity*, and Pathfinder, our robot explorers have flown past, orbited, or landed on every planet, returning images and data that have dazzled both astronomers and the public. In the process, we have also investigated two dwarf planets, hundreds of fascinating moons, four ring systems, a dozen asteroids, and several comets (smaller members of our solar system that we will discuss later).

Our probes have penetrated the atmosphere of Jupiter and landed on the surfaces of Venus, Mars, our Moon, Saturn’s moon Titan, the asteroids Eros and Itokawa, and the Comet Churyumov-Gerasimenko (usually referred to as 67P). Humans have set foot on the Moon and returned samples of its surface soil for laboratory analysis (**Figure 7.2**). We have even discovered other places in our solar system that might be able to support some kind of life.

1 The generic term for a group of planets and other bodies circling a star is *planetary system*. Ours is called the *solar system* because our Sun is sometimes called *Sol*. Strictly speaking, then, there is only one solar system; planets orbiting other stars are in planetary systems.

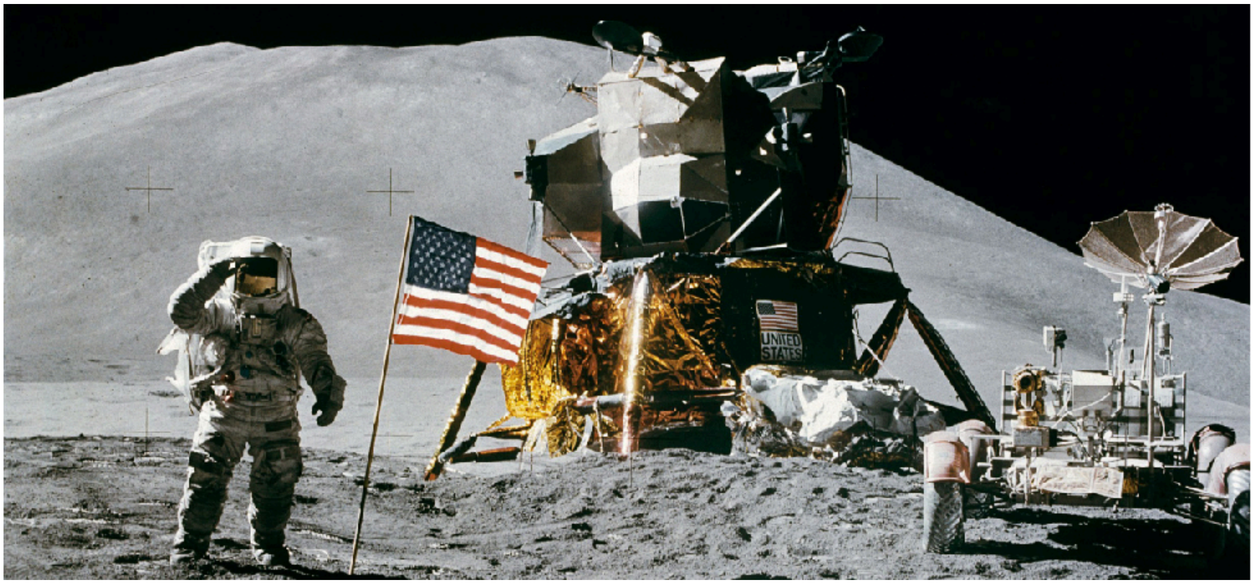


Figure 7.2 Astronauts on the Moon. The lunar lander and surface rover from the Apollo 15 mission are seen in this view of the one place beyond Earth that has been explored directly by humans. (credit: modification of work by David R. Scott, NASA)

LINK TO LEARNING

View this gallery of NASA images (https://openstaxcollege.org/l/30projapolloarc) that trace the history of the Apollo mission.

An Inventory

The Sun, a star that is brighter than about 80% of the stars in the Galaxy, is by far the most massive member of the solar system, as shown in Table 7.1. It is an enormous ball about 1.4 million kilometers in diameter, with surface layers of incandescent gas and an interior temperature of millions of degrees. The Sun will be discussed in later chapters as our first, and best-studied, example of a star.

Mass of Members of the Solar System

Object	Percentage of Total Mass of Solar System
Sun	99.80
Jupiter	0.10
Comets	0.0005–0.03 (estimate)
All other planets and dwarf planets	0.04
Moons and rings	0.00005

Table 7.1

Mass of Members of the Solar System

Object	Percentage of Total Mass of Solar System
Asteroids	0.000002 (estimate)
Cosmic dust	0.0000001 (estimate)

Table 7.1

Table 7.1 also shows that most of the material of the planets is actually concentrated in the largest one, Jupiter, which is more massive than all the rest of the planets combined. Astronomers were able to determine the masses of the planets centuries ago using Kepler's laws of planetary motion and Newton's law of gravity to measure the planets' gravitational effects on one another or on moons that orbit them (see **Orbits and Gravity**). Today, we make even more precise measurements of their masses by tracking their gravitational effects on the motion of spacecraft that pass near them.

Beside Earth, five other planets were known to the ancients—Mercury, Venus, Mars, Jupiter, and Saturn—and two were discovered after the invention of the telescope: Uranus and Neptune. The eight planets all revolve in the same direction around the Sun. They orbit in approximately the same plane, like cars traveling on concentric tracks on a giant, flat racecourse. Each planet stays in its own "traffic lane," following a nearly circular orbit about the Sun and obeying the "traffic" laws discovered by Galileo, Kepler, and Newton. Besides these planets, we have also been discovering smaller worlds beyond Neptune that are called trans-Neptunian objects or TNOs (see **Figure 7.3**). The first to be found, in 1930, was Pluto, but others have been discovered during the twenty-first century. One of them, Eris, is about the same size as Pluto and has at least one moon (Pluto has five known moons.) The largest TNOs are also classed as *dwarf planets,* as is the largest asteroid, Ceres. (Dwarf planets will be discussed further in the chapter on **Rings, Moons, and Pluto**). To date, more than 1750 of these TNOs have been discovered.

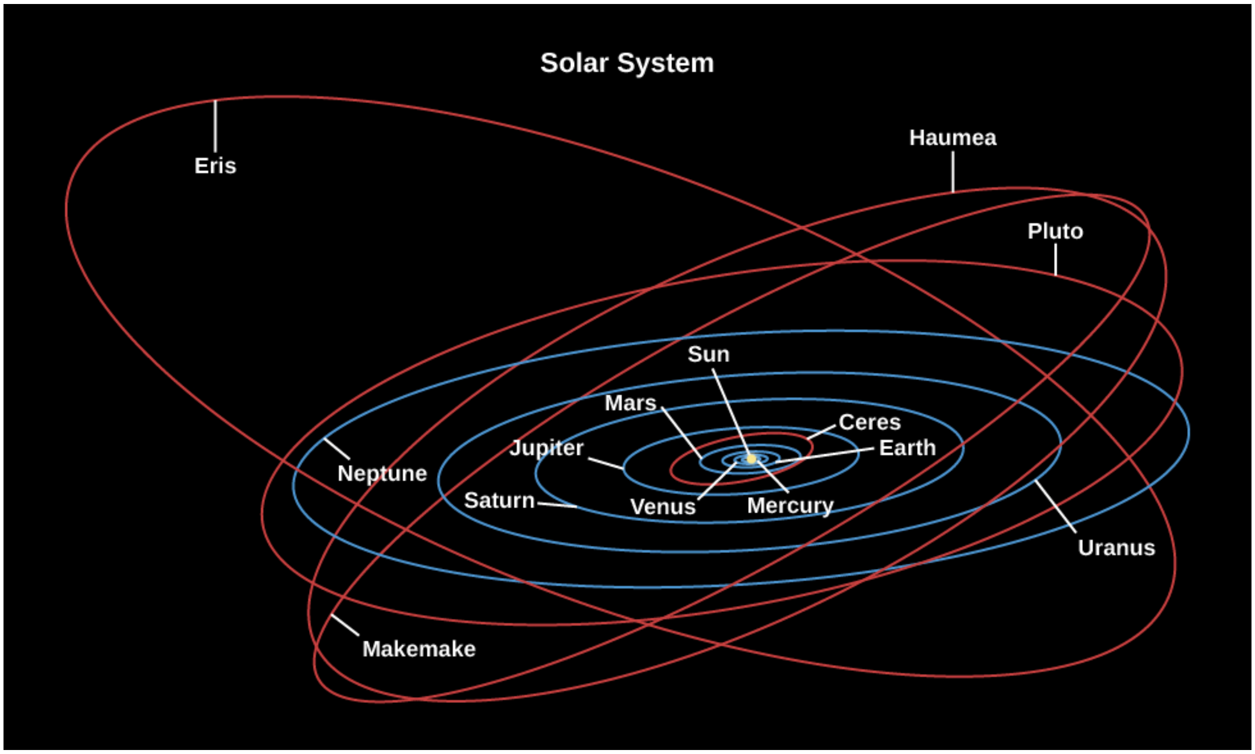


Figure 7.3 Orbits of the Planets. All eight major planets orbit the Sun in roughly the same plane. The five currently known dwarf planets are also shown: Eris, Haumea, Pluto, Ceres, and Makemake. Note that Pluto's orbit is not in the plane of the planets.

Each of the planets and dwarf planets also rotates (spins) about an axis running through it, and in most cases the direction of rotation is the same as the direction of revolution about the Sun. The exceptions are Venus, which rotates backward very slowly (that is, in a retrograde direction), and Uranus and Pluto, which also have strange rotations, each spinning about an axis tipped nearly on its side. We do not yet know the spin orientations of Eris, Haumea, and Makemake.

The four planets closest to the Sun (Mercury through Mars) are called the inner or **terrestrial planets**. Often, the Moon is also discussed as a part of this group, bringing the total of terrestrial objects to five. (We generally call Earth's satellite "the Moon," with a capital M, and the other satellites "moons," with lowercase m's.) The terrestrial planets are relatively small worlds, composed primarily of rock and metal. All of them have solid surfaces that bear the records of their geological history in the forms of craters, mountains, and volcanoes (**Figure 7.4**).

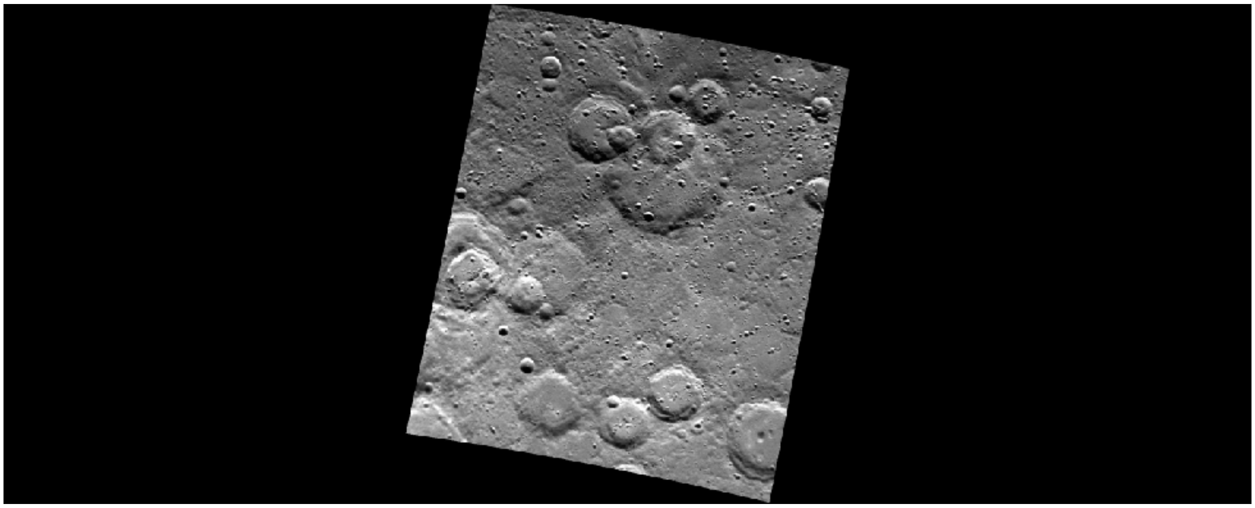


Figure 7.4 Surface of Mercury. The pockmarked face of the terrestrial world of Mercury is more typical of the inner planets than the watery surface of Earth. This black-and-white image, taken with the Mariner 10 spacecraft, shows a region more than 400 kilometers wide. (credit: modification of work by NASA/John Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington)

The next four planets (Jupiter through Neptune) are much larger and are composed primarily of lighter ices, liquids, and gases. We call these four the jovian planets (after "Jove," another name for Jupiter in mythology) or **giant planets**—a name they richly deserve (Figure 7.5). More than 1400 Earths could fit inside Jupiter, for example. These planets do not have solid surfaces on which future explorers might land. They are more like vast, spherical oceans with much smaller, dense cores.

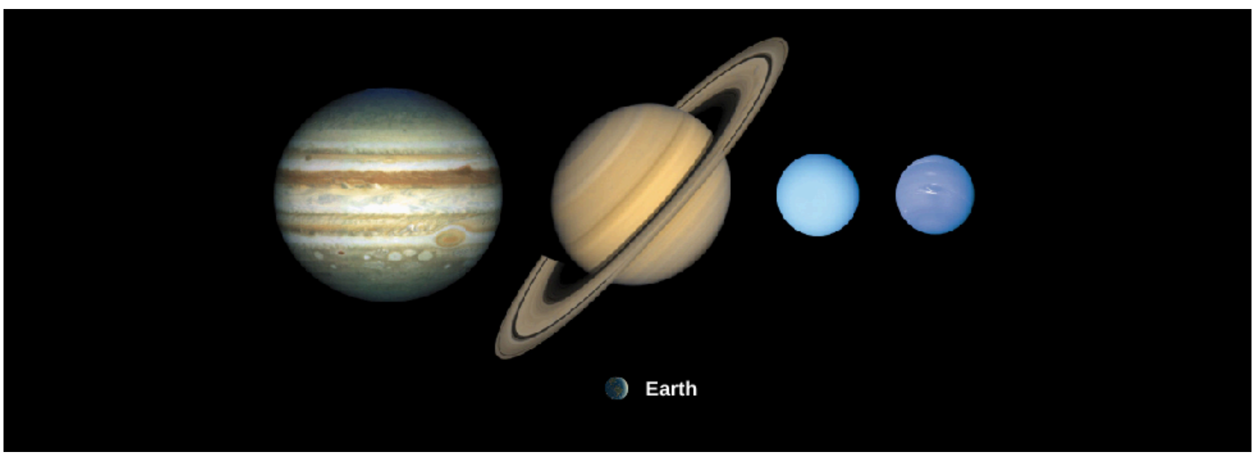


Figure 7.5 The Four Giant Planets. This montage shows the four giant planets: Jupiter, Saturn, Uranus, and Neptune. Below them, Earth is shown to scale. (credit: modification of work by NASA, Solar System Exploration)

Near the outer edge of the system lies Pluto, which was the first of the distant icy worlds to be discovered beyond Neptune (Pluto was visited by a spacecraft, the NASA New Horizons mission, in 2015 [see Figure 7.6]). Table 7.2 summarizes some of the main facts about the planets.

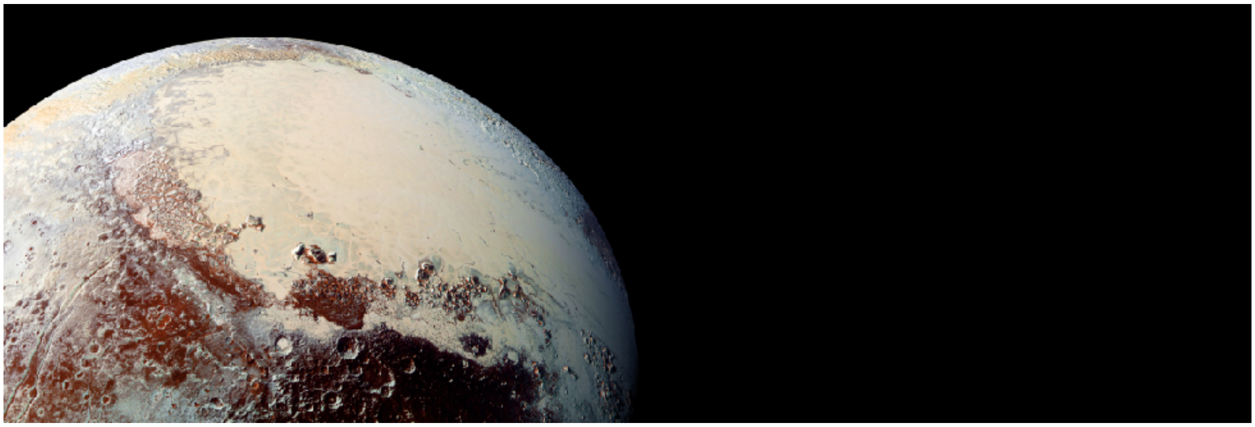


Figure 7.6 Pluto Close-up. This intriguing image from the New Horizons spacecraft, taken when it flew by the dwarf planet in July 2015, shows some of its complex surface features. The rounded white area is temporarily being called the Sputnik Plain, after humanity's first spacecraft. (credit: modification of work by NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute)

The Planets

Name	Distance from Sun (AU)[2]	Revolution Period (y)	Diameter (km)	Mass (10^{23} kg)	Density (g/cm^3)[3]
Mercury	0.39	0.24	4,878	3.3	5.4
Venus	0.72	0.62	12,120	48.7	5.2
Earth	1.00	1.00	12,756	59.8	5.5
Mars	1.52	1.88	6,787	6.4	3.9
Jupiter	5.20	11.86	142,984	18,991	1.3
Saturn	9.54	29.46	120,536	5686	0.7
Uranus	19.18	84.07	51,118	866	1.3
Neptune	30.06	164.82	49,660	1030	1.6

Table 7.2

EXAMPLE 7.1

Comparing Densities

Let's compare the densities of several members of the solar system. The density of an object equals its mass divided by its volume. The volume (*V*) of a sphere (like a planet) is calculated using the equation

2 An AU (or astronomical unit) is the distance from Earth to the Sun.

3 We give densities in units where the density of water is 1 g/cm^3. To get densities in units of kg/m^3, multiply the given value by 1000.

$$V = \frac{4}{3}\pi R^3$$

where π (the Greek letter pi) has a value of approximately 3.14. Although planets are not perfect spheres, this equation works well enough. The masses and diameters of the planets are given in **Table 7.2**. For data on selected moons, see **Appendix G**. Let's use Saturn's moon Mimas as our example, with a mass of 4×10^{19} kg and a diameter of approximately 400 km (radius, 200 km = 2×10^5 m).

Solution

The volume of Mimas is

$$\frac{4}{3} \times 3.14 \times \left(2 \times 10^5 \text{ m}\right)^3 = 3.3 \times 10^{16} \text{ m}^3.$$

Density is mass divided by volume:

$$\frac{4 \times 10^{19} \text{ kg}}{3.3 \times 10^{16} \text{ m}^3} = 1.2 \times 10^3 \text{ kg/m}^3.$$

Note that the density of water in these units is 1000 kg/m^3, so Mimas must be made mainly of ice, not rock. (Note that the density of Mimas given in **Appendix G** is 1.2, but the units used there are different. In that table, we give density in units of
g/cm^3, for which the density of water equals 1. Can you show, by converting units, that 1 g/cm^3 is the same as 1000 kg/m^3?)

Check Your Learning

Calculate the average density of our own planet, Earth. Show your work. How does it compare to the density of an ice moon like Mimas? See **Table 7.2** for data.

Answer:

For a sphere,

$$\text{density} = \frac{\text{mass}}{\left(\frac{4}{3}\pi R^3\right)} \text{ kg/m}^3.$$

For Earth, then,

$$\text{density} = \frac{6 \times 10^{24} \text{ kg}}{4.2 \times 2.6 \times 10^{20} \text{ m}^3} = 5.5 \times 10^3 \text{ kg/m}^3.$$

This density is four to five times greater than Mimas'. In fact, Earth is the densest of the planets.

LINK TO LEARNING

Learn more about NASA's **mission to Pluto (https://openstaxcollege.org/l/30NASAmisspluto)** and see high-resolution images of Pluto's moon Charon.

Smaller Members of the Solar System

Most of the planets are accompanied by one or more moons; only Mercury and Venus move through space alone. There are more than 180 known moons orbiting planets and dwarf planets (see **Appendix G** for a listing of the larger ones), and undoubtedly many other small ones remain undiscovered. The largest of the moons are as big as small planets and just as interesting. In addition to our Moon, they include the four largest moons of Jupiter (called the Galilean moons, after their discoverer) and the largest moons of Saturn and Neptune (confusingly named Titan and Triton).

Each of the giant planets also has rings made up of countless small bodies ranging in size from mountains to mere grains of dust, all in orbit about the equator of the planet. The bright rings of Saturn are, by far, the easiest to see. They are among the most beautiful sights in the solar system (Figure 7.7). But, all four ring systems are interesting to scientists because of their complicated forms, influenced by the pull of the moons that also orbit these giant planets.

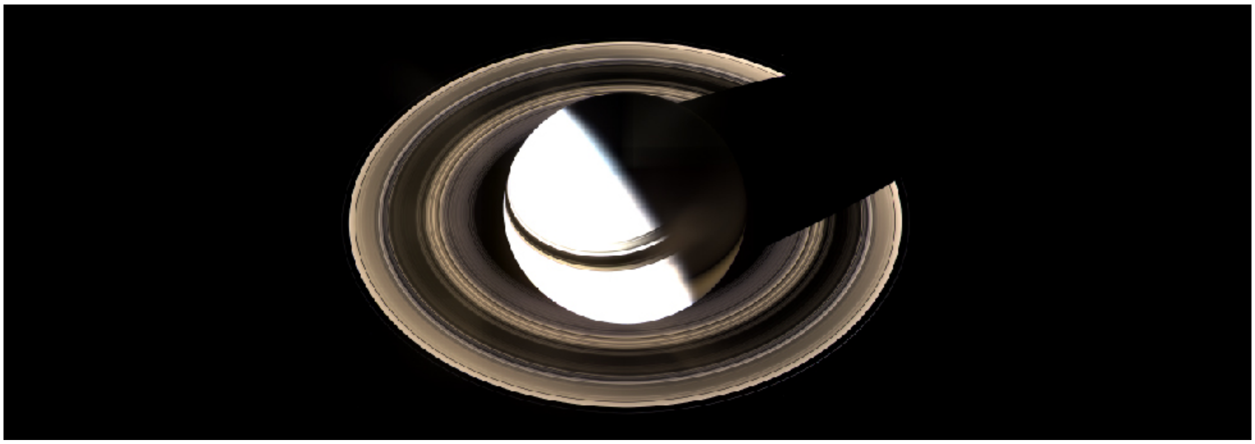


Figure 7.7 Saturn and Its Rings. This 2007 Cassini image shows Saturn and its complex system of rings, taken from a distance of about 1.2 million kilometers. This natural-color image is a composite of 36 images taken over the course of 2.5 hours. (credit: modification of work by NASA/JPL/Space Science Institute)

The solar system has many other less-conspicuous members. Another group is the **asteroids**, rocky bodies that orbit the Sun like miniature planets, mostly in the space between Mars and Jupiter (although some do cross the orbits of planets like Earth—see Figure 7.8). Most asteroids are remnants of the initial population of the solar system that existed before the planets themselves formed. Some of the smallest moons of the planets, such as the moons of Mars, are very likely captured asteroids.

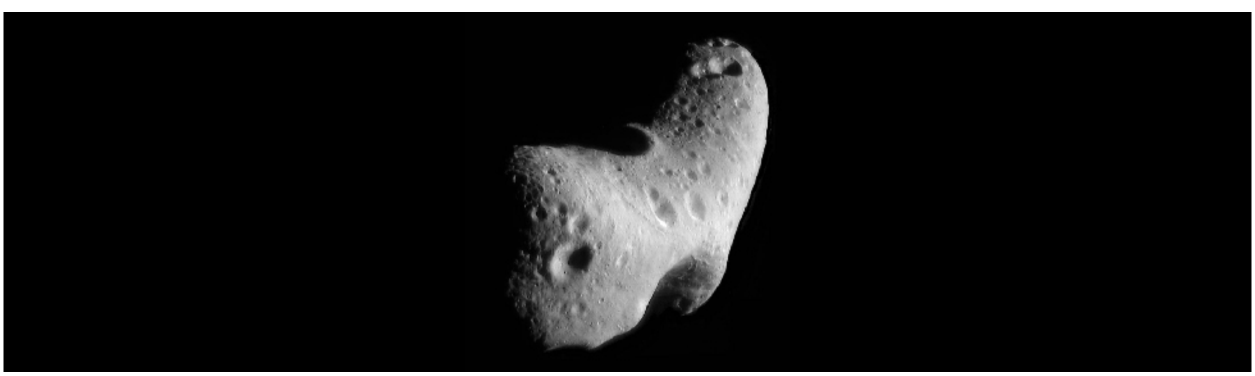


Figure 7.8 Asteroid Eros. This small Earth-crossing asteroid image was taken by the NEAR-Shoemaker spacecraft from an altitude of about 100 kilometers. This view of the heavily cratered surface is about 10 kilometers wide. The spacecraft orbited Eros for a year before landing gently on its surface. (credit: modification of work by NASA/JHUAPL)

Another class of small bodies is composed mostly of ice, made of frozen gases such as water, carbon dioxide, and carbon monoxide; these objects are called **comets** (see Figure 7.9). Comets also are remnants from the formation of the solar system, but they were formed and continue (with rare exceptions) to orbit the Sun in distant, cooler regions—stored in a sort of cosmic deep freeze. This is also the realm of the larger icy worlds, called dwarf planets.

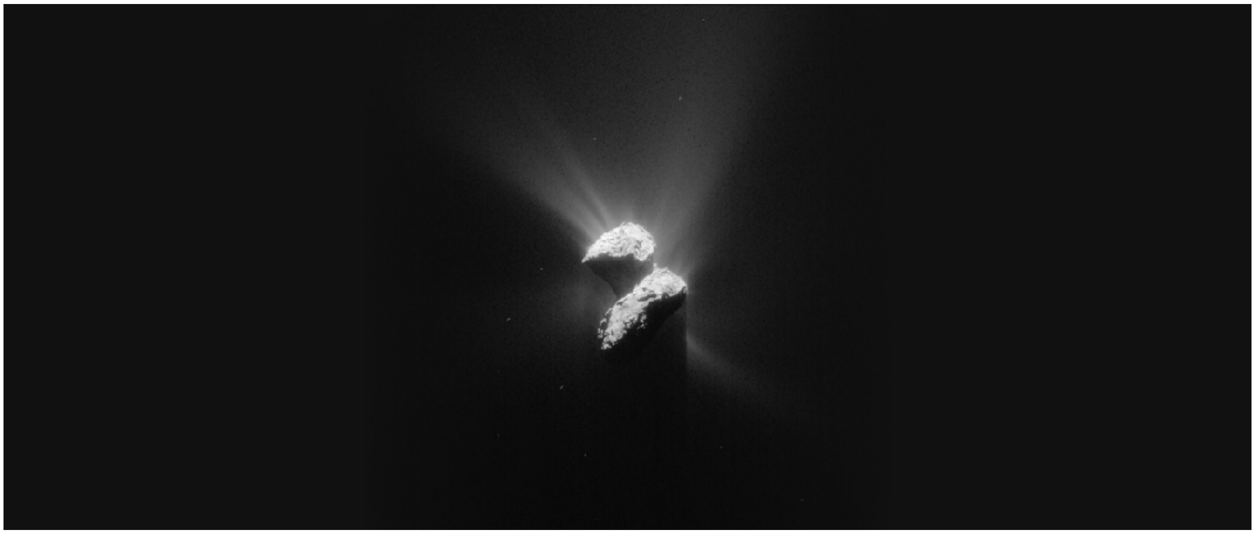


Figure 7.9 Comet Churyumov-Gerasimenko (67P). This image shows Comet Churyumov-Gerasimenko, also known as 67P, near its closest approach to the Sun in 2015, as seen from the *Rosetta* spacecraft. Note the jets of gas escaping from the solid surface. (credit: modification of work by ESA/Rosetta/NAVACAM, **CC BY-SA IGO 3.0 (http://creativecommons.org/licenses/by-sa/3.0/igo/)**)

Finally, there are countless grains of broken rock, which we call cosmic dust, scattered throughout the solar system. When these particles enter Earth's atmosphere (as millions do each day) they burn up, producing a brief flash of light in the night sky known as a **meteor** (meteors are often referred to as shooting stars). Occasionally, some larger chunk of rocky or metallic material survives its passage through the atmosphere and lands on Earth. Any piece that strikes the ground is known as a **meteorite**. (You can see meteorites on display in many natural history museums and can sometimes even purchase pieces of them from gem and mineral dealers.)

VOYAGERS IN ASTRONOMY

Carl Sagan: Solar System Advocate

The best-known astronomer in the world during the 1970s and 1980s, Carl Sagan devoted most of his professional career to studying the planets and considerable energy to raising public awareness of what we can learn from exploring the solar system (see **Figure 7.10**). Born in Brooklyn, New York, in 1934, Sagan became interested in astronomy as a youngster; he also credits science fiction stories for sustaining his fascination with what's out in the universe.

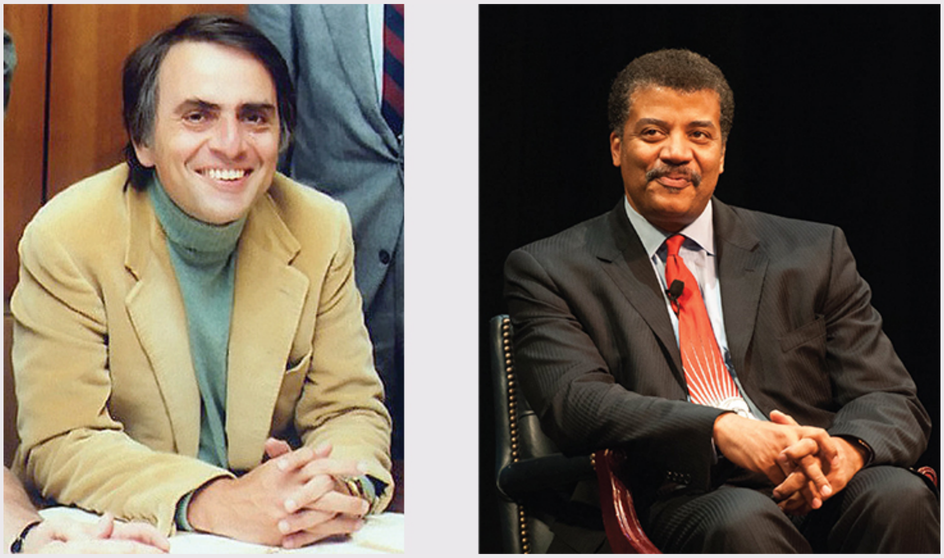


Figure 7.10 Carl Sagan (1934–1996) and Neil deGrasse Tyson. Sagan was Tyson's inspiration to become a scientist. (credit "Sagan": modification of work by NASA, JPL; credit "Tyson": modification of work by Bruce F. Press)

In the early 1960s, when many scientists still thought Venus might turn out to be a hospitable place, Sagan calculated that the thick atmosphere of Venus could act like a giant greenhouse, keeping the heat in and raising the temperature enormously. He showed that the seasonal changes astronomers had seen on Mars were caused, not by vegetation, but by wind-blown dust. He was a member of the scientific teams for many of the robotic missions that explored the solar system and was instrumental in getting NASA to put a message-bearing plaque aboard the Pioneer spacecraft, as well as audio-video records on the Voyager spacecraft—all of them destined to leave our solar system entirely and send these little bits of Earth technology out among the stars.

To encourage public interest and public support of planetary exploration, Sagan helped found The Planetary Society, now the largest space-interest organization in the world. He was a tireless and eloquent advocate of the need to study the solar system close-up and the value of learning about other worlds in order to take better care of our own.

Sagan simulated conditions on early Earth to demonstrate how some of life's fundamental building blocks might have formed from the "primordial soup" of natural compounds on our planet. In addition, he and his colleagues developed computer models showing the consequences of nuclear war for Earth would be even more devastating than anyone had thought (this is now called the nuclear winter hypothesis) and demonstrating some of the serious consequences of continued pollution of our atmosphere.

Sagan was perhaps best known, however, as a brilliant popularizer of astronomy and the author of many books on science, including the best-selling *Cosmos*, and several evocative tributes to solar system exploration such as *The Cosmic Connection* and *Pale Blue Dot*. His book *The Demon Haunted World*, completed just before his death in 1996, is perhaps the best antidote to fuzzy thinking about pseudo-science and irrationality in print today. An intriguing science fiction novel he wrote, titled *Contact*, which became a successful film as well, is still recommended by many science instructors as a scenario for making contact with life elsewhere that is much more reasonable than most science fiction.

Sagan was a master, too, of the television medium. His 13-part public television series, *Cosmos*, was seen by an estimated 500 million people in 60 countries and has become one of the most-watched series in the history of public broadcasting. A few astronomers scoffed at a scientist who spent so much time in the public eye, but it is probably fair to say that Sagan's enthusiasm and skill as an explainer won more friends for the science of astronomy than anyone or anything else in the second half of the twentieth century.

In the two decades since Sagan's death, no other scientist has achieved the same level of public recognition. Perhaps closest is the director of the Hayden Planetarium, Neil deGrasse Tyson, who followed in Sagan's footsteps by making an updated version of the *Cosmos* program in 2014. Tyson is quick to point out that Sagan was his inspiration to become a scientist, telling how Sagan invited him to visit for a day at Cornell when he was a high school student looking for a career. However, the media environment has fragmented a great deal since Sagan's time. It is interesting to speculate whether Sagan could have adapted his communication style to the world of cable television, Twitter, Facebook, and podcasts.

LINK TO LEARNING

Two imaginative videos provide a tour of the solar system objects we have been discussing. Shane Gellert's **I Need Some Space (https://openstaxcollege.org/l/30needsomespace)** uses NASA photography and models to show the various worlds with which we share our system. In the more science fiction-oriented **Wanderers (https://openstaxcollege.org/l/30wanderers)** video, we see some of the planets and moons as tourist destinations for future explorers, with commentary taken from recordings by Carl Sagan.

A Scale Model of the Solar System

Astronomy often deals with dimensions and distances that far exceed our ordinary experience. What does 1.4 billion kilometers—the distance from the Sun to Saturn—really mean to anyone? It can be helpful to visualize such large systems in terms of a scale model.

In our imaginations, let us build a scale model of the solar system, adopting a scale factor of 1 billion (10^9)—that is, reducing the actual solar system by dividing every dimension by a factor of 10^9. Earth, then, has a diameter of 1.3 centimeters, about the size of a grape. The Moon is a pea orbiting this at a distance of 40 centimeters, or a little more than a foot away. The Earth-Moon system fits into a standard backpack.

In this model, the Sun is nearly 1.5 meters in diameter, about the average height of an adult, and our Earth is at a distance of 150 meters—about one city block—from the Sun. Jupiter is five blocks away from the Sun, and its diameter is 15 centimeters, about the size of a very large grapefruit. Saturn is 10 blocks from the Sun; Uranus, 20 blocks; and Neptune, 30 blocks. Pluto, with a distance that varies quite a bit during its 249-year orbit, is currently just beyond 30 blocks and getting farther with time. Most of the moons of the outer solar system are the sizes of various kinds of seeds orbiting the grapefruit, oranges, and lemons that represent the outer planets.

In our scale model, a human is reduced to the dimensions of a single atom, and cars and spacecraft to the size of molecules. Sending the Voyager spacecraft to Neptune involves navigating a single molecule from the Earth–grape toward a lemon 5 kilometers away with an accuracy equivalent to the width of a thread in a spider's web.

If that model represents the solar system, where would the nearest stars be? If we keep the same scale, the closest stars would be tens of thousands of kilometers away. If you built this scale model in the city where you live, you would have to place the representations of these stars on the other side of Earth or beyond.

By the way, model solar systems like the one we just presented have been built in cities throughout the world. In Sweden, for example, Stockholm's huge Globe Arena has become a model for the Sun, and Pluto is represented by a 12-centimeter sculpture in the small town of Delsbo, 300 kilometers away. Another model solar system is in Washington on the Mall between the White House and Congress (perhaps proving they are worlds apart?).

MAKING CONNECTIONS

Names in the Solar System

We humans just don't feel comfortable until something has a name. Types of butterflies, new elements, and the mountains of Venus all need names for us to feel we are acquainted with them. How do we give names to objects and features in the solar system?

Planets and moons are named after gods and heroes in Greek and Roman mythology (with a few exceptions among the moons of Uranus, which have names drawn from English literature). When William Herschel, a German immigrant to England, first discovered the planet we now call Uranus, he wanted to name it Georgium Sidus (George's star) after King George III of his adopted country. This caused such an outcry among astronomers in other nations, however, that the classic tradition was upheld—and has been maintained ever since. Luckily, there were a lot of minor gods in the ancient pantheon, so plenty of names are left for the many small moons we are discovering around the giant planets. (**Appendix G** lists the larger moons).

Comets are often named after their discoverers (offering an extra incentive to comet hunters). Asteroids are named by their discoverers after just about anyone or anything they want. Recently, asteroid names have been used to recognize people who have made significant contributions to astronomy, including the three original authors of this book.

That was pretty much all the naming that was needed while our study of the solar system was confined to Earth. But now, our spacecraft have surveyed and photographed many worlds in great detail, and each world has a host of features that also need names. To make sure that naming things in space remains multinational, rational, and somewhat dignified, astronomers have given the responsibility of approving names to a special committee of the International Astronomical Union (IAU), the body that includes scientists from every country that does astronomy.

This IAU committee has developed a set of rules for naming features on other worlds. For example, craters on Venus are named for women who have made significant contributions to human knowledge and welfare. Volcanic features on Jupiter's moon Io, which is in a constant state of volcanic activity, are named after gods of fire and thunder from the mythologies of many cultures. Craters on Mercury commemorate famous novelists, playwrights, artists, and composers. On Saturn's moon Tethys, all the features are named after characters and places in Homer's great epic poem, *The Odyssey*. As we explore further, it may well turn out that more places in the solar system need names than Earth history can provide. Perhaps by then, explorers and settlers on these worlds will be ready to develop their own names for the places they may (if but for a while) call home.

You may be surprised to know that the meaning of the word *planet* has recently become controversial because we have discovered many other planetary systems that don’t look very much like our own. Even within our solar system, the planets differ greatly in size and chemical properties. The biggest dispute concerns Pluto, which is much smaller than the other eight major planets. The category of dwarf planet was invented to include Pluto and similar icy objects beyond Neptune. But is a dwarf planet also a planet? Logically, it should be, but even this simple issue of grammar has been the subject of heated debate among both astronomers and the general public.

7.2 COMPOSITION AND STRUCTURE OF PLANETS

Learning Objectives

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

- Describe the characteristics of the giant planets, terrestrial planets, and small bodies in the solar system
- Explain what influences the temperature of a planet’s surface
- Explain why there is geological activity on some planets and not on others

The fact that there are two distinct kinds of planets—the rocky terrestrial planets and the gas-rich jovian planets—leads us to believe that they formed under different conditions. Certainly their compositions are dominated by different elements. Let us look at each type in more detail.

The Giant Planets

The two largest planets, Jupiter and Saturn, have nearly the same chemical makeup as the Sun; they are composed primarily of the two elements hydrogen and helium, with 75% of their mass being hydrogen and 25% helium. On Earth, both hydrogen and helium are gases, so Jupiter and Saturn are sometimes called gas planets. But, this name is misleading. Jupiter and Saturn are so large that the gas is compressed in their interior until the hydrogen becomes a liquid. Because the bulk of both planets consists of compressed, liquefied hydrogen, we should really call them liquid planets.

Under the force of gravity, the heavier elements sink toward the inner parts of a liquid or gaseous planet. Both Jupiter and Saturn, therefore, have cores composed of heavier rock, metal, and ice, but we cannot see these regions directly. In fact, when we look down from above, all we see is the atmosphere with its swirling clouds (**Figure 7.11**). We must infer the existence of the denser core inside these planets from studies of each planet’s gravity.

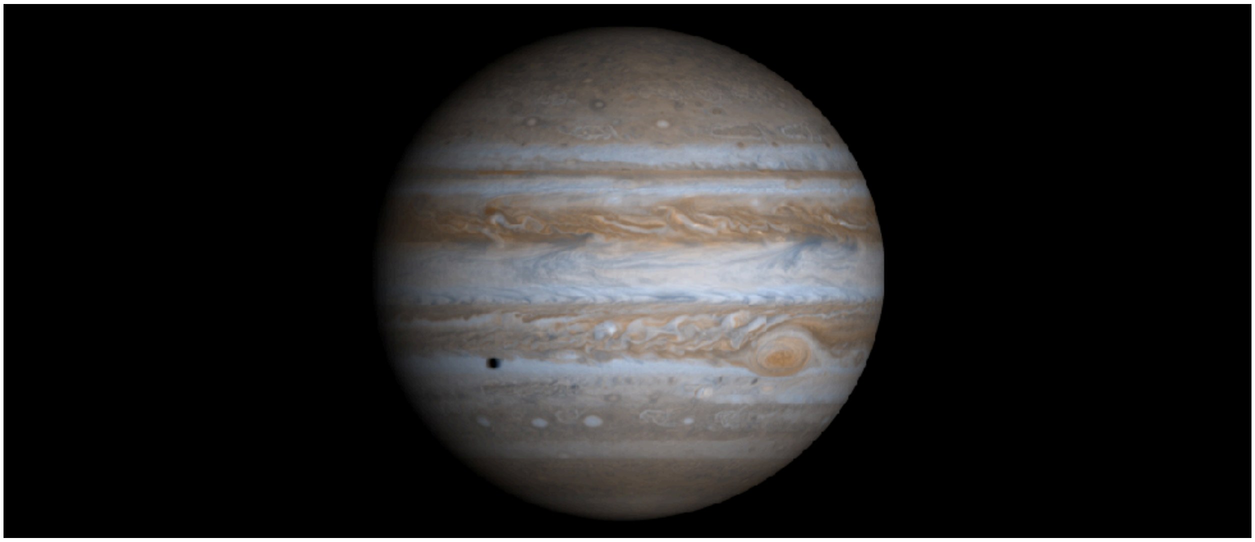


Figure 7.11 Jupiter. This true-color image of Jupiter was taken from the Cassini spacecraft in 2000. (credit: modification of work by NASA/JPL/University of Arizona)

Uranus and Neptune are much smaller than Jupiter and Saturn, but each also has a core of rock, metal, and ice. Uranus and Neptune were less efficient at attracting hydrogen and helium gas, so they have much smaller atmospheres in proportion to their cores.

Chemically, each giant planet is dominated by hydrogen and its many compounds. Nearly all the oxygen present is combined chemically with hydrogen to form water (H_2O). Chemists call such a hydrogen-dominated composition *reduced*. Throughout the outer solar system, we find abundant water (mostly in the form of ice) and reducing chemistry.

The Terrestrial Planets

The terrestrial planets are quite different from the giants. In addition to being much smaller, they are composed primarily of rocks and metals. These, in turn, are made of elements that are less common in the universe as a whole. The most abundant rocks, called silicates, are made of silicon and oxygen, and the most common metal is iron. We can tell from their densities (see **Table 7.2**) that Mercury has the greatest proportion of metals (which are denser) and the Moon has the lowest. Earth, Venus, and Mars all have roughly similar bulk compositions: about one third of their mass consists of iron-nickel or iron-sulfur combinations; two thirds is made of silicates. Because these planets are largely composed of oxygen compounds (such as the silicate minerals of their crusts), their chemistry is said to be *oxidized*.

When we look at the internal structure of each of the terrestrial planets, we find that the densest metals are in a central core, with the lighter silicates near the surface. If these planets were liquid, like the giant planets, we could understand this effect as the result the sinking of heavier elements due to the pull of gravity. This leads us to conclude that, although the terrestrial planets are solid today, at one time they must have been hot enough to melt.

Differentiation is the process by which gravity helps separate a planet’s interior into layers of different compositions and densities. The heavier metals sink to form a core, while the lightest minerals float to the surface to form a crust. Later, when the planet cools, this layered structure is preserved. In order for a rocky planet to differentiate, it must be heated to the melting point of rocks, which is typically more than 1300 K.

Moons, Asteroids, and Comets

Chemically and structurally, Earth's Moon is like the terrestrial planets, but most moons are in the outer solar system, and they have compositions similar to the cores of the giant planets around which they orbit. The three largest moons—Ganymede and Callisto in the jovian system, and Titan in the saturnian system—are composed half of frozen water, and half of rocks and metals. Most of these moons differentiated during formation, and today they have cores of rock and metal, with upper layers and crusts of very cold and—thus very hard—ice (**Figure 7.12**).

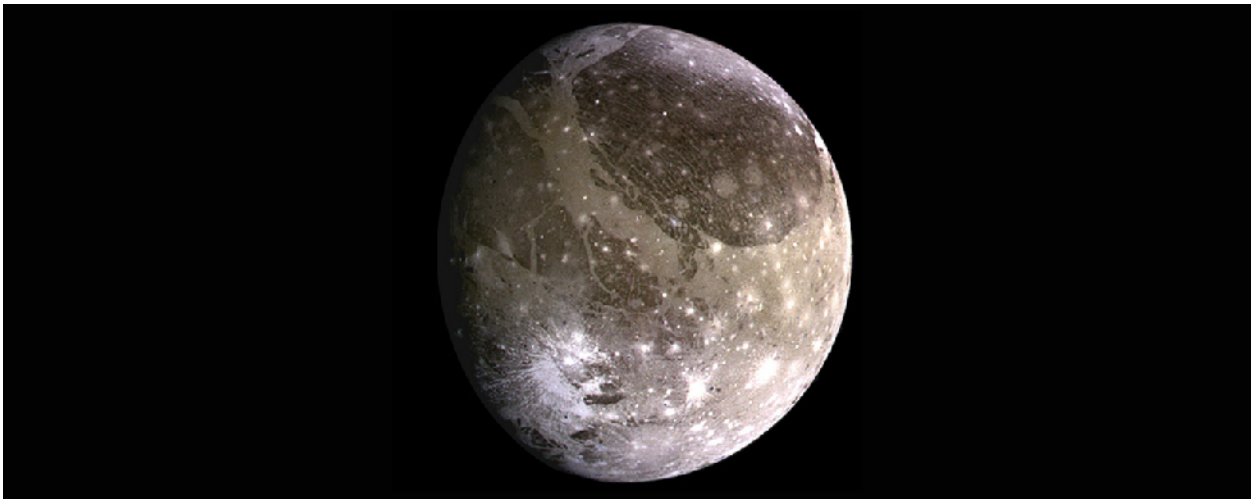


Figure 7.12 Ganymede. This view of Jupiter's moon Ganymede was taken in June 1996 by the Galileo spacecraft. The brownish gray color of the surface indicates a dusty mixture of rocky material and ice. The bright spots are places where recent impacts have uncovered fresh ice from underneath. (credit: modification of work by NASA/JPL)

Most of the asteroids and comets, as well as the smallest moons, were probably never heated to the melting point. However, some of the largest asteroids, such as Vesta, appear to be differentiated; others are fragments from differentiated bodies. Because most asteroids and comets retain their original composition, they represent relatively unmodified material dating back to the time of the formation of the solar system. In a sense, they act as chemical fossils, helping us to learn about a time long ago whose traces have been erased on larger worlds.

Temperatures: Going to Extremes

Generally speaking, the farther a planet or moon is from the Sun, the cooler its surface. The planets are heated by the radiant energy of the Sun, which gets weaker with the square of the distance. You know how rapidly the heating effect of a fireplace or an outdoor radiant heater diminishes as you walk away from it; the same effect applies to the Sun. Mercury, the closest planet to the Sun, has a blistering surface temperature that ranges from 280–430 °C on its sunlit side, whereas the surface temperature on Pluto is only about –220 °C, colder than liquid air.

Mathematically, the temperatures decrease approximately in proportion to the square root of the distance from the Sun. Pluto is about 30 AU at its closest to the Sun (or 100 times the distance of Mercury) and about 49 AU at its farthest from the Sun. Thus, Pluto's temperature is less than that of Mercury by the square root of 100, or a factor of 10: from 500 K to 50 K.

In addition to its distance from the Sun, the surface temperature of a planet can be influenced strongly by its atmosphere. Without our atmospheric insulation (the greenhouse effect, which keeps the heat in), the oceans of Earth would be permanently frozen. Conversely, if Mars once had a larger atmosphere in the past, it could have supported a more temperate climate than it has today. Venus is an even more extreme example, where its thick atmosphere of carbon dioxide acts as insulation, reducing the escape of heat built up at the surface, resulting in temperatures greater than those on Mercury. Today, Earth is the only planet where surface temperatures generally lie between the freezing and boiling points of water. As far as we know, Earth is the only planet to support life.

ASTRONOMY BASICS

There's No Place Like Home

In the classic film *The Wizard of Oz*, Dorothy, the heroine, concludes after her many adventures in "alien" environments that "there's no place like home." The same can be said of the other worlds in our solar system. There are many fascinating places, large and small, that we might like to visit, but humans could not survive on any without a great deal of artificial assistance.

A thick carbon dioxide atmosphere keeps the surface temperature on our neighbor Venus at a sizzling 700 K (near 900 °F). Mars, on the other hand, has temperatures generally below freezing, with air (also mostly carbon dioxide) so thin that it resembles that found at an altitude of 30 kilometers (100,000 feet) in Earth's atmosphere. And the red planet is so dry that it has not had any rain for billions of years.

The outer layers of the jovian planets are neither warm enough nor solid enough for human habitation. Any bases we build in the systems of the giant planets may well have to be in space or one of their moons—none of which is particularly hospitable to a luxury hotel with a swimming pool and palm trees. Perhaps we will find warmer havens deep inside the clouds of Jupiter or in the ocean under the frozen ice of its moon Europa.

All of this suggests that we had better take good care of Earth because it is the only site where life as we know it could survive. Recent human activity may be reducing the habitability of our planet by adding pollutants to the atmosphere, especially the potent greenhouse gas carbon dioxide. Human civilization is changing our planet dramatically, and these changes are not necessarily for the better. In a solar system that seems unready to receive us, making Earth less hospitable to life may be a grave mistake.

Geological Activity

The crusts of all of the terrestrial planets, as well as of the larger moons, have been modified over their histories by both internal and external forces. Externally, each has been battered by a slow rain of projectiles from space, leaving their surfaces pockmarked by impact craters of all sizes (see Figure 7.4). We have good evidence that this bombardment was far greater in the early history of the solar system, but it certainly continues to this day, even if at a lower rate. The collision of more than 20 large pieces of Comet Shoemaker–Levy 9 with Jupiter in the summer of 1994 (see Figure 7.13) is one dramatic example of this process.

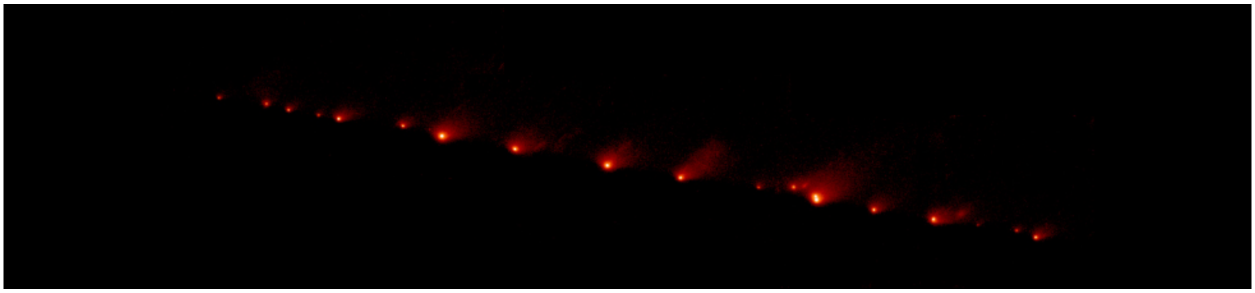


Figure 7.13 Comet Shoemaker–Levy 9. In this image of Comet Shoemaker–Levy 9 taken on May 17, 1994, by NASA's Hubble Space Telescope, you can see about 20 icy fragments into which the comet broke. The comet was approximately 660 million kilometers from Earth, heading on a collision course with Jupiter. (credit: modification of work by NASA, ESA, H. Weaver (STScl), E. Smith (STScl))

Figure 7.14 shows the aftermath of these collisions, when debris clouds larger than Earth could be seen in Jupiter's atmosphere.

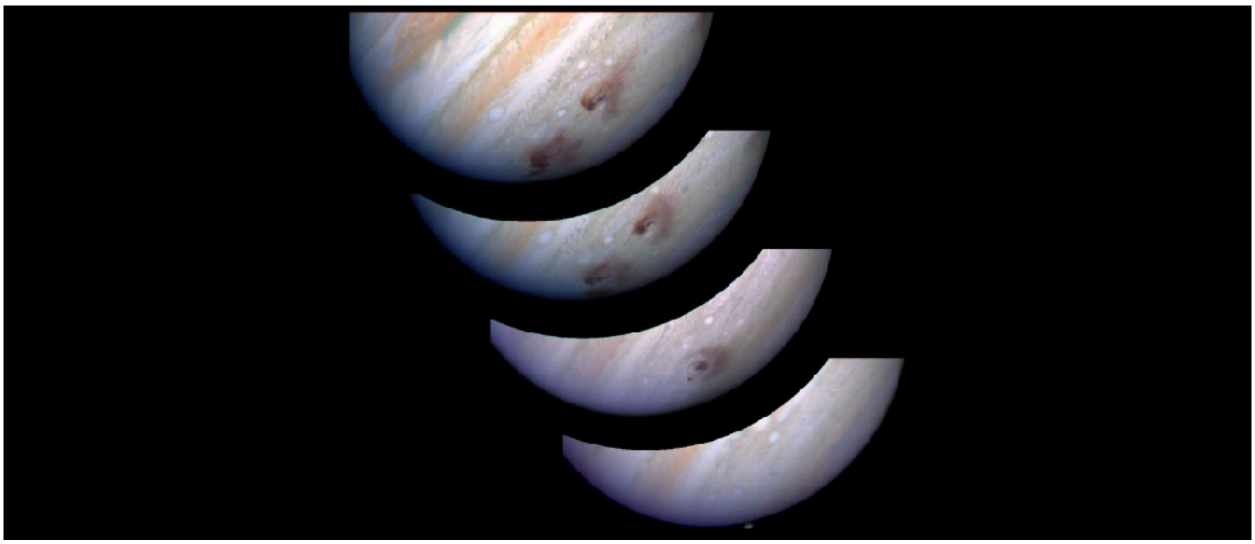


Figure 7.14 Jupiter with Huge Dust Clouds. The Hubble Space Telescope took this sequence of images of Jupiter in summer 1994, when fragments of Comet Shoemaker–Levy 9 collided with the giant planet. Here we see the site hit by fragment G, from five minutes to five days after impact. Several of the dust clouds generated by the collisions became larger than Earth. (credit: modification of work by H. Hammel, NASA)

During the time all the planets have been subject to such impacts, internal forces on the terrestrial planets have buckled and twisted their crusts, built up mountain ranges, erupted as volcanoes, and generally reshaped the surfaces in what we call geological activity. (The prefix *geo* means "Earth," so this is a bit of an "Earth-chauvinist" term, but it is so widely used that we bow to tradition.) Among the terrestrial planets, Earth and Venus have experienced the most geological activity over their histories, although some of the moons in the outer solar system are also surprisingly active. In contrast, our own Moon is a dead world where geological activity ceased billions of years ago.

Geological activity on a planet is the result of a hot interior. The forces of volcanism and mountain building are driven by heat escaping from the interiors of planets. As we will see, each of the planets was heated at the time of its birth, and this primordial heat initially powered extensive volcanic activity, even on our Moon. But, small objects such as the Moon soon cooled off. The larger the planet or moon, the longer it retains its internal heat, and therefore the more we expect to see surface evidence of continuing geological activity. The effect is similar to our own experience with a hot baked potato: the larger the potato, the more slowly it cools. If we want a potato to cool quickly, we cut it into small pieces.

For the most part, the history of volcanic activity on the terrestrial planets conforms to the predictions of this simple theory. The Moon, the smallest of these objects, is a geologically dead world. Although we know less about Mercury, it seems likely that this planet, too, ceased most volcanic activity about the same time the Moon did. Mars represents an intermediate case. It has been much more active than the Moon, but less so than Earth. Earth and Venus, the largest terrestrial planets, still have molten interiors even today, some 4.5 billion years after their birth.

7.3 DATING PLANETARY SURFACES

Learning Objectives

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

- Explain how astronomers can tell whether a planetary surface is geologically young or old
- Describe different methods for dating planets

How do we know the age of the surfaces we see on planets and moons? If a world has a surface (as opposed to being mostly gas and liquid), astronomers have developed some techniques for estimating how long ago that surface solidified. Note that the age of these surfaces is not necessarily the age of the planet as a whole. On geologically active objects (including Earth), vast outpourings of molten rock or the erosive effects of water and ice, which we call planet weathering, have erased evidence of earlier epochs and present us with only a relatively young surface for investigation.

Counting the Craters

One way to estimate the age of a surface is by counting the number of impact craters. This technique works because the rate at which impacts have occurred in the solar system has been roughly constant for several billion years. Thus, in the absence of forces to eliminate craters, the number of craters is simply proportional to the length of time the surface has been exposed. This technique has been applied successfully to many solid planets and moons (**Figure 7.15**).

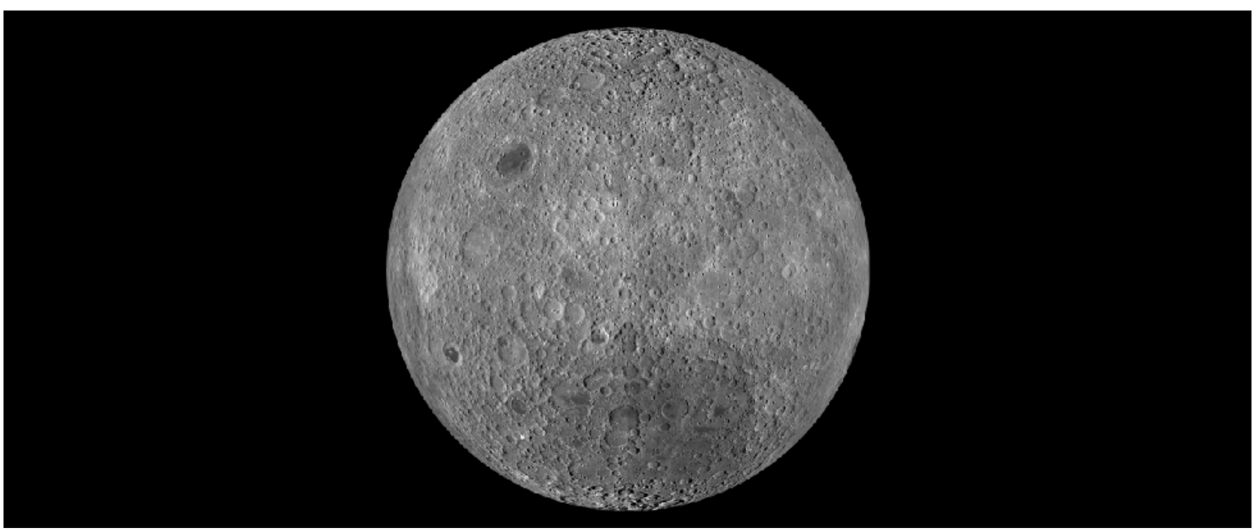


Figure 7.15 Our Cratered Moon. This composite image of the Moon’s surface was made from many smaller images taken between November 2009 and February 2011 by the Lunar Reconnaissance Orbiter (LRO) and shows craters of many different sizes. (credit: modification of work by NASA/GSFC/Arizona State University)

Bear in mind that crater counts can tell us only the time since the surface experienced a major change that could modify or erase preexisting craters. Estimating ages from crater counts is a little like walking along a sidewalk in a snowstorm after the snow has been falling steadily for a day or more. You may notice that in front of one house the snow is deep, while next door the sidewalk may be almost clear. Do you conclude that less snow has fallen in front of Ms. Jones' house than Mr. Smith's? More likely, you conclude that Jones has recently swept the walk clean and Smith has not. Similarly, the numbers of craters indicate how long it has been since a planetary surface was last "swept clean" by ongoing lava flows or by molten materials ejected when a large impact happened nearby.

Still, astronomers can use the numbers of craters on different parts of the same world to provide important clues about how regions on that world evolved. On a given planet or moon, the more heavily cratered terrain will generally be older (that is, more time will have elapsed there since something swept the region clean).

Radioactive Rocks

Another way to trace the history of a solid world is to measure the age of individual rocks. After samples were brought back from the Moon by Apollo astronauts, the techniques that had been developed to date rocks on Earth were applied to rock samples from the Moon to establish a geological chronology for the Moon. Furthermore, a few samples of material from the Moon, Mars, and the large asteroid Vesta have fallen to Earth as meteorites and can be examined directly (see the chapter on **Cosmic Samples and the Origin of the Solar System**).

Scientists measure the age of rocks using the properties of natural **radioactivity**. Around the beginning of the twentieth century, physicists began to understand that some atomic nuclei are not stable but can split apart (decay) spontaneously into smaller nuclei. The process of radioactive decay involves the emission of particles such as electrons, or of radiation in the form of gamma rays (see the chapter on **Radiation and Spectra**).

For any one radioactive nucleus, it is not possible to predict when the decay process will happen. Such decay is random in nature, like the throw of dice: as gamblers have found all too often, it is impossible to say just when the dice will come up 7 or 11. But, for a very large number of dice tosses, we can calculate the odds that 7 or 11 will come up. Similarly, if we have a very large number of radioactive atoms of one type (say, uranium), there is a specific time period, called its **half-life**, during which the chances are fifty-fifty that decay will occur for any of the nuclei.

A particular nucleus may last a shorter or longer time than its half-life, but in a large sample, almost exactly half of the nuclei will have decayed after a time equal to one half-life. Half of the remaining nuclei will have decayed after two half-lives pass, leaving only one half of a half—or one quarter—of the original sample (**Figure 7.16**).

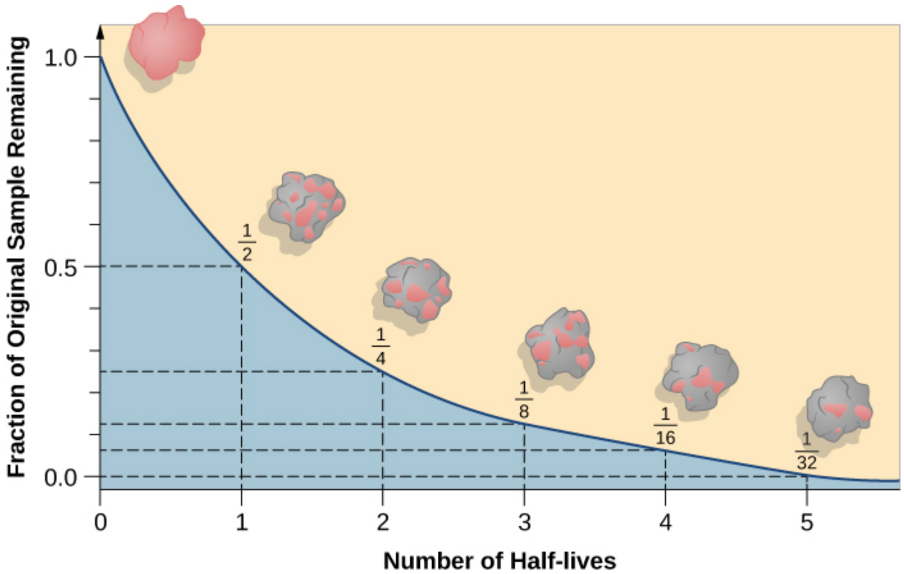


Figure 7.16 Radioactive Decay. This graph shows (in pink) the amount of a radioactive sample that remains after several half-lives have passed. After one half-life, half the sample is left; after two half-lives, one half of the remainder (or one quarter) is left; and after three half-lives, one half of that (or one eighth) is left. Note that, in reality, the decay of radioactive elements in a rock sample would not cause any visible change in the appearance of the rock; the splashes of color are shown here for conceptual purposes only.

If you had 1 gram of pure radioactive nuclei with a half-life of 100 years, then after 100 years you would have 1/2 gram; after 200 years, 1/4 gram; after 300 years, only 1/8 gram; and so forth. However, the material does not disappear. Instead, the radioactive atoms are replaced with their decay products. Sometimes the radioactive atoms are called *parents* and the decay products are called *daughter* elements.

In this way, radioactive elements with half-lives we have determined can provide accurate nuclear clocks. By comparing how much of a radioactive parent element is left in a rock to how much of its daughter products have accumulated, we can learn how long the decay process has been going on and hence how long ago the rock formed. Table 7.3 summarizes the decay reactions used most often to date lunar and terrestrial rocks.

Radioactive Decay Reaction Used to Date Rocks[4]

Parent	Daughter	Half-Life (billions of years)
Samarium-147	Neodymium-143	106
Rubidium-87	Strontium-87	48.8
Thorium-232	Lead-208	14.0
Uranium-238	Lead-206	4.47
Potassium-40	Argon-40	1.31

Table 7.3

4 The number after each element is its atomic weight, equal to the number of protons plus neutrons in its nucleus. This specifies the *isotope* of the element; different isotopes of the same element differ in the number of neutrons.

LINK TO LEARNING

PBS provides an **evolution series excerpt (https://openstaxcollege.org/l/30pbsradiomat)** that explains how we use radioactive elements to date Earth.

This **Science Channel video (https://openstaxcollege.org/l/30billnyevideo)** features Bill Nye the Science Guy showing how scientists have used radioactive dating to determine the age of Earth.

When astronauts first flew to the Moon, one of their most important tasks was to bring back lunar rocks for radioactive age-dating. Until then, astronomers and geologists had no reliable way to measure the age of the lunar surface. Counting craters had let us calculate relative ages (for example, the heavily cratered lunar highlands were older than the dark lava plains), but scientists could not measure the actual age in years. Some thought that the ages were as young as those of Earth's surface, which has been resurfaced by many geological events. For the Moon's surface to be so young would imply active geology on our satellite. Only in 1969, when the first Apollo samples were dated, did we learn that the Moon is an ancient, geologically dead world. Using such dating techniques, we have been able to determine the ages of both Earth and the Moon: each was formed about 4.5 billion years ago (although, as we shall see, Earth probably formed earlier).

We should also note that the decay of radioactive nuclei generally releases energy in the form of heat. Although the energy from a single nucleus is not very large (in human terms), the enormous numbers of radioactive nuclei in a planet or moon (especially early in its existence) can be a significant source of internal energy for that world. Geologists estimate that about half of Earth's current internal heat budget comes from the decay of radioactive isotopes in its interior.

7.4 ORIGIN OF THE SOLAR SYSTEM

Learning Objectives

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

- Describe the characteristics of planets that are used to create formation models of the solar system
- Describe how the characteristics of extrasolar systems help us to model our own solar system
- Explain the importance of collisions in the formation of the solar system

Much of astronomy is motivated by a desire to understand the origin of things: to find at least partial answers to age-old questions of where the universe, the Sun, Earth, and we ourselves came from. Each planet and moon is a fascinating place that may stimulate our imagination as we try to picture what it would be like to visit. Taken together, the members of the solar system preserve patterns that can tell us about the formation of the entire system. As we begin our exploration of the planets, we want to introduce our modern picture of how the solar system formed.

The recent discovery of hundreds of planets in orbit around other stars has shown astronomers that many exoplanetary systems can be quite different from our own solar system. For example, it is common for these systems to include planets intermediate in size between our terrestrial and giant planets. These are often called *superearths*. Some exoplanet systems even have giant planets close to the star, reversing the order we see in our system. In **The Birth of Stars and the Discovery of Planets outside the Solar System**, we will look at these exoplanet systems. But for now, let us focus on theories of how our own particular system has formed and evolved.

Looking for Patterns

One way to approach our question of origin is to look for regularities among the planets. We found, for example, that all the planets lie in nearly the same plane and revolve in the same direction around the Sun. The Sun also spins in the same direction about its own axis. Astronomers interpret this pattern as evidence that the Sun and planets formed together from a spinning cloud of gas and dust that we call the **solar nebula** (**Figure 7.17**).

Figure 7.17 Solar Nebula. This artist's conception of the solar nebula shows the flattened cloud of gas and dust from which our planetary system formed. Icy and rocky planetesimals (precursors of the planets) can be seen in the foreground. The bright center is where the Sun is forming. (credit: William K. Hartmann, Planetary Science Institute)

The composition of the planets gives another clue about origins. Spectroscopic analysis allows us to determine which elements are present in the Sun and the planets. The Sun has the same hydrogen-dominated composition as Jupiter and Saturn, and therefore appears to have been formed from the same reservoir of material. In comparison, the terrestrial planets and our Moon are relatively deficient in the light gases and the various ices that form from the common elements oxygen, carbon, and nitrogen. Instead, on Earth and its neighbors, we see mostly the rarer heavy elements such as iron and silicon. This pattern suggests that the processes that led to planet formation in the inner solar system must somehow have excluded much of the lighter materials that are common elsewhere. These lighter materials must have escaped, leaving a residue of heavy stuff.

The reason for this is not hard to guess, bearing in mind the heat of the Sun. The inner planets and most of the asteroids are made of rock and metal, which can survive heat, but they contain very little ice or gas, which evaporate when temperatures are high. (To see what we mean, just compare how long a rock and an ice cube survive when they are placed in the sunlight.) In the outer solar system, where it has always been cooler, the planets and their moons, as well as icy dwarf planets and comets, are composed mostly of ice and gas.

The Evidence from Far Away

A second approach to understanding the origins of the solar system is to look outward for evidence that other systems of planets are forming elsewhere. We cannot look back in time to the formation of our own system, but many stars in space are much younger than the Sun. In these systems, the processes of planet formation might still be accessible to direct observation. We observe that there are many other “solar nebulas” or *circumstellar disks*—flattened, spinning clouds of gas and dust surrounding young stars. These disks resemble our own solar system’s initial stages of formation billions of years ago (**Figure 7.18**).

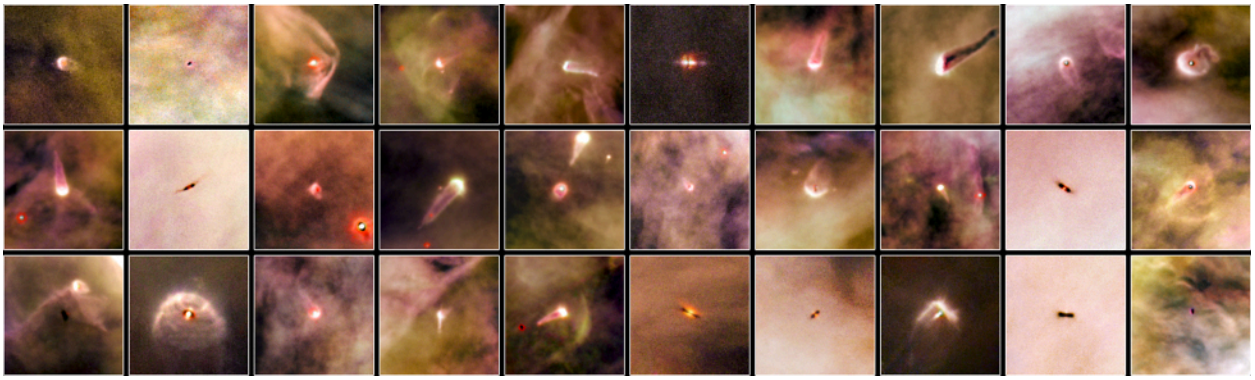


Figure 7.18 Atlas of Planetary Nurseries. These Hubble Space Telescope photos show sections of the Orion Nebula, a relatively close-by region where stars are currently forming. Each image shows an embedded circumstellar disk orbiting a very young star. Seen from different angles, some are energized to glow by the light of a nearby star while others are dark and seen in silhouette against the bright glowing gas of the Orion Nebula. Each is a contemporary analog of our own solar nebula—a location where planets are probably being formed today. (credit: modification of work by NASA/ESA, L. Ricci (ESO))

Building Planets

Circumstellar disks are a common occurrence around very young stars, suggesting that disks and stars form together. Astronomers can use theoretical calculations to see how solid bodies might form from the gas and dust in these disks as they cool. These models show that material begins to coalesce first by forming smaller objects, precursors of the planets, which we call **planetesimals**.

Today’s fast computers can simulate the way millions of planetesimals, probably no larger than 100 kilometers in diameter, might gather together under their mutual gravity to form the planets we see today. We are beginning to understand that this process was a violent one, with planetesimals crashing into each other and sometimes even disrupting the growing planets themselves. As a consequence of those violent impacts (and the heat from radioactive elements in them), all the planets were heated until they were liquid and gas, and therefore differentiated, which helps explain their present internal structures.

The process of impacts and collisions in the early solar system was complex and, apparently, often random. The solar nebula model can explain many of the regularities we find in the solar system, but the random collisions of massive collections of planetesimals could be the reason for some exceptions to the “rules” of solar system behavior. For example, why do the planets Uranus and Pluto spin on their sides? Why does Venus spin slowly and in the opposite direction from the other planets? Why does the composition of the Moon resemble Earth in many ways and yet exhibit substantial differences? The answers to such questions probably lie in enormous collisions that took place in the solar system long before life on Earth began.

Today, some 4.5 billion years after its origin, the solar system is—thank goodness—a much less violent place. As we will see, however, some planetesimals have continued to interact and collide, and their fragments move about the solar system as roving “transients” that can make trouble for the established members of the Sun’s family, such as our own Earth. (We discuss this “troublemaking” in **Comets and Asteroids: Debris of the Solar System**.)

LINK TO LEARNING

A great variety of **infographics (https://openstaxcollege.org/l/30worldsinsolar)** at space.com let you explore what it would be like to live on various worlds in the solar system.

CHAPTER 7 REVIEW

KEY TERMS

asteroid a stony or metallic object orbiting the Sun that is smaller than a major planet but that shows no evidence of an atmosphere or of other types of activity associated with comets

comet a small body of icy and dusty matter that revolves about the Sun; when a comet comes near the Sun, some of its material vaporizes, forming a large head of tenuous gas and often a tail

differentiation gravitational separation of materials of different density into layers in the interior of a planet or moon

giant planet any of the planets Jupiter, Saturn, Uranus, and Neptune in our solar system, or planets of roughly that mass and composition in other planetary systems

half-life time required for half of the radioactive atoms in a sample to disintegrate

meteor a small piece of solid matter that enters Earth’s atmosphere and burns up, popularly called a *shooting star* because it is seen as a small flash of light

meteorite a portion of a meteor that survives passage through an atmosphere and strikes the ground

planetesimals objects, from tens to hundreds of kilometers in diameter, that formed in the solar nebula as an intermediate step between tiny grains and the larger planetary objects we see today; the comets and some asteroids may be leftover planetesimals

radioactivity process by which certain kinds of atomic nuclei decay naturally, with the spontaneous emission of subatomic particles and gamma rays

solar nebula the cloud of gas and dust from which the solar system formed

terrestrial planet any of the planets Mercury, Venus, Earth, or Mars; sometimes the Moon is included in the list

SUMMARY

7.1 Overview of Our Planetary System

Our solar system currently consists of the Sun, eight planets, five dwarf planets, nearly 200 known moons, and a host of smaller objects. The planets can be divided into two groups: the inner terrestrial planets and the outer giant planets. Pluto, Eris, Haumea, and Makemake do not fit into either category; as icy dwarf planets, they exist in an ice realm on the fringes of the main planetary system. The giant planets are composed mostly of liquids and gases. Smaller members of the solar system include asteroids (including the dwarf planet Ceres), which are rocky and metallic objects found mostly between Mars and Jupiter; comets, which are made mostly of frozen gases and generally orbit far from the Sun; and countless smaller grains of cosmic dust. When a meteor survives its passage through our atmosphere and falls to Earth, we call it a meteorite.

7.2 Composition and Structure of Planets

The giant planets have dense cores roughly 10 times the mass of Earth, surrounded by layers of hydrogen and helium. The terrestrial planets consist mostly of rocks and metals. They were once molten, which allowed their structures to differentiate (that is, their denser materials sank to the center). The Moon resembles the terrestrial planets in composition, but most of the other moons—which orbit the giant planets—have larger quantities of frozen ice within them. In general, worlds closer to the Sun have higher surface temperatures. The surfaces of terrestrial planets have been modified by impacts from space and by varying degrees of geological activity.

7.3 Dating Planetary Surfaces

The ages of the surfaces of objects in the solar system can be estimated by counting craters: on a given world, a more heavily cratered region will generally be older than one that is less cratered. We can also use samples of rocks with radioactive elements in them to obtain the time since the layer in which the rock formed last solidified. The half-life of a radioactive element is the time it takes for half the sample to decay; we determine how many half-lives have passed by how much of a sample remains the radioactive element and how much has become the decay product. In this way, we have estimated the age of the Moon and Earth to be roughly 4.5 billion years.

7.4 Origin of the Solar System

Regularities among the planets have led astronomers to hypothesize that the Sun and the planets formed together in a giant, spinning cloud of gas and dust called the solar nebula. Astronomical observations show tantalizingly similar circumstellar disks around other stars. Within the solar nebula, material first coalesced into planetesimals; many of these gathered together to make the planets and moons. The remainder can still be seen as comets and asteroids. Probably all planetary systems have formed in similar ways, but many exoplanet systems have evolved along quite different paths, as we will see in **Cosmic Samples and the Origin of the Solar System**.

FOR FURTHER EXPLORATION

Articles

Davidson, K. "Carl Sagan's Coming of Age." *Astronomy.* (November 1999): 40. About the noted popularizer of science and how he developed his interest in astronomy.

Garget, J. "Mysterious Microworlds." *Astronomy.* (July 2005): 32. A quick tour of a number of the moons in the solar system.

Hartmann, W. "The Great Solar System Revision." *Astronomy*. (August 1998): 40. How our views have changed over the past 25 years.

Kross, J. "What's in a Name?" *Sky & Telescope*. (May 1995): 28. How worlds are named.

Rubin, A. "Secrets of Primitive Meteorites." *Scientific American*. (February 2013): 36. What meteorites can teach us about the environment in which the solar system formed.

Soter, S. "What Is a Planet?" *Scientific American*. (January 2007): 34. The IAU's new definition of a planet in our solar system, and what happened to Pluto as a result.

Talcott, R. "How the Solar System Came to Be." *Astronomy*. (November 2012): 24. On the formation period of the Sun and the planets.

Wood, J. "Forging the Planets: The Origin of our Solar System." *Sky & Telescope*. (January 1999): 36. Good overview.

Websites

Gazetteer of Planetary Nomenclature: **http://planetarynames.wr.usgs.gov/ (http://planetarynames.wr.usgs.gov/)** . Outlines the rules for naming bodies and features in the solar system.

Planetary Photojournal: **http://photojournal.jpl.nasa.gov/index.html (http://photojournal.jpl.nasa.gov/index.html)** . This NASA site features thousands of the best images from planetary exploration, with detailed captions and excellent indexing. You can find images by world, feature name, or mission, and download them in a number of formats. And the images are copyright-free because your tax dollars paid for them.

The following sites present introductory information and pictures about each of the worlds of our solar system:

- NASA/JPL Solar System Exploration pages: **http://solarsystem.nasa.gov/index.cfm (http://solarsystem.nasa.gov/index.cfm)** .
- National Space Science Data Center Lunar and Planetary Science pages: **http://nssdc.gsfc.nasa.gov/planetary/ (http://nssdc.gsfc.nasa.gov/planetary/)** .
- Nine [now 8] Planets Solar System Tour: **http://www.nineplanets.org/ (http://www.nineplanets.org/)** .
- Planetary Society solar system pages: **http://www.planetary.org/explore/space-topics/ (http://www.planetary.org/explore/space-topics/)** .
- Views of the Solar System by Calvin J. Hamilton: **http://www.solarviews.com/eng/homepage.htm (http://www.solarviews.com/eng/homepage.htm)** .

Videos

Brown Dwarfs and Free Floating Planets: When You Are Just Too Small to Be a Star: **https://www.youtube.com/watch?v=zXCDsb4n4KU (https://www.youtube.com/watch?v=zXCDsb4n4KU)** . A nontechnical talk by Gibor Basri of the University of California at Berkeley, discussing some of the controversies about the meaning of the word “planet” (1:32:52).

In the Land of Enchantment: The Epic Story of the Cassini Mission to Saturn: **https://www.youtube.com/watch?v=Vx135n8VFxY (https://www.youtube.com/watch?v=Vx135n8VFxY)** . A public lecture by Dr. Carolyn Porco that focuses mainly on the exploration of Saturn and its moons, but also presents an eloquent explanation of why we explore the solar system (1:37:52).

Origins of the Solar System: **http://www.pbs.org/wgbh/nova/space/origins-solar-system.html (http://www.pbs.org/wgbh/nova/space/origins-solar-system.html)** . A video from PBS that focuses on the evidence from meteorites, narrated by Neil deGrasse Tyson (13:02).

To Scale: The Solar System: **https://www.youtube.com/watch?t=84&v=zR3Igc3Rhfg (https://www.youtube.com/watch?t=84&v=zR3Igc3Rhfg)** . Constructing a scale model of the solar system in the Nevada desert (7:06).

COLLABORATIVE GROUP ACTIVITIES

A. Discuss and make a list of the reasons why we humans might want to explore the other worlds in the solar system. Does your group think such missions of exploration are worth the investment? Why?

B. Your instructor will assign each group a world. Your task is to think about what it would be like to be there. (Feel free to look ahead in the book to the relevant chapters.) Discuss where on or around your world we would establish a foothold and what we would need to survive there.

C. In the **There's No Place Like Home** feature, we discuss briefly how human activity is transforming our planet's overall environment. Can you think of other ways that this is happening?

D. Some scientists criticized Carl Sagan for "wasting his research time" popularizing astronomy. To what extent do you think scientists should spend their time interpreting their field of research for the public? Why or why not? Are there ways that scientists who are not as eloquent or charismatic as Carl Sagan or Neil deGrasse Tyson can still contribute to the public understanding of science?

E. Your group has been named to a special committee by the International Astronomical Union to suggest names of features (such as craters, trenches, and so on) on a newly explored asteroid. Given the restriction that any people after whom features are named must no longer be alive, what names or types of names would you suggest? (Keep in mind that you are not restricted to names of people, by the way.)

F. A member of your group has been kidnapped by a little-known religious cult that worships the planets. They will release him only if your group can tell which of the planets are currently visible in the sky during the evening and morning. You are forbidden from getting your instructor involved. How and where else could you find out the information you need? (Be as specific as you can. If your instructor says it's okay, feel free to answer this question using online or library resources.)

G. In the **Carl Sagan: Solar System Advocate** feature, you learned that science fiction helped spark and sustain his interest in astronomy. Did any of the members of your group get interested in astronomy as a result of a science fiction story, movie, or TV show? Did any of the stories or films you or your group members saw take place on the planets of our solar system? Can you remember any specific ones that inspired you? If no one in the group is into science fiction, perhaps you can interview some friends or classmates who are and report back to the group.

H. A list of NASA solar system spacecraft missions can be found at http://www.nasa.gov/content/solar-missions-list. Your instructor will assign each group a mission. Look up when the mission was launched and executed, and describe the mission goals, the basic characteristics of the spacecraft (type of instruments, propellant, size, and so on), and what was learned from the mission. If time allows, each group should present its findings to the rest of the class.

I. What would be some of the costs or risks of developing a human colony or base on another planetary body? What technologies would need to be developed? What would people need to give up to live on a different world in our solar system?

EXERCISES

Review Questions

1. Venus rotates backward and Uranus and Pluto spin about an axis tipped nearly on its side. Based on what you learned about the motion of small bodies in the solar system and the surfaces of the planets, what might be the cause of these strange rotations?

2. What is the difference between a differentiated body and an undifferentiated body, and how might that influence a body's ability to retain heat for the age of the solar system?
3. What does a planet need in order to retain an atmosphere? How does an atmosphere affect the surface of a planet and the ability of life to exist?
4. Which type of planets have the most moons? Where did these moons likely originate?
5. What is the difference between a meteor and a meteorite?
6. Explain our ideas about why the terrestrial planets are rocky and have less gas than the giant planets.
7. Do all planetary systems look the same as our own?
8. What is comparative planetology and why is it useful to astronomers?
9. What changed in our understanding of the Moon and Moon-Earth system as a result of humans landing on the Moon's surface?
10. If Earth was to be hit by an extraterrestrial object, where in the solar system could it come from and how would we know its source region?
11. List some reasons that the study of the planets has progressed more in the past few decades than any other branch of astronomy.
12. Imagine you are a travel agent in the next century. An eccentric billionaire asks you to arrange a "Guinness Book of Solar System Records" kind of tour. Where would you direct him to find the following (use this chapter and **Appendix F** and **Appendix G**):
    - **A.** the least-dense planet
    - **B.** the densest planet
    - **C.** the largest moon in the solar system
    - **D.** excluding the jovian planets, the planet where you would weigh the most on its surface (Hint: Weight is directly proportional to surface gravity.)
    - **E.** the smallest planet
    - **F.** the planet that takes the longest time to rotate
    - **G.** the planet that takes the shortest time to rotate
    - **H.** the planet with a diameter closest to Earth's
    - **I.** the moon with the thickest atmosphere
    - **J.** the densest moon
    - **K.** the most massive moon
13. What characteristics do the worlds in our solar system have in common that lead astronomers to believe that they all formed from the same "mother cloud" (solar nebula)?
14. How do terrestrial and giant planets differ? List as many ways as you can think of.
15. Why are there so many craters on the Moon and so few on Earth?

16. How do asteroids and comets differ?

17. How and why is Earth’s Moon different from the larger moons of the giant planets?

18. Where would you look for some “original” planetesimals left over from the formation of our solar system?

19. Describe how we use radioactive elements and their decay products to find the age of a rock sample. Is this necessarily the age of the entire world from which the sample comes? Explain.

20. What was the solar nebula like? Why did the Sun form at its center?

Thought Questions

21. What can we learn about the formation of our solar system by studying other stars? Explain.

22. Earlier in this chapter, we modeled the solar system with Earth at a distance of about one city block from the Sun. If you were to make a model of the distances in the solar system to match your height, with the Sun at the top of your head and Pluto at your feet, which planet would be near your waist? How far down would the zone of the terrestrial planets reach?

23. Seasons are a result of the inclination of a planet’s axial tilt being inclined from the normal of the planet’s orbital plane. For example, Earth has an axis tilt of 23.4° (**Appendix F**). Using information about just the inclination alone, which planets might you expect to have seasonal cycles similar to Earth, although different in duration because orbital periods around the Sun are different?

24. Again using **Appendix F**, which planet(s) might you expect not to have significant seasonal activity? Why?

25. Again using **Appendix F**, which planets might you expect to have extreme seasons? Why?

26. Using some of the astronomical resources in your college library or the Internet, find five names of features on each of three other worlds that are named after real people. In a sentence or two, describe each of these people and what contributions they made to the progress of science or human thought.

27. Explain why the planet Venus is differentiated, but asteroid Fraknoi, a very boring and small member of the asteroid belt, is not.

28. Would you expect as many impact craters per unit area on the surface of Venus as on the surface of Mars? Why or why not?

29. Interview a sample of 20 people who are not taking an astronomy class and ask them if they can name a living astronomer. What percentage of those interviewed were able to name one? Typically, the two living astronomers the public knows these days are Stephen Hawking and Neil deGrasse Tyson. Why are they better known than most astronomers? How would your result have differed if you had asked the same people to name a movie star or a professional basketball player?

30. Using **Appendix G**, complete the following table that describes the characteristics of the Galilean moons of Jupiter, starting from Jupiter and moving outward in distance.

Moon	Semimajor Axis (km^3)	Diameter	Density (g/cm^3)
Io			
Europa			
Ganymede			
Callisto			

Table A

This system has often been described as a mini solar system. Why might this be so? If Jupiter were to represent the Sun and the Galilean moons represented planets, which moons could be considered more terrestrial in nature and which ones more like gas/ice giants? Why? (Hint: Use the values in your table to help explain your categorization.)

Figuring For Yourself

31. Calculate the density of Jupiter. Show your work. Is it more or less dense than Earth? Why?

32. Calculate the density of Saturn. Show your work. How does it compare with the density of water? Explain how this can be.

33. What is the density of Jupiter's moon Europa (see **Appendix G** for data on moons)? Show your work.

34. Look at **Appendix F** and **Appendix G** and indicate the moon with a diameter that is the largest fraction of the diameter of the planet or dwarf planet it orbits.

35. Barnard's Star, the second closest star to us, is about 56 trillion (5.6×10^{12}) km away. Calculate how far it would be using the scale model of the solar system given in **Overview of Our Planetary System**.

36. A radioactive nucleus has a half-life of 5×10^8 years. Assuming that a sample of rock (say, in an asteroid) solidified right after the solar system formed, approximately what fraction of the radioactive element should be left in the rock today?

8 EARTH AS A PLANET

Figure 8.1 Active Geology. This image, taken from the International Space Station in 2006, shows a plume of ash coming from the Cleveland Volcano in the Aleutian Islands. Although the plume was only visible for around two hours, such events are a testament to the dynamic nature of Earth's crust. (credit: modification of work by NASA)

Chapter Outline

- **8.1** The Global Perspective
- **8.2** Earth's Crust
- **8.3** Earth's Atmosphere
- **8.4** Life, Chemical Evolution, and Climate Change
- **8.5** Cosmic Influences on the Evolution of Earth

Thinking Ahead

Airless worlds in our solar system seem peppered with craters large and small. Earth, on the other hand, has few craters, but a thick atmosphere and much surface activity. Although impacts occurred on Earth at the same rate, craters have since been erased by forces in the planet's crust and atmosphere. What can the comparison between the obvious persistent cratering on so many other worlds, and the different appearance of Earth, tell us about the history of our planet?

As our first step in exploring the solar system in more detail, we turn to the most familiar planet, our own Earth. The first humans to see Earth as a blue sphere floating in the blackness of space were the astronauts who made the first voyage around the Moon in 1968. For many people, the historic images showing our world as a small, distant globe represent a pivotal moment in human history, when it became difficult for educated human beings to view our world without a global perspective. In this chapter, we examine the composition and structure of our planet with its envelope of ocean and atmosphere. We ask how our terrestrial environment came to be the way it is today, and how it compares with other planets.

8.1 THE GLOBAL PERSPECTIVE

Learning Objectives

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

- Describe the components of Earth's interior and explain how scientists determined its structure
- Specify the origin, size, and extent of Earth's magnetic field

Earth is a medium-size planet with a diameter of approximately 12,760 kilometers (**Figure 8.2**). As one of the inner or terrestrial planets, it is composed primarily of heavy elements such as iron, silicon, and oxygen—very different from the composition of the Sun and stars, which are dominated by the light elements hydrogen and helium. Earth's orbit is nearly circular, and Earth is warm enough to support liquid water on its surface. It is the only planet in our solar system that is neither too hot nor too cold, but "just right" for the development of life as we know it. Some of the basic properties of Earth are summarized in **Table 8.1**.

Figure 8.2 Blue Marble. This image of Earth from space, taken by the Apollo 17 astronauts, is known as the "Blue Marble." This is one of the rare images of a full Earth taken during the Apollo program; most images show only part of Earth's disk in sunlight. (credit: modification of work by NASA)

Some Properties of Earth

Property	Measurement
Semimajor axis	1.00 AU
Period	1.00 year
Mass	5.98×10^{24} kg
Diameter	12,756 km
Radius	6378 km

Table 8.1

Some Properties of Earth

Property	Measurement
Escape velocity	11.2 km/s
Rotational period	23 h 56 m 4 s
Surface area	5.1×10^8 km^2
Density	5.514 g/cm^3
Atmospheric pressure	1.00 bar

Table 8.1

Earth's Interior

The interior of a planet—even our own Earth—is difficult to study, and its composition and structure must be determined indirectly. Our only direct experience is with the outermost skin of Earth's crust, a layer no more than a few kilometers deep. It is important to remember that, in many ways, we know less about our own planet 5 kilometers beneath our feet than we do about the surfaces of Venus and Mars.

Earth is composed largely of metal and silicate rock (see the **Composition and Structure of Planets** section). Most of this material is in a solid state, but some of it is hot enough to be molten. The structure of material in Earth's interior has been probed in considerable detail by measuring the transmission of **seismic waves** through Earth. These are waves that spread through the interior of Earth from earthquakes or explosion sites.

Seismic waves travel through a planet rather like sound waves through a struck bell. Just as the sound frequencies vary depending on the material the bell is made of and how it is constructed, so a planet's response depends on its composition and structure. By monitoring the seismic waves in different locations, scientists can learn about the layers through which the waves have traveled. Some of these vibrations travel along the surface; others pass directly through the interior. Seismic studies have shown that Earth's interior consists of several distinct layers with different compositions, illustrated in **Figure 8.3**. As waves travel through different materials in Earth's interior, the waves—just like light waves in telescope lenses—bend (or refract) so that some seismic stations on Earth receive the waves and others are in "shadows." Detecting the waves in a network of seismographs helps scientists construct a model of Earth's interior, showing liquid and solid layers. This type of seismic imaging is not unlike that used in ultrasound, a type of imaging used to see inside the body.

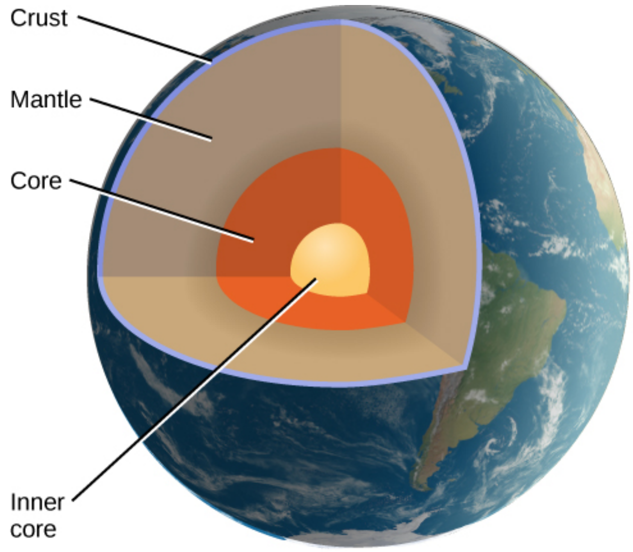


Figure 8.3 Interior Structure of Earth. The crust, mantle, and inner and outer cores (liquid and solid, respectively) as shown as revealed by seismic studies.

The top layer is the **crust**, the part of Earth we know best (Figure 8.4). Oceanic crust covers 55% of Earth's surface and lies mostly submerged under the oceans. It is typically about 6 kilometers thick and is composed of volcanic rocks called **basalt**. Produced by the cooling of volcanic lava, basalts are made primarily of the elements silicon, oxygen, iron, aluminum, and magnesium. The continental crust covers 45% of the surface, some of which is also beneath the oceans. The continental crust is 20 to 70 kilometers thick and is composed predominantly of a different volcanic class of silicates (rocks made of silicon and oxygen) called **granite**. These crustal rocks, both oceanic and continental, typically have densities of about 3 g/cm^3. (For comparison, the density of water is 1 g/cm^3.) The crust is the easiest layer for geologists to study, but it makes up only about 0.3% of the total mass of Earth.

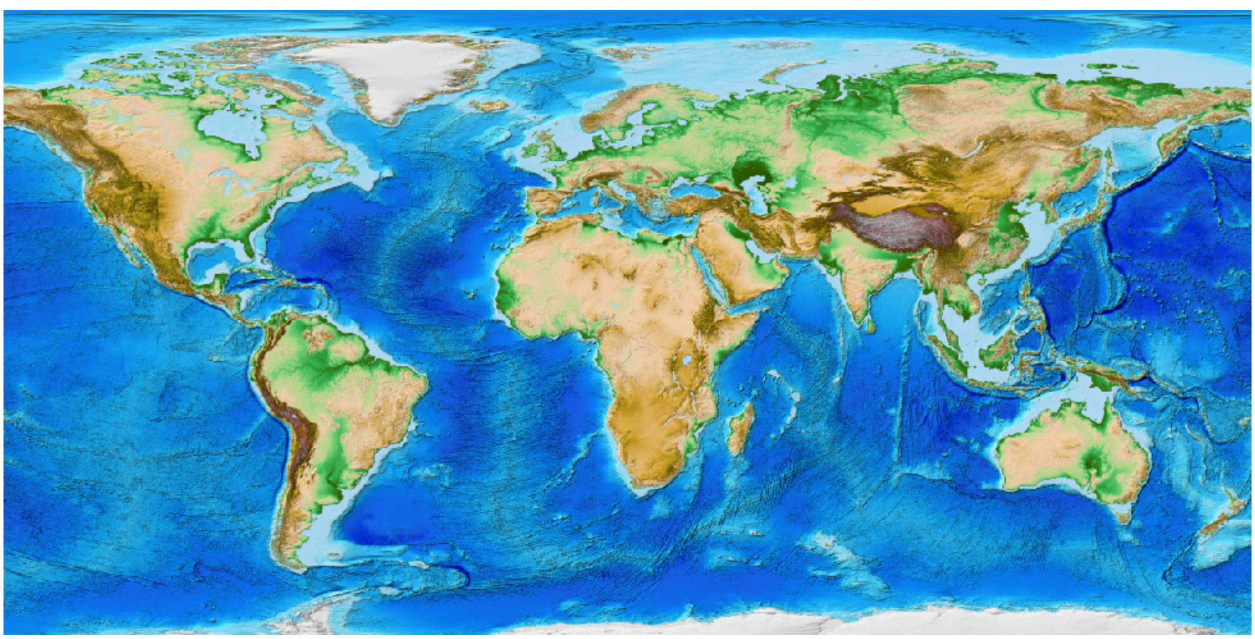


Figure 8.4 Earth's Crust. This computer-generated image shows the surface of Earth's crust as determined from satellite images and ocean floor radar mapping. Oceans and lakes are shown in blue, with darker areas representing depth. Dry land is shown in shades of green and brown, and the Greenland and Antarctic ice sheets are depicted in shades of white. (credit: modification of work by C. Amante, B. W. Eakins, National Geophysical Data Center, NOAA)

The largest part of the solid Earth, called the **mantle**, stretches from the base of the crust downward to a depth of 2900 kilometers. The mantle is more or less solid, but at the temperatures and pressures found there, mantle rock can deform and flow slowly. The density in the mantle increases downward from about 3.5 g/cm^3 to more than 5 g/cm^3 as a result of the compression produced by the weight of overlying material. Samples of upper mantle material are occasionally ejected from volcanoes, permitting a detailed analysis of its chemistry.

Beginning at a depth of 2900 kilometers, we encounter the dense metallic **core** of Earth. With a diameter of 7000 kilometers, our core is substantially larger than the entire planet Mercury. The outer core is liquid, but the innermost part of the core (about 2400 kilometers in diameter) is probably solid. In addition to iron, the core probably also contains substantial quantities of nickel and sulfur, all compressed to a very high density.

The separation of Earth into layers of different densities is an example of *differentiation,* the process of sorting the major components of a planet by density. The fact that Earth is differentiated suggests that it was once warm enough for its interior to melt, permitting the heavier metals to sink to the center and form the dense core. Evidence for differentiation comes from comparing the planet's bulk density (5.5 g/cm^3) with the surface materials (3 g/cm^3) to suggest that denser material must be buried in the core.

Magnetic Field and Magnetosphere

We can find additional clues about Earth's interior from its magnetic field. Our planet behaves in some ways as if a giant bar magnet were inside it, aligned approximately with the rotational poles of Earth. This magnetic field is generated by moving material in Earth's liquid metallic core. As the liquid metal inside Earth circulates, it sets up a circulating electric current. When many charged particles are moving together like that—in the laboratory or on the scale of an entire planet—they produce a magnetic field.

Earth's magnetic field extends into surrounding space. When a charged particle encounters a magnetic field in space, it becomes trapped in the magnetic zone. Above Earth's atmosphere, our field is able to trap small quantities of electrons and other atomic particles. This region, called the **magnetosphere**, is defined as the zone within which Earth's magnetic field dominates over the weak interplanetary magnetic field that extends outward from the Sun (**Figure 8.5**).

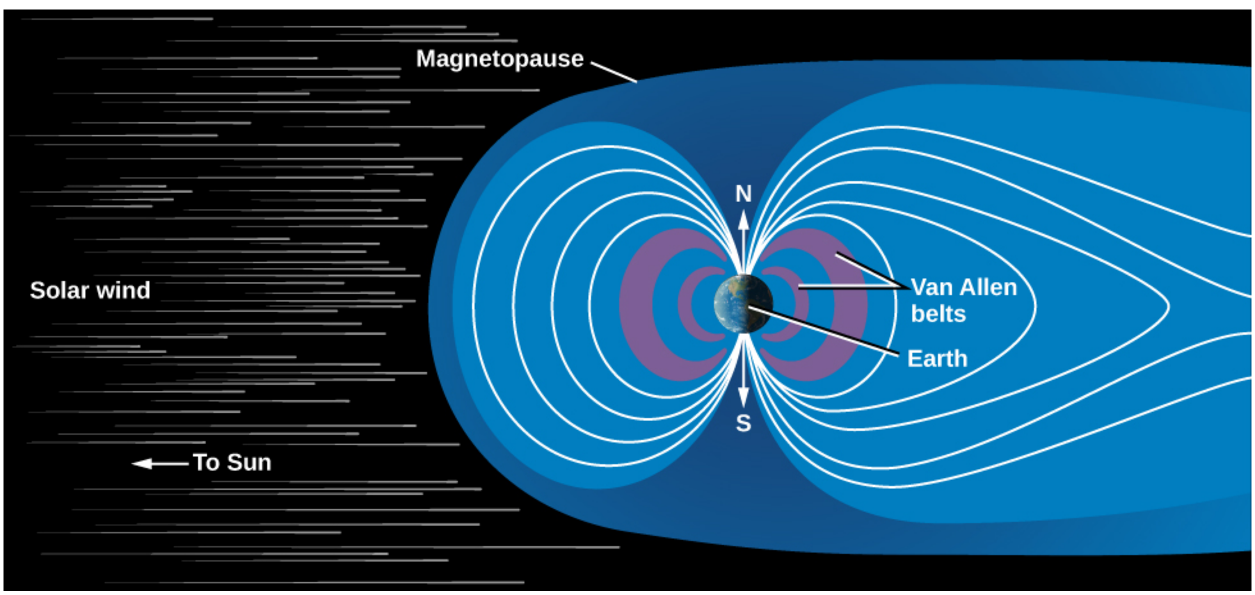


Figure 8.5 Earth's Magnetosphere. A cross-sectional view of our magnetosphere (or zone of magnetic influence), as revealed by numerous spacecraft missions. Note how the wind of charged particles from the Sun "blows" the magnetic field outward like a wind sock.

Where do the charged particles trapped in our magnetosphere come from? They flow outward from the hot surface of the Sun; this is called the *solar wind*. It not only provides particles for Earth's magnetic field to trap, it also stretches our field in the direction pointing away from the Sun. Typically, Earth's magnetosphere extends about 60,000 kilometers, or 10 Earth radii, in the direction of the Sun. But, in the direction away from the Sun, the magnetic field can reach as far as the orbit of the Moon, and sometimes farther.

The magnetosphere was discovered in 1958 by instruments on the first US Earth satellite, *Explorer 1*, which recorded the ions (charged particles) trapped in its inner part. The regions of high-energy ions in the magnetosphere are often called the *Van Allen belts* in recognition of the University of Iowa professor who built the scientific instrumentation for *Explorer 1*. Since 1958, hundreds of spacecraft have explored various regions of the magnetosphere. You can read more about its interaction with the Sun in a later chapter.

8.2 EARTH'S CRUST

Learning Objectives

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

- Denote the primary types of rock that constitute Earth's crust
- Explain the theory of plate tectonics
- Describe the difference between rift and subduction zones
- Describe the relationship between fault zones and mountain building
- Explain the various types of volcanic activity occurring on Earth

Let us now examine our planet's outer layers in more detail. Earth's crust is a dynamic place. Volcanic eruptions, erosion, and large-scale movements of the continents rework the surface of our planet constantly. Geologically, ours is the most active planet. Many of the geological processes described in this section have taken place on other planets as well, but usually in their distant pasts. Some of the moons of the giant planets also have impressive activity levels. For example, Jupiter's moon Io has a remarkable number of active volcanoes.

Composition of the Crust

Earth's crust is largely made up of oceanic basalt and continental granite. These are both **igneous rock**, the term used for any rock that has cooled from a molten state. All volcanically produced rock is igneous (Figure 8.6).

Figure 8.6 Formation of Igneous Rock as Liquid Lava Cools and Freezes. This is a lava flow from a basaltic eruption. Basaltic lava flows quickly and can move easily over distances of more than 20 kilometers. (credit: USGS)

Two other kinds of rock are familiar to us on Earth, although it turns out that neither is common on other planets. **Sedimentary rocks** are made of fragments of igneous rock or the shells of living organisms deposited by wind or water and cemented together without melting. On Earth, these rocks include the common sandstones, shales, and limestones. **Metamorphic rocks** are produced when high temperature or pressure alters igneous or sedimentary rock physically or chemically (the word *metamorphic* means "changed in form"). Metamorphic rocks are produced on Earth because geological activity carries surface rocks down to considerable depths and then brings them back up to the surface. Without such activity, these changed rocks would not exist at the surface.

There is a fourth very important category of rock that can tell us much about the early history of the planetary system: **primitive rock**, which has largely escaped chemical modification by heating. Primitive rock represents the original material out of which the planetary system was made. No primitive material is left on Earth because the entire planet was heated early in its history. To find primitive rock, we must look to smaller objects such as comets, asteroids, and small planetary moons. We can sometimes see primitive rock in samples that fall to Earth from these smaller objects.

A block of quartzite on Earth is composed of materials that have gone through all four of these states. Beginning as primitive material before Earth was born, it was heated in the early Earth to form igneous rock, transformed chemically and redeposited (perhaps many times) to form sedimentary rock, and finally changed several kilometers below Earth's surface into the hard, white metamorphic stone we see today.

Plate Tectonics

Geology is the study of Earth's crust and the processes that have shaped its surface throughout history. (Although *geo-* means "related to Earth," astronomers and planetary scientists also talk about the geology of other planets.) Heat escaping from the interior provides energy for the formation of our planet's mountains, valleys, volcanoes, and even the continents and ocean basins themselves. But not until the middle of the twentieth century did geologists succeed in understanding just how these landforms are created.

Plate tectonics is a theory that explains how slow motions within the mantle of Earth move large segments of the crust, resulting in a gradual "drifting" of the continents as well as the formation of mountains and other large-scale geological features. Plate tectonics is a concept as basic to geology as evolution by natural selection is to biology or gravity is to understanding the orbits of planets. Looking at it from a different perspective, plate tectonics is a mechanism for Earth to transport heat efficiently from the interior, where it has accumulated, out to space. It is a cooling system for the planet. All planets develop a heat transfer process as they evolve; mechanisms may differ from that on Earth as a result of chemical makeup and other constraints.

Earth's crust and upper mantle (to a depth of about 60 kilometers) are divided into about a dozen tectonic plates that fit together like the pieces of a jigsaw puzzle (**Figure 8.7**). In some places, such as the Atlantic Ocean, the plates are moving apart; in others, such as off the western coast of South America, they are being forced together. The power to move the plates is provided by slow **convection** of the mantle, a process by which heat escapes from the interior through the upward flow of warmer material and the slow sinking of cooler material. (Convection, in which energy is transported from a warm region, such as the interior of Earth, to a cooler region, such as the upper mantle, is a process we encounter often in astronomy—in stars as well as planets. It is also important in boiling water for coffee while studying for astronomy exams.)

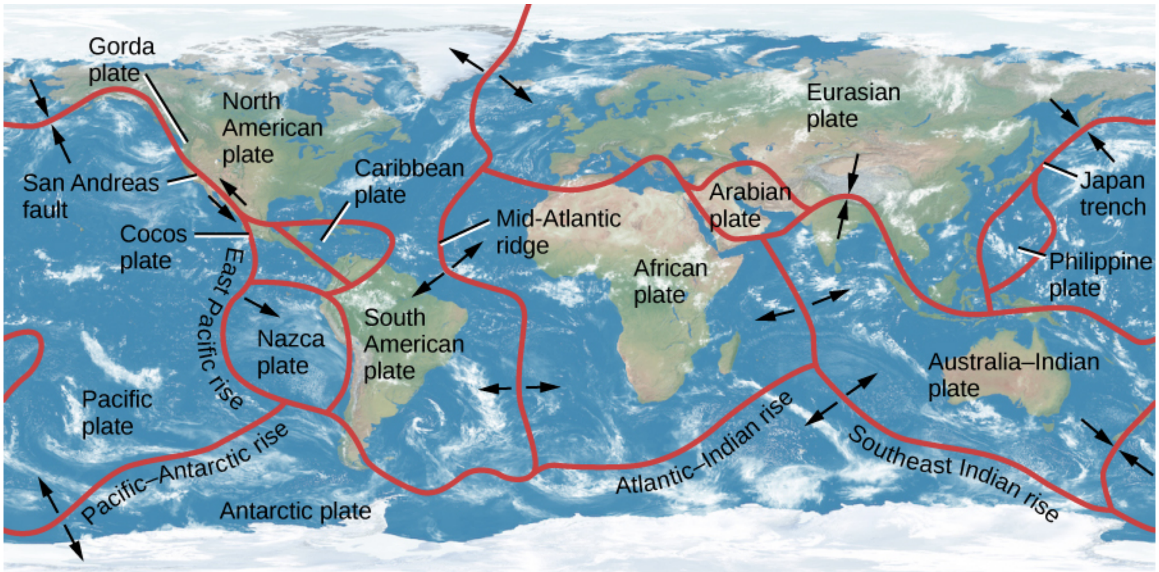


Figure 8.7 Earth's Continental Plates. This map shows the major plates into which the crust of Earth is divided. Arrows indicate the motion of the plates at average speeds of 4 to 5 centimeters per year, similar to the rate at which your hair grows.

LINK TO LEARNING

The US Geological Survey provides a **map of recent earthquakes (https://openstax.org/l/30geosurmapeart)** and shows the boundaries of the tectonic plates and where earthquakes occur in relation to these boundaries. You can look close-up at the United States or zoom out for a global view.

As the plates slowly move, they bump into each other and cause dramatic changes in Earth's crust over time. Four basic kinds of interactions between crustal plates are possible at their boundaries: (1) they can pull apart, (2) one plate can burrow under another, (3) they can slide alongside each other, or (4) they can jam together. Each of these activities is important in determining the geology of Earth.

VOYAGERS IN ASTRONOMY

Alfred Wegener: Catching the Drift of Plate Tectonics

When studying maps or globes of Earth, many students notice that the coast of North and South America, with only minor adjustments, could fit pretty well against the coast of Europe and Africa. It seems as if these great landmasses could once have been together and then were somehow torn apart. The same idea had occurred to others (including Francis Bacon as early as 1620), but not until the twentieth century could such a proposal be more than speculation. The scientist who made the case for continental drift in 1920 was a German meteorologist and astronomer named Alfred Wegener (**Figure 8.8**).

Figure 8.8 Alfred Wegener (1880–1930). Wegener proposed a scientific theory for the slow shifting of the continents.

Born in Berlin in 1880, Wegener was, from an early age, fascinated by Greenland, the world's largest island, which he dreamed of exploring. He studied at the universities in Heidelberg, Innsbruck, and Berlin, receiving a doctorate in astronomy by reexamining thirteenth-century astronomical tables. But, his interests turned more and more toward Earth, particularly its weather. He carried out experiments using kites and balloons, becoming so accomplished that he and his brother set a world record in 1906 by flying for 52 hours in a balloon.

Wegener first conceived of continental drift in 1910 while examining a world map in an atlas, but it took 2 years for him to assemble sufficient data to propose the idea in public. He published the results in book form in 1915. Wegener's evidence went far beyond the congruence in the shapes of the continents. He proposed that the similarities between fossils found only in South America and Africa indicated that these two continents were joined at one time. He also showed that resemblances among living animal species on different continents could best be explained by assuming that the continents were once connected in a supercontinent he called *Pangaea* (from Greek elements meaning "all land").

Wegener's suggestion was met with a hostile reaction from most scientists. Although he had marshaled an impressive list of arguments for his hypothesis, he was missing a *mechanism*. No one could explain *how* solid continents could drift over thousands of miles. A few scientists were sufficiently impressed by Wegener's work to continue searching for additional evidence, but many found the notion of moving continents too revolutionary to take seriously. Developing an understanding of the mechanism (plate tectonics) would take decades of further progress in geology, oceanography, and geophysics.

Wegener was disappointed in the reception of his suggestion, but he continued his research and, in 1924, he was appointed to a special meteorology and geophysics professorship created especially for him at the University of Graz (where he was, however, ostracized by most of the geology faculty). Four years later, on his fourth expedition to his beloved Greenland, he celebrated his fiftieth birthday with colleagues and then set off on foot toward a different camp on the island. He never made it; he was found a few days later, dead of an apparent heart attack.

Critics of science often point to the resistance to the continental drift hypothesis as an example of the flawed way that scientists regard new ideas. (Many people who have advanced crackpot theories have claimed that they are being ridiculed unjustly, just as Wegener was.) But we think there is a more positive light in which to view the story of Wegener's suggestion. Scientists in his day maintained a skeptical attitude because they needed more evidence and a clear mechanism that would fit what they understood about nature. Once the evidence and the mechanism were clear, Wegener's hypothesis quickly became the centerpiece of our view of a dynamic Earth.

LINK TO LEARNING

See how the **drift of the continents (https://openstax.org/l/30contintdrift)** has changed the appearance of our planet's crust.

Rift and Subduction Zones

Plates pull apart from each other along **rift zones**, such as the Mid-Atlantic ridge, driven by upwelling currents in the mantle (Figure 8.9). A few rift zones are found on land. The best known is the central African rift—an area where the African continent is slowly breaking apart. Most rift zones, however, are in the oceans. Molten rock rises from below to fill the space between the receding plates; this rock is basaltic lava, the kind of igneous rock that forms most of the ocean basins.

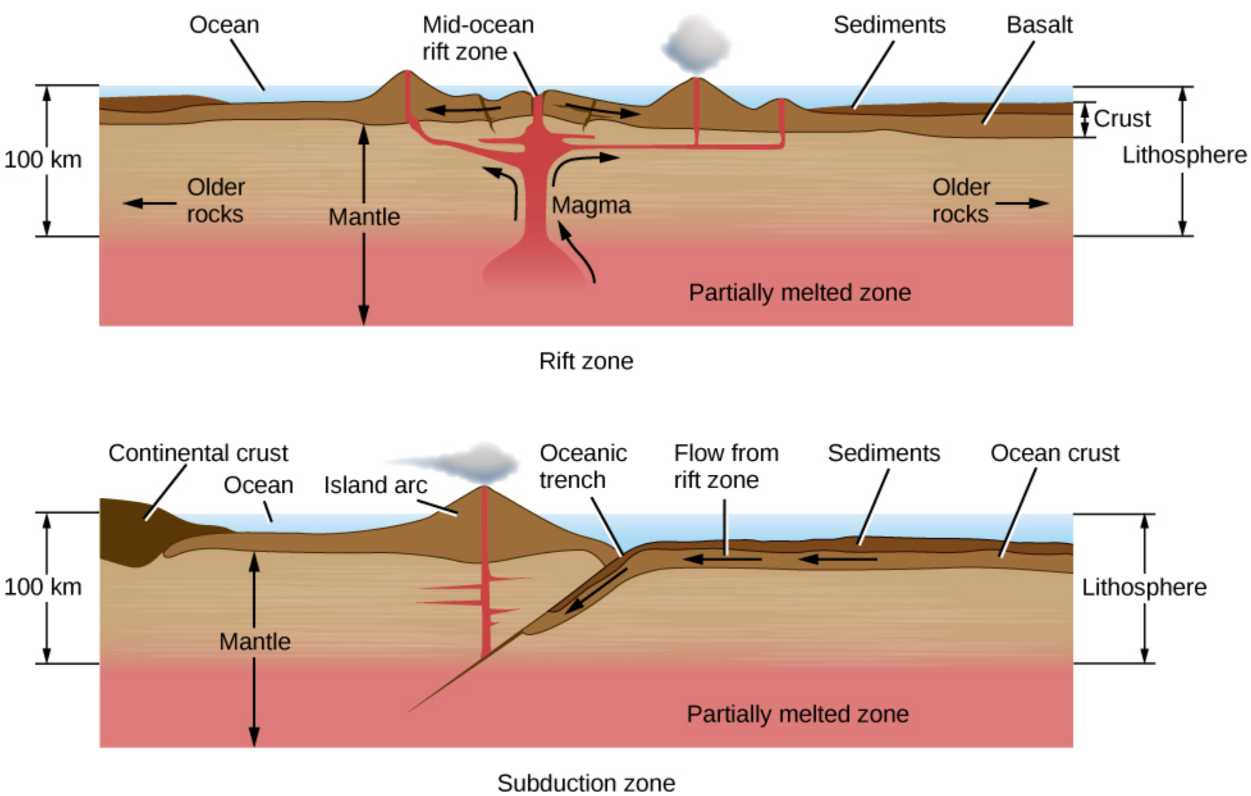


Figure 8.9 Rift Zone and Subduction Zone. Rift and subduction zones are the regions (mostly beneath the oceans) where new crust is formed and old crust is destroyed as part of the cycle of plate tectonics.

From a knowledge of how the seafloor is spreading, we can calculate the average age of the oceanic crust. About 60,000 kilometers of active rifts have been identified, with average separation rates of about 4 centimeters per year. The new area added to Earth each year is about 2 square kilometers, enough to renew the entire oceanic crust in a little more than 100 million years. This is a very short interval in geological time—less than 3% of the age of Earth. The present ocean basins thus turn out to be among the youngest features on our planet.

As new crust is added to Earth, the old crust must go somewhere. When two plates come together, one plate is often forced beneath another in what is called a **subduction** zone (**Figure 8.9**). In general, the thick continental masses cannot be subducted, but the thinner oceanic plates can be rather readily thrust down into the upper mantle. Often a subduction zone is marked by an ocean trench; a fine example of this type of feature is the deep Japan trench along the coast of Asia. The subducted plate is forced down into regions of high pressure and temperature, eventually melting several hundred kilometers below the surface. Its material is recycled into a downward-flowing convection current, ultimately balancing the flow of material that rises along rift zones. The amount of crust destroyed at subduction zones is approximately equal to the amount formed at rift zones.

All along the subduction zone, earthquakes and volcanoes mark the death throes of the plate. Some of the most destructive earthquakes in history have taken place along subduction zones, including the 1923 Yokohama earthquake and fire that killed 100,000 people, the 2004 Sumatra earthquake and tsunami that killed more than 200,000 people, and the 2011 Tohoku earthquake that resulted in the meltdown of three nuclear power reactors in Japan.

Fault Zones and Mountain Building

Along much of their length, the crustal plates slide parallel to each other. These plate boundaries are marked by cracks or **faults**. Along active fault zones, the motion of one plate with respect to the other is several centimeters per year, about the same as the spreading rates along rifts.

One of the most famous faults is the San Andreas Fault in California, which lies at the boundary between the Pacific plate and the North American plate (**Figure 8.10**). This fault runs from the Gulf of California to the Pacific Ocean northwest of San Francisco. The Pacific plate, to the west, is moving northward, carrying Los Angeles, San Diego, and parts of the southern California coast with it. In several million years, Los Angeles may be an island off the coast of San Francisco.

Figure 8.10 San Andreas Fault. We see part of a very active region in California where one crustal plate is sliding sideways with respect to the other. The fault is marked by the valley running up the right side of the photo. Major slippages along this fault can produce extremely destructive earthquakes. (credit: John Wiley)

Unfortunately for us, the motion along fault zones does not take place smoothly. The creeping motion of the plates against each other builds up stresses in the crust that are released in sudden, violent slippages that generate earthquakes. Because the average motion of the plates is constant, the longer the interval between earthquakes, the greater the stress and the more energy released when the surface finally moves.

For example, the part of the San Andreas Fault near the central California town of Parkfield has slipped every 25 years or so during the past century, moving an average of about 1 meter each time. In contrast, the average interval between major earthquakes in the Los Angeles region is about 150 years, and the average motion is about 7 meters. The last time the San Andreas fault slipped in this area was in 1857; tension has been building ever since, and sometime soon it is bound to be released. Sensitive instruments placed within the Los Angeles basin show that the basin is distorting and contracting in size as these tremendous pressures build up beneath the surface.

EXAMPLE 8.1

Fault Zones and Plate Motion

After scientists mapped the boundaries between tectonic plates in Earth's crust and measured the annual rate at which the plates move (which is about 5 cm/year), we could estimate quite a lot about the rate at which the geology of Earth is changing. As an example, let's suppose that the next slippage along the San Andreas Fault in southern California takes place in the year 2017 and that it completely relieves the accumulated strain in this region. How much slippage is required for this to occur?

Solution

The speed of motion of the Pacific plate relative to the North American plate is 5 cm/y. That's 500 cm (or 5 m) per century. The last southern California earthquake was in 1857. The time from 1857 to 2017 is

160 y, or 1.6 centuries, so the slippage to relieve the strain completely would be
5 m/century × 1.6 centuries = 8.0 m.

Check Your Learning

If the next major southern California earthquake occurs in 2047 and only relieves one-half of the accumulated strain, how much slippage will occur?

Answer:

The difference in time from 1857 to 2047 is 190 y, or 1.9 centuries. Because only half the strain is released, this is equivalent to half the annual rate of motion. The total slippage comes to
0.5 × 5 m/century × 1.9 centuries = 4.75 m.

When two continental masses are moving on a collision course, they push against each other under great pressure. Earth buckles and folds, dragging some rock deep below the surface and raising other folds to heights of many kilometers. This is the way many, but not all, of the mountain ranges on Earth were formed. The Alps, for example, are a result of the African plate bumping into the Eurasian plate. As we will see, however, quite different processes produced the mountains on other planets.

Once a mountain range is formed by upthrusting of the crust, its rocks are subject to erosion by water and ice. The sharp peaks and serrated edges have little to do with the forces that make the mountains initially. Instead, they result from the processes that tear down mountains. Ice is an especially effective sculptor of rock (Figure 8.11). In a world without moving ice or running water (such as the Moon or Mercury), mountains remain smooth and dull.

Figure 8.11 Mountains on Earth. The Torres del Paine are a young region of Earth’s crust where sharp mountain peaks are being sculpted by glaciers. We owe the beauty of our young, steep mountains to the erosion by ice and water. (credit: David Morrison)

Volcanoes

Volcanoes mark locations where lava rises to the surface. One example is mid ocean ridges, which are long undersea mountain ranges formed by lava rising from Earth’s mantle at plate boundaries. A second major kind of volcanic activity is associated with subduction zones, and volcanoes sometimes also appear in regions where continental plates are colliding. In each case, the volcanic activity gives us a way to sample some of the material from deeper within our planet.

Other volcanic activity occurs above mantle "hot spots"—areas far from plate boundaries where heat is nevertheless rising from the interior of Earth. One of the best-known hot spot is under the island of Hawaii, where it currently supplies the heat to maintain three active volcanoes, two on land and one under the ocean. The Hawaii hot spot has been active for at least 100 million years. As Earth's plates have moved during that time, the hot spot has generated a 3500-kilometer-long chain of volcanic islands. The tallest Hawaiian volcanoes are among the largest individual mountains on Earth, more than 100 kilometers in diameter and rising 9 kilometers above the ocean floor. One of the Hawaiian volcanic mountains, the now-dormant Mauna Kea, has become one of the world's great sites for doing astronomy.

LINK TO LEARNING

The US Geological Service provides **an interactive map (https://openstax.org/l/30mapringoffire)** of the famous "ring of fire," which is the chain of volcanoes surrounding the Pacific Ocean, and shows the Hawaiian "hot spot" enclosed within.

Not all volcanic eruptions produce mountains. If lava flows rapidly from long cracks, it can spread out to form lava plains. The largest known terrestrial eruptions, such as those that produced the Snake River basalts in the northwestern United States or the Deccan plains in India, are of this type. Similar lava plains are found on the Moon and the other terrestrial planets.

8.3 EARTH'S ATMOSPHERE

Learning Objectives

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

- Differentiate between Earth's various atmospheric layers
- Describe the chemical composition and possible origins of our atmosphere
- Explain the difference between weather and climate

We live at the bottom of the ocean of air that envelops our planet. The atmosphere, weighing down upon Earth's surface under the force of gravity, exerts a pressure at sea level that scientists define as 1 **bar** (a term that comes from the same root as *barometer*, an instrument used to measure atmospheric pressure). A bar of pressure means that each square centimeter of Earth's surface has a weight equivalent to 1.03 kilograms pressing down on it. Humans have evolved to live at this pressure; make the pressure a lot lower or higher and we do not function well.

The total mass of Earth's atmosphere is about 5×10^{18} kilograms. This sounds like a large number, but it is only about a millionth of the total mass of Earth. The atmosphere represents a smaller fraction of Earth than the fraction of your mass represented by the hair on your head.

Structure of the Atmosphere

The structure of the atmosphere is illustrated in Figure 8.12. Most of the atmosphere is concentrated near the surface of Earth, within about the bottom 10 kilometers where clouds form and airplanes fly. Within this region—called the **troposphere**—warm air, heated by the surface, rises and is replaced by descending currents of cooler air; this is an example of convection. This circulation generates clouds and wind. Within the troposphere, temperature decreases rapidly with increasing elevation to values near 50 °C below freezing at its upper boundary, where the **stratosphere** begins. Most of the stratosphere, which extends to about 50 kilometers above the surface, is cold and free of clouds.

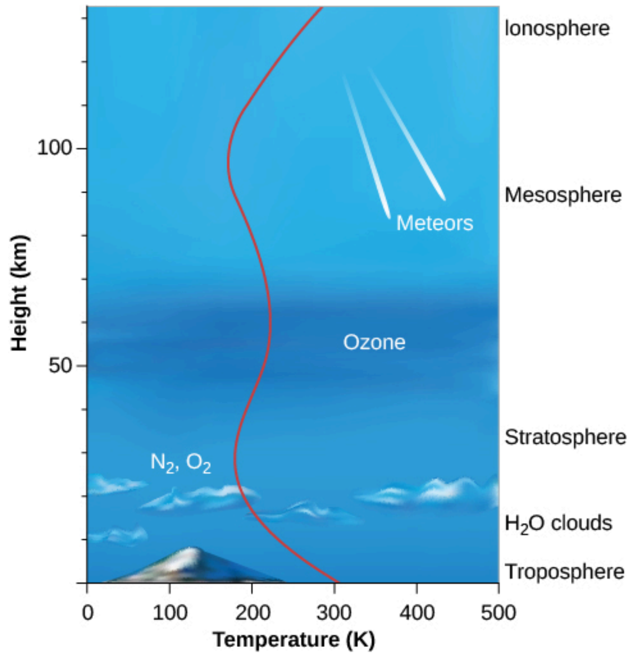


Figure 8.12 Structure of Earth's Atmosphere. Height increases up the left side of the diagram, and the names of the different atmospheric layers are shown at the right. In the upper ionosphere, ultraviolet radiation from the Sun can strip electrons from their atoms, leaving the atmosphere ionized. The curving red line shows the temperature (see the scale on the *x*-axis).

Near the top of the stratosphere is a layer of **ozone** (O_3), a heavy form of oxygen with three atoms per molecule instead of the usual two. Because ozone is a good absorber of ultraviolet light, it protects the surface from some of the Sun's dangerous ultraviolet radiation, making it possible for life to exist on Earth. The breakup of ozone adds heat to the stratosphere, reversing the decreasing temperature trend in the troposphere. Because ozone is essential to our survival, we reacted with justifiable concern to evidence that became clear in the 1980s that atmospheric ozone was being destroyed by human activities. By international agreement, the production of industrial chemicals that cause ozone depletion, called chlorofluorocarbons, or CFCs, has been phased out. As a result, ozone loss has stopped and the "ozone hole" over the Antarctic is shrinking gradually. This is an example of how concerted international action can help maintain the habitability of Earth.

LINK TO LEARNING

Visit NASA's scientific visualization studio for a **short video (https://openstax.org/l/302065regcfc)** of what would have happened to Earth's ozone layer by 2065 if CFCs had not been regulated.

At heights above 100 kilometers, the atmosphere is so thin that orbiting satellites can pass through it with very little friction. Many of the atoms are ionized by the loss of an electron, and this region is often called the ionosphere. At these elevations, individual atoms can occasionally escape completely from the gravitational field of Earth. There is a continuous, slow leaking of atmosphere—especially of lightweight atoms, which move faster than heavy ones. Earth's atmosphere cannot, for example, hold on for long to hydrogen or helium, which escape into space. Earth is not the only planet to experience atmosphere leakage. Atmospheric leakage also created Mars' thin atmosphere. Venus' dry atmosphere evolved because its proximity to the Sun vaporized and dissociated any water, with the component gases lost to space.

Atmospheric Composition and Origin

At Earth's surface, the atmosphere consists of 78% nitrogen (N_2), 21% oxygen (O_2), and 1% argon (Ar), with traces of water vapor (H_2O), carbon dioxide (CO_2), and other gases. Variable amounts of dust particles and water droplets are also found suspended in the air.

A complete census of Earth's volatile materials, however, should look at more than the gas that is now present. *Volatile* materials are those that evaporate at a relatively low temperature. If Earth were just a little bit warmer, some materials that are now liquid or solid might become part of the atmosphere. Suppose, for example, that our planet were heated to above the boiling point of water (100 °C, or 373 K); that's a large change for humans, but a small change compared to the range of possible temperatures in the universe. At 100 °C, the oceans would boil and the resulting water vapor would become a part of the atmosphere.

To estimate how much water vapor would be released, note that there is enough water to cover the entire Earth to a depth of about 300 meters. Because the pressure exerted by 10 meters of water is equal to about 1 bar, the average pressure at the ocean floor is about 300 bars. Water weighs the same whether in liquid or vapor form, so if the oceans boiled away, the atmospheric pressure of the water would still be 300 bars. Water would therefore greatly dominate Earth's atmosphere, with nitrogen and oxygen reduced to the status of trace constituents.

On a warmer Earth, another source of additional atmosphere would be found in the sedimentary carbonate rocks of the crust. These minerals contain abundant carbon dioxide. If all these rocks were heated, they would release about 70 bars of CO_2, far more than the current CO_2 pressure of only 0.0005 bar. Thus, the atmosphere of a warm Earth would be dominated by water vapor and carbon dioxide, with a surface pressure nearing 400 bars.

Several lines of evidence show that the composition of Earth's atmosphere has changed over our planet's history. Scientists can infer the amount of atmospheric oxygen, for example, by studying the chemistry of minerals that formed at various times. We examine this issue in more detail later in this chapter.

Today we see that CO_2, H_2O, sulfur dioxide (SO_2), and other gases are released from deeper within Earth through the action of volcanoes. (For CO_2, the primary source today is the burning of fossil fuels, which releases far more CO_2 than that from volcanic eruptions.) Much of this apparently new gas, however, is recycled material that has been subducted through plate tectonics. But where did our planet's original atmosphere come from?

Three possibilities exist for the original source of Earth's atmosphere and oceans: (1) the atmosphere could have been formed with the rest of Earth as it accumulated from debris left over from the formation of the Sun; (2) it could have been released from the interior through volcanic activity, subsequent to the formation of Earth; or (3) it may have been derived from impacts by comets and asteroids from the outer parts of the solar system. Current evidence favors a combination of the interior and impact sources.

Weather and Climate

All planets with atmospheres have *weather*, which is the name we give to the circulation of the atmosphere. The energy that powers the weather is derived primarily from the sunlight that heats the surface. Both the rotation of the planet and slower seasonal changes cause variations in the amount of sunlight striking different parts of Earth. The atmosphere and oceans redistribute the heat from warmer to cooler areas. Weather on any planet represents the response of its atmosphere to changing inputs of energy from the Sun (see **Figure 8.13** for a dramatic example).

Figure 8.13 Storm from Space. This satellite image shows Hurricane Irene in 2011, shortly before the storm hit land in New York City. The combination of Earth's tilted axis of rotation, moderately rapid rotation, and oceans of liquid water can lead to violent weather on our planet. (credit: NASA/NOAA GOES Project)

Climate is a term used to refer to the effects of the atmosphere that last through decades and centuries. Changes in climate (as opposed to the random variations in weather from one year to the next) are often difficult to detect over short time periods, but as they accumulate, their effect can be devastating. One saying is that "Climate is what you expect, and weather is what you get." Modern farming is especially sensitive to temperature and rainfall; for example, calculations indicate that a drop of only 2 °C throughout the growing season would cut the wheat production by half in Canada and the United States. At the other extreme, an increase of 2 °C in the average temperature of Earth would be enough to melt many glaciers, including much of the ice cover of Greenland, raising sea level by as much as 10 meters, flooding many coastal cities and ports, and putting small islands completely under water.

The best documented changes in Earth's climate are the great ice ages, which have lowered the temperature of the Northern Hemisphere periodically over the past half million years or so (**Figure 8.14**). The last ice age, which ended about 14,000 years ago, lasted some 20,000 years. At its height, the ice was almost 2 kilometers thick over Boston and stretched as far south as New York City.

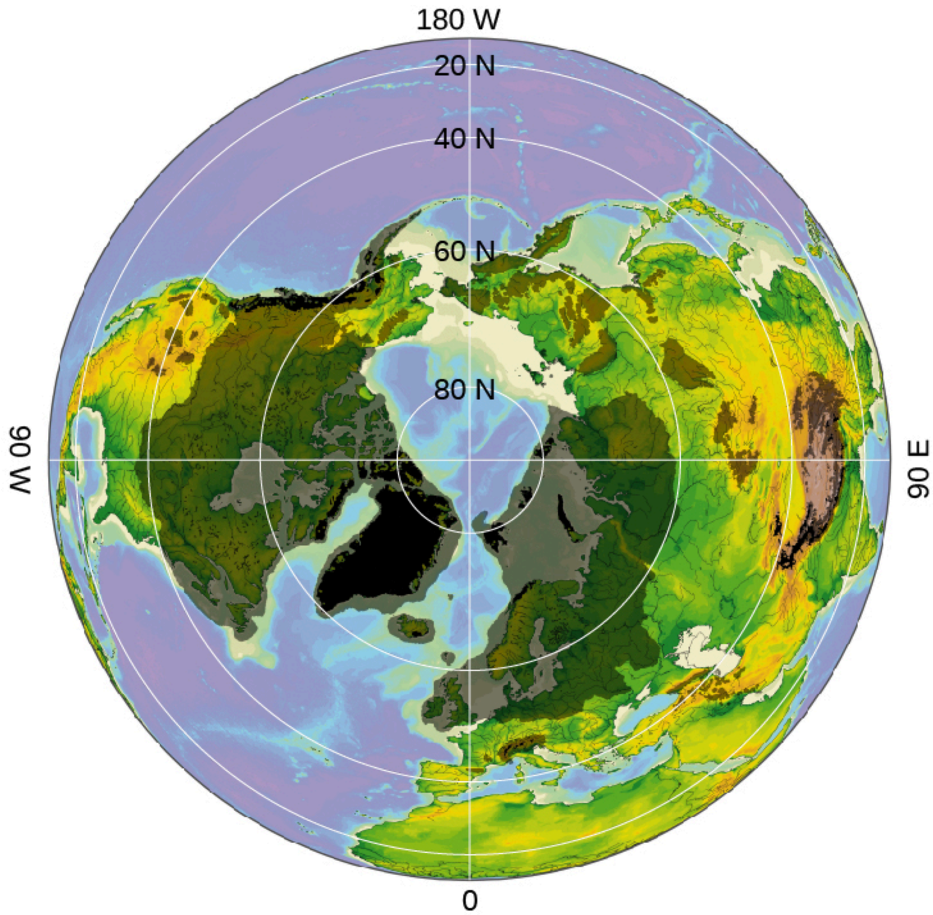


Figure 8.14 Ice Age. This computer-generated image shows the frozen areas of the Northern Hemisphere during past ice ages from the vantage point of looking down on the North Pole. The area in black indicates the most recent glaciation (coverage by glaciers), and the area in gray shows the maximum level of glaciation ever reached. (credit: modification of work by Hannes Grobe/AWI)

These ice ages were primarily the result of changes in the tilt of Earth's rotational axis, produced by the gravitational effects of the other planets. We are less certain about evidence that at least once (and perhaps twice) about a billion years ago, the entire ocean froze over, a situation called *snowball Earth*.

The development and evolution of life on Earth has also produced changes in the composition and temperature of our planet's atmosphere, as we shall see in the next section.

LINK TO LEARNING

Watch this **short excerpt (https://openstax.org/l/30natgeoearth)** from the National Geographic documentary *Earth: The Biography*. In this segment, Dr. Iain Stewart explains the fluid nature of our atmosphere.

8.4 LIFE, CHEMICAL EVOLUTION, AND CLIMATE CHANGE

Learning Objectives

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

- Outline the origins and subsequent diversity of life on Earth
- Explain the ways that life and geological activity have influenced the evolution of the atmosphere
- Describe the causes and effects of the atmospheric greenhouse effect and global warming
- Describe the impact of human activity on our planet's atmosphere and ecology

As far as we know, Earth seems to be the only planet in the solar system with life. The origin and development of life are an important part of our planet's story. Life arose early in Earth's history, and living organisms have been interacting with their environment for billions of years. We recognize that life-forms have evolved to adapt to the environment on Earth, and we are now beginning to realize that Earth itself has been changed in important ways by the presence of living matter. The study of the coevolution of life and our planet is one of the subjects of the modern science of *astrobiology*.

The Origin of Life

The record of the birth of life on Earth has been lost in the restless motions of the crust. According to chemical evidence, by the time the oldest surviving rocks were formed about 3.9 billion years ago, life already existed. At 3.5 billion years ago, life had achieved the sophistication to build large colonies called *stromatolites*, a form so successful that stromatolites still grow on Earth today (**Figure 8.15**). But, few rocks survive from these ancient times, and abundant fossils have been preserved only during the past 600 million years—less than 15% of our planet's history.

Figure 8.15 Cross-Sections of Fossil Stromatolites. This polished cross-section of a fossilized colony of stromatolites dates to the Precambrian Era. The layered, domelike structures are mats of sediment trapped in shallow waters by large numbers of blue-green bacteria that can photosynthesize. Such colonies of microorganisms date back more than 3 billion years. (credit: James St. John)

There is little direct evidence about the actual origin of life. We know that the atmosphere of early Earth, unlike today's, contained abundant carbon dioxide and some methane, but no oxygen gas. In the absence of oxygen, many complex chemical reactions are possible that lead to the production of amino acids, proteins, and other chemical building blocks of life. Therefore, it seems likely that these chemical building blocks were available very early in Earth's history and they would have combined to make living organisms.

For tens of millions of years after Earth's formation, life (perhaps little more than large molecules, like the viruses of today) probably existed in warm, nutrient-rich seas, living off accumulated organic chemicals. When this easily accessible food became depleted, life began the long evolutionary road that led to the vast numbers of different organisms on Earth today. As it did so, life began to influence the chemical composition of the atmosphere.

In addition to the study of life's history as revealed by chemical and fossil evidence in ancient rocks, scientists use tools from the rapidly advancing fields of genetics and *genomics*—the study of the genetic code that is shared by all life on Earth. While each individual has a unique set of genes (which is why genetic "fingerprinting" is so useful for the study of crime), we also have many genetic traits in common. Your *genome*, the complete map of the DNA in your body, is identical at the 99.9% level to that of Julius Caesar or Marie Curie. At the 99% level, human and chimpanzee genomes are the same. By looking at the gene sequences of many organisms, we can determine that all life on Earth is descended from a common ancestor, and we can use the genetic variations among species as a measure of how closely different species are related.

These genetic analysis tools have allowed scientists to construct what is called the " tree of life" (**Figure 8.16**). This diagram illustrates the way organisms are related by examining one sequence of the nucleic acid RNA that all species have in common. This figure shows that life on Earth is dominated by microscopic creatures that you have probably never heard of. Note that the plant and animal kingdoms are just two little branches at the far right. Most of the diversity of life, and most of our evolution, has taken place at the microbial level. Indeed, it may surprise you to know that there are more microbes in a bucket of soil than there are stars in the Galaxy. You may want to keep this in mind when, later in this book, we turn to the search for life on other worlds. The "aliens" that are most likely to be out there are microbes.

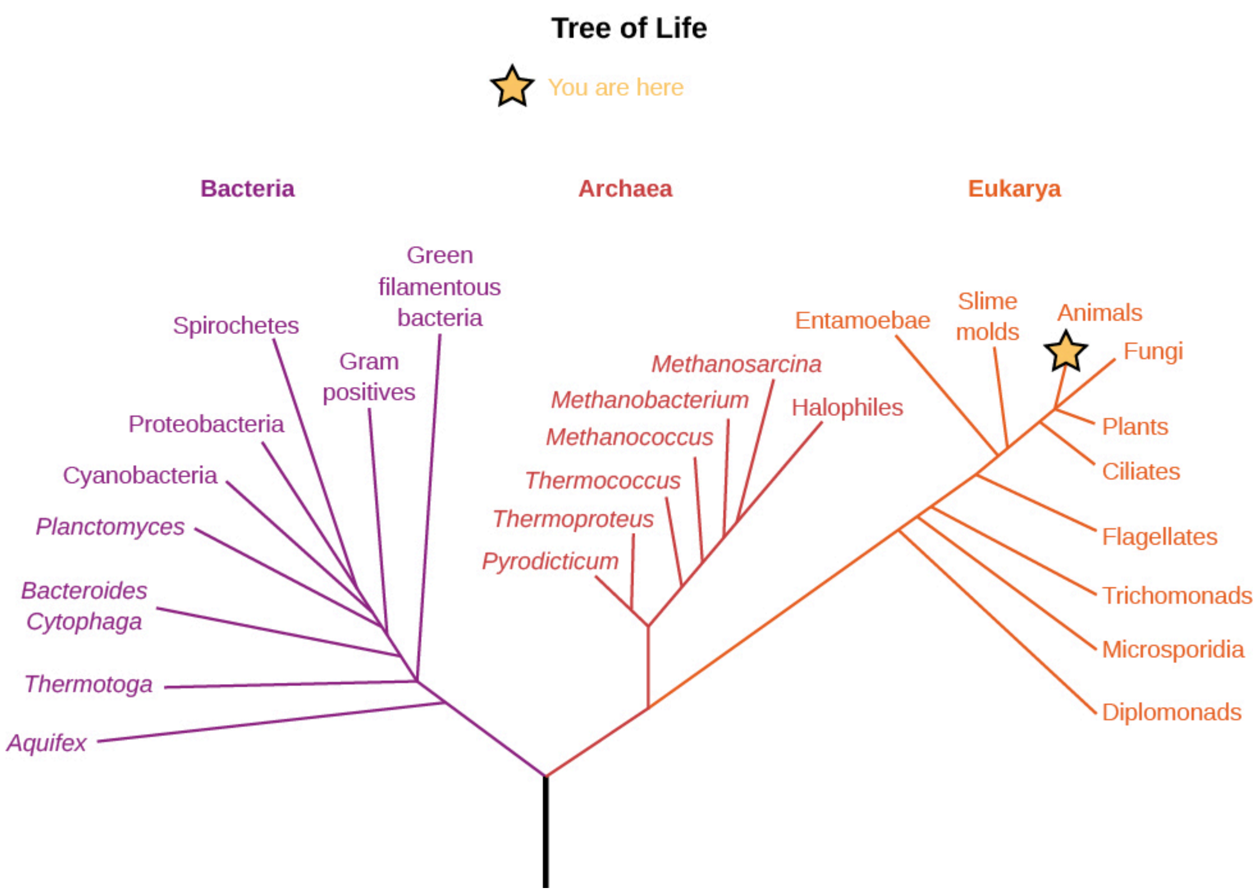


Figure 8.16 Tree of Life. This chart shows the main subdivisions of life on Earth and how they are related. Note that the animal and plant kingdoms are just short branches on the far right, along with the fungi. The most fundamental division of Earth's living things is onto three large domains called bacteria, archaea, and eukarya. Most of the species listed are microscopic. (credit: modification of work by Eric Gaba)

Such genetic studies lead to other interesting conclusions as well. For example, it appears that the earliest surviving terrestrial life-forms were all adapted to live at high temperatures. Some biologists think that life might actually have begun in locations on our planet that were extremely hot. Yet another intriguing possibility is that life began on Mars (which cooled sooner) rather than Earth and was "seeded" onto our planet by meteorites traveling from Mars to Earth. Mars rocks are still making their way to Earth, but so far none has shown evidence of serving as a "spaceship" to carry microorganisms from Mars to Earth.

The Evolution of the Atmosphere

One of the key steps in the evolution of life on Earth was the development of blue-green algae, a very successful life-form that takes in carbon dioxide from the environment and releases oxygen as a waste product. These successful microorganisms proliferated, giving rise to all the lifeforms we call plants. Since the energy for making new plant material from chemical building blocks comes from sunlight, we call the process **photosynthesis**.

Studies of the chemistry of ancient rocks show that Earth's atmosphere lacked abundant free oxygen until about 2 billion years ago, despite the presence of plants releasing oxygen by photosynthesis. Apparently, chemical reactions with Earth's crust removed the oxygen gas as quickly as it formed. Slowly, however, the increasing evolutionary sophistication of life led to a growth in the plant population and thus increased oxygen production. At the same time, it appears that increased geological activity led to heavy erosion on our planet's surface. This buried much of the plant carbon before it could recombine with oxygen to form CO_2.

Free oxygen began accumulating in the atmosphere about 2 billion years ago, and the increased amount of this gas led to the formation of Earth's ozone layer (recall that ozone is a triple molecule of oxygen, O_3), which protects the surface from deadly solar ultraviolet light. Before that, it was unthinkable for life to venture outside the protective oceans, so the landmasses of Earth were barren.

The presence of oxygen, and hence ozone, thus allowed colonization of the land. It also made possible a tremendous proliferation of animals, which lived by taking in and using the organic materials produced by plants as their own energy source.

As animals evolved in an environment increasingly rich in oxygen, they were able to develop techniques for breathing oxygen directly from the atmosphere. We humans take it for granted that plenty of free oxygen is available in Earth's atmosphere, and we use it to release energy from the food we take in. Although it may seem funny to think of it this way, we are lifeforms that have evolved to breathe in the waste product of plants. It is plants and related microbes that are the primary producers, using sunlight to create energy-rich "food" for the rest of us.

On a planetary scale, one of the consequences of life has been a decrease in atmospheric carbon dioxide. In the absence of life, Earth would probably have an atmosphere dominated by CO_2, like Mars or Venus. But living things, in combination with high levels of geological activity, have effectively stripped our atmosphere of most of this gas.

The Greenhouse Effect and Global Warming

We have a special interest in the carbon dioxide content of the atmosphere because of the key role this gas plays in retaining heat from the Sun through a process called the **greenhouse effect**. To understand how the greenhouse effect works, consider the fate of sunlight that strikes the surface of Earth. The light penetrates our atmosphere, is absorbed by the ground, and heats the surface layers. At the temperature of Earth's surface, that energy is then reemitted as infrared or heat radiation (**Figure 8.17**). However, the molecules of our atmosphere, which allow visible light through, are good at absorbing infrared energy. As a result, CO_2 (along with methane and water vapor) acts like a blanket, trapping heat in the atmosphere and impeding its flow back to space. To maintain an energy balance, the temperature of the surface and lower atmosphere must increase until the total energy radiated by Earth to space equals the energy received from the Sun. The more CO_2 there is in our atmosphere, the higher the temperature at which Earth's surface reaches a new balance.

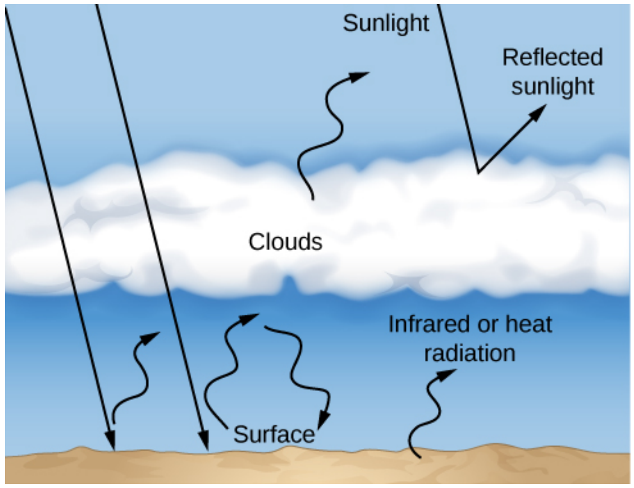


Figure 8.17 How the Greenhouse Effect Works. Sunlight that penetrates to Earth's lower atmosphere and surface is reradiated as infrared or heat radiation, which is trapped by greenhouse gases such as water vapor, methane, and CO_2 in the atmosphere. The result is a higher surface temperature for our planet.

The greenhouse effect in a planetary atmosphere is similar to the heating of a gardener's greenhouse or the inside of a car left out in the Sun with the windows rolled up. In these examples, the window glass plays the role of **greenhouse gases**, letting sunlight in but reducing the outward flow of heat radiation. As a result, a greenhouse or car interior winds up much hotter than would be expected from the heating of sunlight alone. On Earth, the current greenhouse effect elevates the surface temperature by about 23 °C. Without this greenhouse effect, the average surface temperature would be well below freezing and Earth would be locked in a global ice age.

That's the good news; the bad news is that the heating due to the greenhouse effect is increasing. Modern industrial society depends on energy extracted from burning fossil fuels. In effect, we are exploiting the energy-rich material created by photosynthesis tens of millions of years ago. As these ancient coal and oil deposits are oxidized (burned using oxygen), large quantities of carbon dioxide are released into the atmosphere. The problem is exacerbated by the widespread destruction of tropical forests, which we depend on to extract CO_2 from the atmosphere and replenish our supply of oxygen. In the past century of increased industrial and agricultural development, the amount of CO_2 in the atmosphere increased by about 30% and continues to rise at more than 0.5% per year.

Before the end of the present century, Earth's CO_2 level is predicted to reach twice the value it had before the industrial revolution (Figure 8.18). The consequences of such an increase for Earth's surface and atmosphere (and the creatures who live there) are likely to be complex changes in climate, and may be catastrophic for many species. Many groups of scientists are now studying the effects of such global warming with elaborate computer models, and climate change has emerged as the greatest known threat (barring nuclear war) to both industrial civilization and the ecology of our planet.

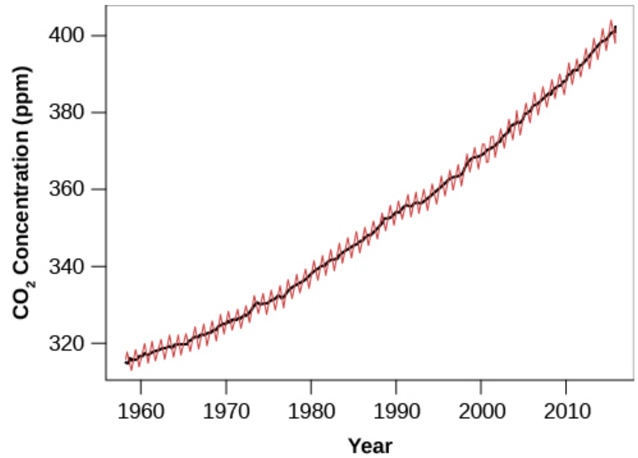


Figure 8.18 Increase of Atmospheric Carbon Dioxide over Time. Scientists expect that the amount of CO_2 will double its preindustrial level before the end of the twenty-first century. Measurements of the isotopic signatures of this added CO_2 demonstrate that it is mostly coming from burning fossil fuels. (credit: modification of work by NOAA)

LINK TO LEARNING

This **short PBS video (https://openstax.org/l/30pbsgreengas)** explains the physics of the greenhouse effect.

Already climate change is widely apparent. Around the world, temperature records are constantly set and broken; all but one of the hottest recorded years have taken place since 2000. Glaciers are retreating, and the Arctic Sea ice is now much thinner than when it was first explored with nuclear submarines in the 1950s. Rising sea levels (from both melting glaciers and expansion of the water as its temperature rises) pose one of the most immediate threats, and many coastal cities have plans to build dikes or seawalls to hold back the expected flooding. The rate of temperature increase is without historical precedent, and we are rapidly entering “unknown territory” where human activities are leading to the highest temperatures on Earth in more than 50 million years.

Human Impacts on Our Planet

Earth is so large and has been here for so long that some people have trouble accepting that humans are really changing the planet, its atmosphere, and its climate. They are surprised to learn, for example, that the carbon dioxide released from burning fossil fuels is 100 times greater than that emitted by volcanoes. But, the data clearly tell the story that our climate is changing rapidly, and that almost all of the change is a result of human activity.

This is not the first time that humans have altered our environment dramatically. Some of the greatest changes were caused by our ancestors, before the development of modern industrial society. If aliens had visited Earth 50,000 years ago, they would have seen much of the planet supporting large animals of the sort that now survive only in Africa. The plains of Australia were occupied by giant marsupials such as diprododon and zygomaturus (the size of our elephants today), and a species of kangaroo that stood 10 feet high. North America and North Asia hosted mammoths, saber tooth cats, mastodons, giant sloths, and even camels. The Islands of the Pacific teemed with large birds, and vast forests covered what are now the farms of Europe and China. Early human hunters killed many large mammals and marsupials, early farmers cut down most of the forests, and the Polynesian expansion across the Pacific doomed the population of large birds.

An even greater mass extinction is underway as a result of rapid climate change. In recognition of our impact on the environment, scientists have proposed giving a new name to the current epoch, the *anthropocine*, when human activity started to have a significant global impact. Although not an officially approved name, the concept of “anthropocine” is useful for recognizing that we humans now represent the dominant influence on our planet’s atmosphere and ecology, for better or for worse.

8.5 COSMIC INFLUENCES ON THE EVOLUTION OF EARTH

Learning Objectives

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

- Explain the scarcity of impact craters on Earth compared with other planets and moons
- Describe the evidence for recent impacts on Earth
- Detail how a massive impact changed the conditions for life on Earth, leading to the extinction of the dinosaurs
- Describe how impacts have influenced the evolution of life on Earth
- Discuss the search for objects that could potentially collide with our planet

In discussing Earth’s geology earlier in this chapter, we dealt only with the effects of internal forces, expressed through the processes of plate tectonics and volcanism. On the Moon, in contrast, we see primarily craters, produced by the impacts of interplanetary debris such as asteroids and comets. Why don’t we see more evidence on Earth of the kinds of impact craters that are so prominent on the Moon and other worlds?

Where Are the Craters on Earth?

It is not possible that Earth escaped being struck by the interplanetary debris that has pockmarked the Moon. From a cosmic perspective, the Moon is almost next door. Our atmosphere does make small pieces of cosmic debris burn up (which we see as *meteors*—commonly called shooting stars). But, the layers of our air provide no shield against the large impacts that form craters several kilometers in diameter and are common on the Moon.

In the course of its history, Earth must therefore have been impacted as heavily as the Moon. The difference is that, on Earth, these craters are destroyed by our active geology before they can accumulate. As plate tectonics constantly renews our crust, evidence of past cratering events is slowly erased. Only in the past few decades have geologists succeeded in identifying the eroded remnants of many impact craters (**Figure 8.19**). Even more recent is our realization that, over the history of Earth, these impacts have had an important influence on the evolution of life.

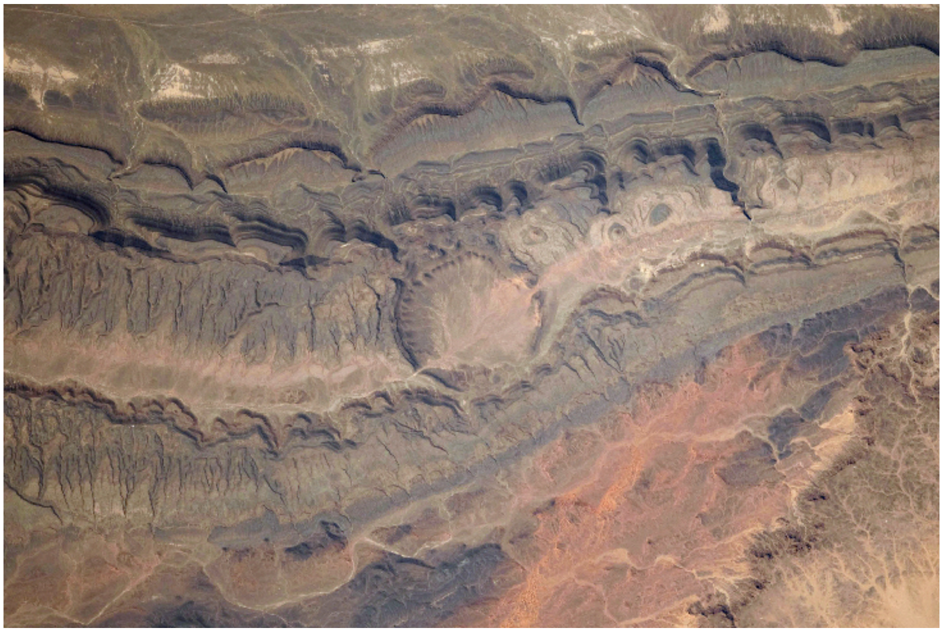


Figure 8.19 Ouarkziz Impact Crater. Located in Algeria, this crater (the round feature in the center) is the result of a meteor impact during the Cretaceous period. Although the crater has experienced heavy erosion, this image from the International Space Station shows the circular pattern resulting from impact. (credit: modification of work by NASA)

Recent Impacts

The collision of interplanetary debris with Earth is not a hypothetical idea. Evidence of relatively recent impacts can be found on our planet’s surface. One well-studied historic collision took place on June 30, 1908, near the Tunguska River in Siberia. In this desolate region, there was a remarkable explosion in the atmosphere about 8 kilometers above the surface. The shock wave flattened more than a thousand square kilometers of forest (**Figure 8.20**). Herds of reindeer and other animals were killed, and a man at a trading post 80 kilometers from the blast was thrown from his chair and knocked unconscious. The blast wave spread around the world, as recorded by instruments designed to measure changes in atmospheric pressure.

Figure 8.20 Aftermath of the Tunguska Explosion. This photograph, taken 21 years after the blast, shows a part of the forest that was destroyed by the 5-megaton explosion, resulting when a stony projectile about the size of a small office building (40 meters in diameter) collided with our planet. (credit: modification of work by Leonid Kulik)

Despite this violence, no craters were formed by the Tunguska explosion. Shattered by atmospheric pressure, the stony projectile with a mass of approximately 10,000 tons disintegrated above our planet's surface to create a blast equivalent to a 5-megaton nuclear bomb. Had it been smaller or more fragile, the impacting body would have dissipated its energy at high altitude and probably attracted no attention. Today, such high-altitude atmospheric explosions are monitored regularly by military surveillance systems.

If it had been larger or made of stronger material (such as metal), the Tunguska projectile would have penetrated all the way to the surface of Earth and exploded to form a crater. Instead, only the heat and shock of the atmospheric explosion reached the surface, but the devastation it left behind in Siberia bore witness to the power of such impacts. Imagine if the same rocky impactor had exploded over New York City in 1908; history books might today record it as one of the most deadly events in human history.

Tens of thousands of people witnessed directly the explosion of a smaller (20-meter) projectile over the Russian city of Chelyabinsk on an early winter morning in 2013. It exploded at a height of 21 kilometers in a burst of light brighter than the Sun, and the shockwave of the 0.5-megaton explosion broke tens of thousands of windows and sent hundreds of people to the hospital. Rock fragments (meteorites) were easily collected by people in the area after the blast because they landed on fresh snow.

LINK TO LEARNING

Dr. David Morrison, one of the original authors of this textbook, provides a **nontechnical talk (https://openstax.org/l/30chelyabinskex)** about the Chelyabinsk explosion, and impacts in general.

The best-known recent crater on Earth was formed about 50,000 years ago in Arizona. The projectile in this case was a lump of iron about 40 meters in diameter. Now called *Meteor Crater* and a major tourist attraction on the way to the Grand Canyon, the crater is about a mile across and has all the features associated with similar-size lunar impact craters (**Figure 8.21**). Meteor Crater is one of the few impact features on Earth that remains relatively intact; some older craters are so eroded that only a trained eye can distinguish them. Nevertheless, more than 150 have been identified. (See the list of suggested online sites at the end of this chapter if you want to find out more about these other impact scars.)

Figure 8.21 Meteor Crater in Arizona. Here we see a 50,000-year-old impact crater made by the collision of a 40-meter lump of iron with our planet. Although impact craters are common on less active bodies such as the Moon, this is one of the very few well-preserved craters on Earth. (modification of work by D. Roddy/USGS)

Mass Extinction

The impact that produced Meteor Crater would have been dramatic indeed to any humans who witnessed it (from a safe distance) since the energy release was equivalent to a 10-megaton nuclear bomb. But such explosions are devastating only in their local areas; they have no *global* consequences. Much larger (and rarer) impacts, however, can disturb the ecological balance of the entire planet and thus influence the course of evolution.

The best-documented large impact took place 65 million years ago, at the end of what is now called the Cretaceous period of geological history. This time in the history of life on Earth was marked by a **mass extinction**, in which more than half of the species on our planet died out. There are a dozen or more mass extinctions in the geological record, but this particular event (nicknamed the "great dying") has always intrigued paleontologists because it marks the end of the dinosaur age. For tens of millions of years these great creatures had flourished and dominated. Then, they suddenly disappeared (along with many other species), and thereafter mammals began the development and diversification that ultimately led to all of us.

The object that collided with Earth at the end of the Cretaceous period struck a shallow sea in what is now the Yucatán peninsula of Mexico. Its mass must have been more than a trillion tons, determined from study of a worldwide layer of sediment deposited from the dust cloud that enveloped the planet after its impact. First identified in 1979, this sediment layer is rich in the rare metal iridium and other elements that are relatively abundant in asteroids and comets, but exceedingly rare in Earth's crust. Even though it was diluted by the material that the explosion excavated from the surface of Earth, this cosmic component can still be identified. In addition, this layer of sediment contains many minerals characteristic of the temperatures and pressures of a gigantic explosion.

The impact that led to the extinction of dinosaurs released energy equivalent to 5 billion Hiroshima-size nuclear bombs and excavated a crater 200 kilometers across and deep enough to penetrate through Earth's crust. This large crater, named Chicxulub for a small town near its center, has subsequently been buried in sediment, but its outlines can still be identified (**Figure 8.22**). The explosion that created the Chicxulub crater lifted about 100 trillion tons of dust into the atmosphere. We can determine this amount by measuring the thickness of the sediment layer that formed when this dust settled to the surface.

Figure 8.22 Site of the Chicxulub Crater. This map shows the location of the impact crater created 65 million years ago on Mexico's Yucatán peninsula. The crater is now buried under more than 500 meters of sediment. (credit: modification of work by "Carport"/Wikimedia)

Such a quantity of airborne material would have blocked sunlight completely, plunging Earth into a period of cold and darkness that lasted several months. Many plants dependent on sunlight would have died, leaving plant-eating animals without a food supply. Other worldwide effects included large-scale fires (started by the hot, flying debris from the explosion) that destroyed much of the planet's forests and grasslands, and a long period in which rainwater around the globe was acidic. It was these environmental effects, rather than the explosion itself, that were responsible for the mass extinction, including the demise of the dinosaurs.

Impacts and the Evolution of Life

It is becoming clear that many—perhaps most—mass extinctions in Earth's long history resulted from a variety of other causes, but in the case of the dinosaur killer, the cosmic impact certainly played a critical role and may have been the "final straw" in a series of climactic disturbances that resulted in the "great dying."

A catastrophe for one group of living things, however, may create opportunities for another group. Following each mass extinction, there is a sudden evolutionary burst as new species develop to fill the ecological niches opened by the event. Sixty-five million years ago, our ancestors, the mammals, began to thrive when so many other species died out. We are the lucky beneficiaries of this process.

Impacts by comets and asteroids represent the only mechanisms we know of that could cause truly global catastrophes and seriously influence the evolution of life all over the planet. As paleontologist Stephen Jay Gould of Harvard noted, such a perspective changes fundamentally our view of biological evolution. The central issues for the survival of a species must now include more than just its success in competing with other species and adapting to slowly changing environments, as envisioned by Darwin's idea of natural selection. Also required is an ability to survive random global catastrophes due to impacts.

Still earlier in its history, Earth was subject to even larger impacts from the leftover debris of planet formation. We know that the Moon was struck repeatedly by objects larger than 100 kilometers in diameter—1000 times more massive than the object that wiped out most terrestrial life 65 million years ago. Earth must have experienced similar large impacts during its first 700 million years of existence. Some of them were probably violent enough to strip the planet of most its atmosphere and to boil away its oceans. Such events would sterilize the planet, destroying any life that had begun. Life may have formed and been wiped out several times before our own microbial ancestors took hold sometime about 4 billion years ago.

The fact that the oldest surviving microbes on Earth are thermophiles (adapted to very high temperatures) can also be explained by such large impacts. An impact that was just a bit too small to sterilize the planet would still have destroyed anything that lived in what we consider "normal" environments, and only the creatures adapted to high temperatures would survive. Thus, the oldest surviving terrestrial lifeforms are probably the remnants of a sort of evolutionary bottleneck caused by repeated large impacts early in the planet's history.

Impacts in Our Future?

The impacts by asteroids and comets that have had such a major influence on life are not necessarily a thing of the past. In the full scope of planetary history, 65 million years ago was just yesterday. Earth actually orbits the Sun within a sort of cosmic shooting gallery, and although major impacts are rare, they are by no means over. Humanity could suffer the same fate as the dinosaurs, or lose a city to the much more frequent impacts like the one over Tunguska, unless we figure out a way to predict the next big impact and to protect our planet. The fact that our solar system is home to some very large planets in outer orbits may be beneficial to us; the gravitational fields of those planets can be very effective at pulling in cosmic debris and shielding us from larger, more frequent impacts.

Beginning in the 1990s, a few astronomers began to analyze the cosmic impact hazard and to persuade the government to support a search for potentially hazardous asteroids. Several small but sophisticated wide-field telescopes are now used for this search, which is called the NASA Spaceguard Survey. Already we know that there are currently no asteroids on a collision course with Earth that are as big (10–15 kilometers) as the one that killed the dinosaurs. The Spaceguard Survey now concentrates on finding smaller potential impactors. By 2015, the search had netted more than 15,000 near-Earth-asteroids, including most of those larger than 1 kilometer. None of those discovered so far poses any danger to us. Of course, we cannot make a similar statement about the asteroids that have not yet been discovered, but these will be found and evaluated one by one for their potential hazard. These asteroid surveys are one of the few really life-and-death projects carried out by astronomers, with a potential to help to save our planet from future major impacts.

LINK TO LEARNING

The **Torino Impact Hazard Scale (https://openstax.org/l/30torhazscale)** is a method for categorizing the impact hazard associated with near-Earth objects such as asteroids and comets. It is a communication tool for astronomers and the public to assess the seriousness of collision predictions by combining probability statistics and known kinetic damage potentials into a single threat value.

Purdue University's **"Impact: Earth" calculator (https://openstax.org/l/30purimpearcal)** lets you input the characteristics of an approaching asteroid to determine the effect of its impact on our planet.

CHAPTER 8 REVIEW

KEY TERMS

bar a force of 100,000 Newtons acting on a surface area of 1 square meter; the average pressure of Earth's atmosphere at sea level is 1.013 bars

basalt igneous rock produced by the cooling of lava; makes up most of Earth's oceanic crust and is found on other planets that have experienced extensive volcanic activity

convection movement caused within a gas or liquid by the tendency of hotter, and therefore less dense material, to rise and colder, denser material to sink under the influence of gravity, which consequently results in transfer of heat

core the central part of the planet; consists of higher density material

crust the outer layer of a terrestrial planet

fault in geology, a crack or break in the crust of a planet along which slippage or movement can take place, accompanied by seismic activity

granite a type of igneous silicate rock that makes up most of Earth's continental crust

greenhouse effect the blanketing (absorption) of infrared radiation near the surface of a planet—for example, by CO_2 in its atmosphere

greenhouse gas a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range; on Earth, these atmospheric gases primarily include carbon dioxide, methane, and water vapor

igneous rock rock produced by cooling from a molten state

magnetosphere the region around a planet in which its intrinsic magnetic field dominates the interplanetary field carried by the solar wind; hence, the region within which charged particles can be trapped by the planetary magnetic field

mantle the largest part of Earth's interior; lies between the crust and the core

mass extinction the sudden disappearance in the fossil record of a large number of species of life, to be replaced by fossils of new species in subsequent layers; mass extinctions are indicators of catastrophic changes in the environment, such as might be produced by a large impact on Earth

metamorphic rock rock produced by physical and chemical alteration (without melting) under high temperature and pressure

ozone (O_3) a heavy molecule of oxygen that contains three atoms rather than the more normal two

photosynthesis a complex sequence of chemical reactions through which some living things can use sunlight to manufacture products that store energy (such as carbohydrates), releasing oxygen as one by-product

plate tectonics the motion of segments or plates of the outer layer of a planet over the underlying mantle

primitive rock rock that has not experienced great heat or pressure and therefore remains representative of the original condensed materials from the solar nebula

rift zone in geology, a place where the crust is being torn apart by internal forces generally associated with the injection of new material from the mantle and with the slow separation of tectonic plates

sedimentary rock rock formed by the deposition and cementing of fine grains of material, such as pieces of igneous rock or the shells of living things

seismic wave a vibration that travels through the interior of Earth or any other object; on Earth, these are generally caused by earthquakes

stratosphere the layer of Earth's atmosphere above the troposphere and below the ionosphere

subduction the sideways and downward movement of the edge of a plate of Earth's crust into the mantle beneath another plate

troposphere the lowest level of Earth's atmosphere, where most weather takes place

volcano a place where material from a planet's mantle erupts on its surface

SUMMARY

8.1 The Global Perspective

Earth is the prototype terrestrial planet. Its interior composition and structure are probed using seismic waves. Such studies reveal that Earth has a metal core and a silicate mantle. The outer layer, or crust, consists primarily of oceanic basalt and continental granite. A global magnetic field, generated in the core, produces Earth's magnetosphere, which can trap charged atomic particles.

8.2 Earth's Crust

Terrestrial rocks can be classified as igneous, sedimentary, or metamorphic. A fourth type, primitive rock, is not found on Earth. Our planet's geology is dominated by plate tectonics, in which crustal plates move slowly in response to mantle convection. The surface expression of plate tectonics includes continental drift, recycling of the ocean floor, mountain building, rift zones, subduction zones, faults, earthquakes, and volcanic eruptions of lava from the interior.

8.3 Earth's Atmosphere

The atmosphere has a surface pressure of 1 bar and is composed primarily of N_2 and O_2, plus such important trace gases as H_2O, CO_2, and O_3. Its structure consists of the troposphere, stratosphere, mesosphere, and ionosphere. Changing the composition of the atmosphere also influences the temperature. Atmospheric circulation (weather) is driven by seasonally changing deposition of sunlight. Many longer term climate variations, such as the ice ages, are related to changes in the planet's orbit and axial tilt.

8.4 Life, Chemical Evolution, and Climate Change

Life originated on Earth at a time when the atmosphere lacked O_2 and consisted mostly of CO_2. Later, photosynthesis gave rise to free oxygen and ozone. Modern genomic analysis lets us see how the wide diversity of species on the planet are related to each other. CO_2 and methane in the atmosphere heat the surface through the greenhouse effect; today, increasing amounts of atmospheric CO_2 are leading to the global warming of our planet.

8.5 Cosmic Influences on the Evolution of Earth

Earth, like the Moon and other planets, has been influenced by the impacts of cosmic debris, including such recent examples as Meteor Crater and the Tunguska explosion. Larger past impacts are implicated in some mass extinctions, including the large impact 65 million years ago at the end of the Cretaceous period that wiped out the dinosaurs and many other species. Today, astronomers are working to predict the next impact in advance, while other scientists are coming to grips with the effect of impacts on the evolution and diversity of life on Earth.

FOR FURTHER EXPLORATION

Articles

Earth

Collins, W., et al. "The Physical Science behind Climate Change." *Scientific American* (August 2007): 64. Why scientists are now confident that human activities are changing our planet's climate.

Glatzmaier, G., & Olson, P. "Probing the Geodynamo." *Scientific American* (April 2005): 50. Experiments and modeling that tell us about the source and reversals of Earth's magnetic field.

Gurnis, M. "Sculpting the Earth from Inside Out." *Scientific American* (March 2001): 40. On motions that lift and lower the continents.

Hartmann, W. "Piecing Together Earth's Early History." *Astronomy* (June 1989): 24.

Jewitt, D., & Young, E. "Oceans from the Skies." *Scientific American* (March 2015): 36. How did Earth get its water after its initial hot period?

Impacts

Boslaugh, M. "In Search of Death-Plunge Asteroids." *Astronomy (*July 2015): 28. On existing and proposed programs to search for earth-crossing asteroids.

Brusatte, S. "What Killed the Dinosaurs?" *Scientific American* (December 2015): 54. The asteroid hit Earth at an already vulnerable time.

Chyba, C. "Death from the Sky: Tunguska." *Astronomy* (December 1993): 38. Excellent review article.

Durda, D. "The Chelyabinsk Super-Meteor." *Sky & Telescope* (June 2013): 24. A nice summary with photos and eyewitness reporting.

Gasperini, L., et al. "The Tunguska Mystery." *Scientific American* (June 2008): 80. A more detailed exploration of the site of the 1908 impact over Siberia.

Kring, D. "Blast from the Past." *Astronomy* (August 2006): 46. Six-page introduction to Arizona's meteor crater.

Websites

Earth

Astronaut Photography of Earth from Space: **http://earth.jsc.nasa.gov/ (http://earth.jsc.nasa.gov/)** . A site with many images and good information.

Exploration of the Earth's Magnetosphere: **http://phy6.org/Education/Intro.html (http://phy6.org/Education/Intro.html)** . An educational website by Dr. Daniel Stern.

NASA Goddard: Earth from Space: Fifteen Amazing Things in 15 Years: **https://www.nasa.gov/content/goddard/earth-from-space-15-amazing-things-in-15-years (https://www.nasa.gov/content/goddard/earth-from-space-15-amazing-things-in-15-years)** . Images and videos that reveal things about our planet and its atmosphere.

U.S. Geological Survey: Earthquake Information Center: **http://earthquake.usgs.gov/learn/**

(http://earthquake.usgs.gov/learn/)

Views of the Solar System: http://www.solarviews.com/eng/earth.htm (http://www.solarviews.com/eng/earth.htm) . Overview of Earth.

Impacts

B612 Foundation : https://b612foundation.org/ (https://b612foundation.org/) . Set up by several astronauts for research and education about the asteroid threat to Earth and to build a telescope in space to search for dangerous asteroids.

Lunar and Planetary Institute: Introduction to Terrestrial Impact Craters: http://www.lpi.usra.edu/publications/slidesets/craters/ (http://www.lpi.usra.edu/publications/slidesets/craters/) . Includes images.

Meteor Crater Tourist Site: http://meteorcrater.com/ (http://meteorcrater.com/) .

NASA/Jet Propulsion Lab Near Earth Object Program: http://neo.jpl.nasa.gov/neo/ (http://neo.jpl.nasa.gov/neo/) .

What Are Near-Earth-Objects: http://spaceguardcentre.com/what-are-neos/ (http://spaceguardcentre.com/what-are-neos/) . From the British Spaceguard Centre.

Videos

Earth

All Alone in the Night: http://apod.nasa.gov/apod/ap120305.html (http://apod.nasa.gov/apod/ap120305.html) . Flying over Earth at night (2:30).

Earth Globes Movies (including Earth at night): http://astro.uchicago.edu/cosmus/projects/earth/ (http://astro.uchicago.edu/cosmus/projects/earth/) .

Earth: The Operator's Manual: http://earththeoperatorsmanual.com/feature-video/earth-the-operators-manual (http://earththeoperatorsmanual.com/feature-video/earth-the-operators-manual) . A National Science Foundation–sponsored miniseries on climate change and energy, with geologist Richard Alley (53:43).

PBS NOVA Videos about Earth: http://www.pbs.org/wgbh/nova/earth/ (http://www.pbs.org/wgbh/nova/earth/) . Programs and information about planet Earth. Click full episodes on the menu at left to be taken to a nice array of videos.

U. S. National Weather Service: http://earth.nullschool.net (http://earth.nullschool.net) . Real Time Globe of Earth showing wind patterns which can be zoomed and moved to your preferred view.

Impacts

Chelyabinsk Meteor: Can We Survive a Bigger Impact?: https://www.youtube.com/watch?v=Y-e6xyUZLLs (https://www.youtube.com/watch?v=Y-e6xyUZLLs) . Talk by Dr. David Morrison (1:34:48).

Large Asteroid Impact Simulation: https://www.youtube.com/watch?v=bU1QPtOZQZU (https://www.youtube.com/watch?v=bU1QPtOZQZU) . Large asteroid impact simulation from the Discovery Channel (4:45).

Meteor Hits Russia February 15, 2013: https://www.youtube.com/watch?v=dpmXyJrs7iU (https://www.youtube.com/watch?v=dpmXyJrs7iU) . Archive of eyewitness footage (10:11).

Sentinel Mission: Finding an Asteroid Headed for Earth: https://www.youtube.com/watch?v=efz8c3ijD_A (https://www.youtube.com/watch?v=efz8c3ijD_A) . Public lecture by astronaut Ed Lu (1:08:57).

COLLABORATIVE GROUP ACTIVITIES

A. If we can predict that lots of ground movement takes place along subduction zones and faults, then why do so many people live there? Should we try to do anything to discourage people from living in these areas? What inducement would your group offer people to move? Who would pay for the relocation? (Note that two of the original authors of this book live quite close to the San Andreas and Hayward faults. If they wrote this chapter and haven't moved, what are the chances others living in these kinds of areas will move?)

B. After your group reads the feature box on **Alfred Wegener: Catching the Drift of Plate Tectonics**, discuss some reasons his idea did not catch on right away among scientists. From your studies in this course and in other science courses (in college and before), can you cite other scientific ideas that we now accept but that had controversial beginnings? Can you think of any scientific theories that are still controversial today? If your group comes up with some, discuss ways scientists could decide whether each theory on your list is right.

C. Suppose we knew that a large chunk of rock or ice (about the same size as the one that hit 65 million years ago) will impact Earth in about 5 years. What could or should we do about it? (The film *Deep Impact* dealt with this theme.) Does your group think that the world as a whole should spend more money to find and predict the orbits of cosmic debris near Earth?

D. Carl Sagan pointed out that any defensive weapon that we might come up with to deflect an asteroid *away* from Earth could be used as an offensive weapon by an unstable dictator in the future to cause an asteroid not heading our way to come toward Earth. The history of human behavior, he noted, has shown that most weapons that are built (even with the best of motives) seem to wind up being used. Bearing this in mind, does your group think we should be building weapons to protect Earth from asteroid or comet impact? Can we afford not to build them? How can we safeguard against these collisions?

E. Is there evidence of climate change in your area over the past century? How would you distinguish a true climate change from the random variations in weather that take place from one year to the next?

EXERCISES

Review Questions

1. What is the thickest interior layer of Earth? The thinnest?

2. What are Earth's core and mantle made of? Explain how we know.

3. Describe the differences among primitive, igneous, sedimentary, and metamorphic rock, and relate these differences to their origins.

4. Explain briefly how the following phenomena happen on Earth, relating your answers to the theory of plate tectonics

A. earthquakes

B. continental drift

C. mountain building

D. volcanic eruptions

E. creation of the Hawaiian island chain

5. What is the source of Earth’s magnetic field?

6. Why is the shape of the magnetosphere not spherical like the shape of Earth?

7. Although he did not present a mechanism, what were the key points of Alfred Wegener’s proposal for the concept of continental drift?

8. List the possible interactions between Earth’s crustal plates that can occur at their boundaries.

9. List, in order of decreasing altitude, the principle layers of Earth’s atmosphere.

10. In which atmospheric layer are almost all water-based clouds formed?

11. What is, by far, the most abundant component of Earth’s atmosphere?

12. In which domain of living things do you find humankind?

13. Describe three ways in which the presence of life has affected the composition of Earth’s atmosphere.

14. Briefly describe the greenhouse effect.

15. How do impacts by comets and asteroids influence Earth’s geology, its atmosphere, and the evolution of life?

16. Why are there so many impact craters on our neighbor world, the Moon, and so few on Earth?

17. Detail some of the anthropogenic changes to Earth’s climate and their potential impact on life.

Thought Questions

18. If you wanted to live where the chances of a destructive earthquake were small, would you pick a location near a fault zone, near a mid ocean ridge, near a subduction zone, or on a volcanic island such as Hawaii? What are the relative risks of earthquakes at each of these locations?

19. Which type of object would likely cause more damage if it struck near an urban area: a small metallic object or a large stony/icy one?

20. If all life were destroyed on Earth by a large impact, would new life eventually form to take its place? Explain how conditions would have to change for life to start again on our planet.

21. Why is a decrease in Earth’s ozone harmful to life?

22. Why are we concerned about the increases in CO_2 and other gases that cause the greenhouse effect in Earth’s atmosphere? What steps can we take in the future to reduce the levels of CO_2 in our atmosphere? What factors stand in the way of taking the steps you suggest? (You may include technological, economic, and political factors in your answer.)

23. Do you think scientists should make plans to defend Earth from future asteroid impacts? Is it right to intervene in the same evolutionary process that made the development of mammals (including us) possible after the big impact 65 million years ago?

Figuring For Yourself

24. Europe and North America are moving apart by about 5 m per century. As the continents separate, new ocean floor is created along the mid-Atlantic Rift. If the rift is 5000 km long, what is the total area of new ocean floor created in the Atlantic each century? (Remember that 1 km = 1000 m.)

25. Over the entire Earth, there are 60,000 km of active rift zones, with average separation rates of 5 m/century. How much area of new ocean crust is created each year over the entire planet? (This area is approximately equal to the amount of ocean crust that is subducted since the total area of the oceans remains about the same.)

26. With the information from **Exercise 8.25**, you can calculate the average age of the ocean floor. First, find the total area of the ocean floor (equal to about 60% of the surface area of Earth). Then compare this with the area created (or destroyed) each year. The average lifetime is the ratio of these numbers: the total area of ocean crust compared to the amount created (or destroyed) each year.

27. What is the volume of new oceanic basalt added to Earth's crust each year? Assume that the thickness of the new crust is 5 km, that there are 60,000 km of rifts, and that the average speed of plate motion is 4 cm/y. What fraction of Earth's entire volume does this annual addition of new material represent?

28. Suppose a major impact that produces a mass extinction takes place on Earth once every 5 million years. Suppose further that if such an event occurred today, you and most other humans would be killed (this would be true even if the human species as a whole survived). Such impact events are random, and one could take place at any time. Calculate the probability that such an impact will occur within the next 50 years (within your lifetime).

29. How do the risks of dying from the impact of an asteroid or comet compare with other risks we are concerned about, such as dying in a car accident or from heart disease or some other natural cause? (Hint: To find the annual risk, go to the library or internet and look up the annual number of deaths from a particular cause in a particular country, and then divide by the population of that country.)

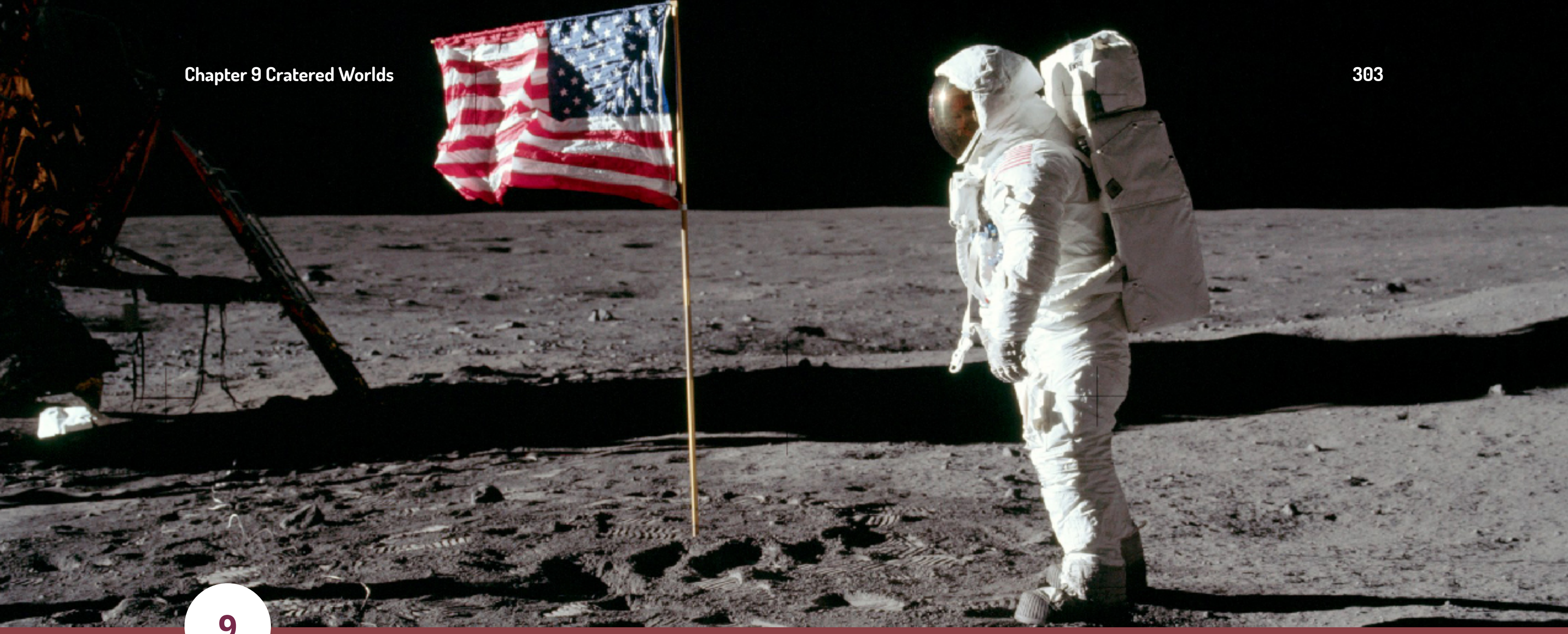
30. What fraction of Earth's volume is taken up by the core?

31. Approximately what percentage of Earth's radius is represented by the crust?

32. What is the drift rate of the Pacific plate over the Hawaiian hot spot?

33. What is the percent increase of atmospheric CO_2 in the past 20 years?

34. Estimate the mass of the object that formed Meteor Crater in Arizona.



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.

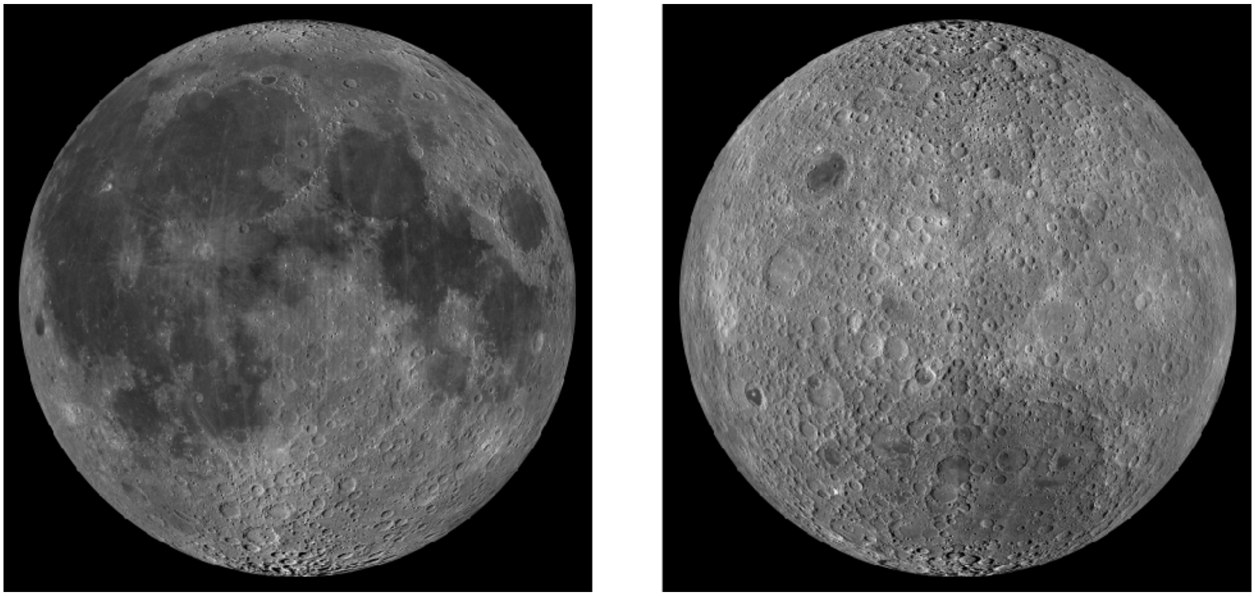


Figure 9.2 Two Sides of the Moon. The left image shows part of the hemisphere that faces Earth; several dark maria are visible. The right image shows part of the hemisphere that faces away from Earth; it is dominated by highlands. The resolution of this image is several kilometers, similar to that of 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.

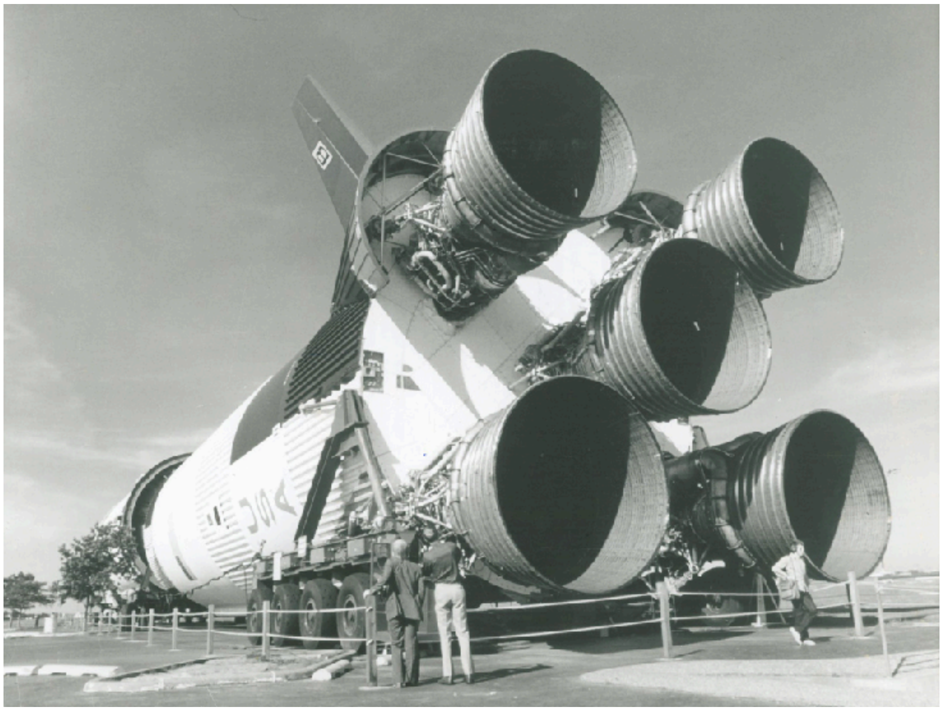


Figure 9.5 Moon Rocket on Display. One of the unused Saturn 5 rockets built to go to the Moon is now a tourist attraction at NASA's Johnson Space Center in Houston, although it has been moved indoors since this photo was taken. (credit: modification of work by David Morrison)

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.

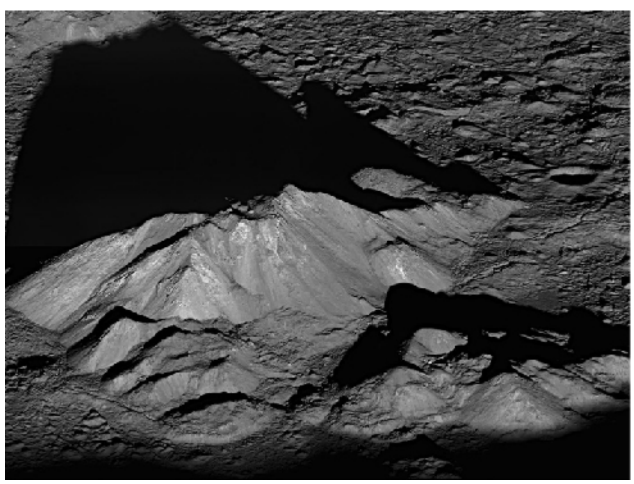


Figure 9.6 Sunrise on the Central Mountain Peaks of Tycho Crater, as Imaged by the NASA Lunar Reconnaissance Orbiter. Tycho, about 82 kilometers in diameter, is one of the youngest of the very large lunar craters. The central mountain rises 12 kilometers above the crater floor. (credit: modification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

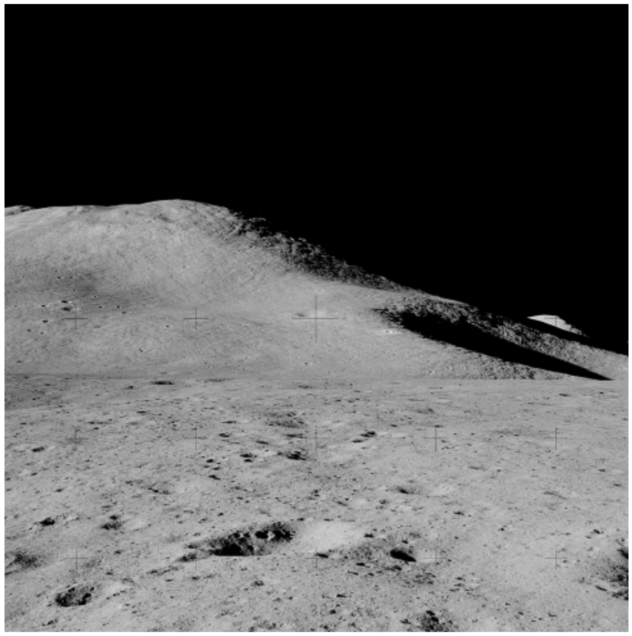


Figure 9.8 Lunar Mountain. This photo of Mt. Hadley on the edge of Mare Imbrium was taken by Dave Scott, one of the Apollo 15 astronauts. Note the smooth contours of the lunar mountains, which have not been sculpted by water or ice. (credit: NASA/Apollo Lunar Surface Journal)

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**).

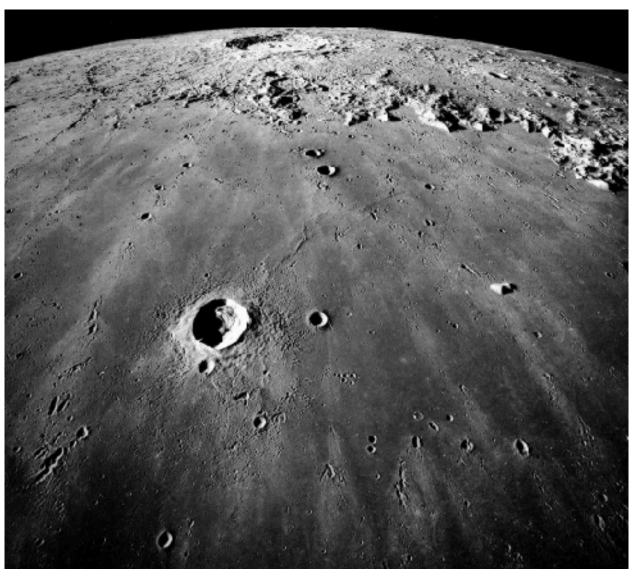


Figure 9.9 Lunar Maria. About 17% of the Moon's surface consists of the maria—flat plains of basaltic lava. This view of Mare Imbrium also shows numerous secondary craters and evidence of material ejected from the large crater Copernicus on the upper horizon. Copernicus is an impact crater almost 100 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)

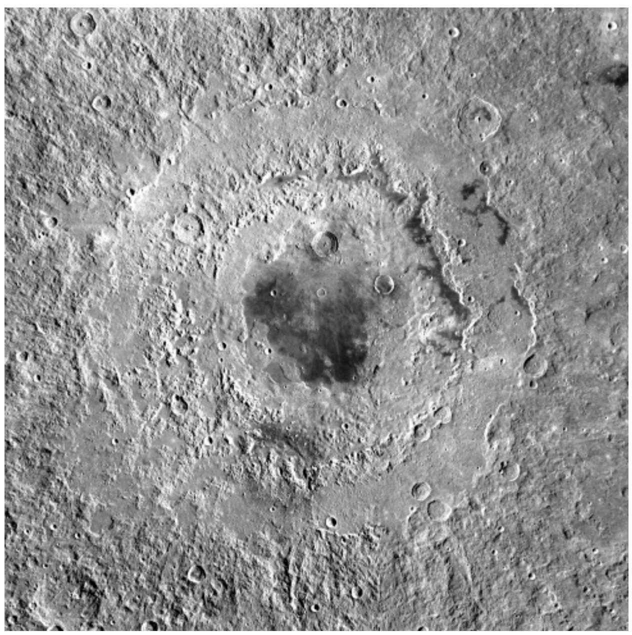


Figure 9.11 Mare Orientale. The youngest of the large lunar impact basins is Orientale, formed 3.8 billion years ago. Its outer ring is about 1000 kilometers in diameter, roughly the distance between New York City and Detroit, Michigan. Unlike most of the other basins, Orientale has not been completely 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.

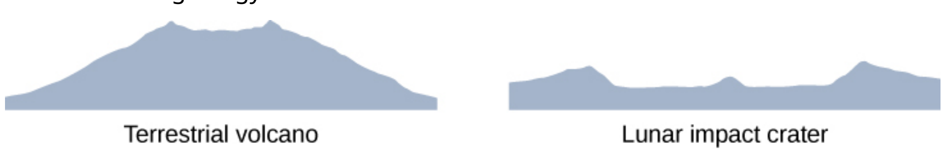


Figure 9.13 Volcanic and Impact Craters. Profiles of a typical terrestrial volcanic crater and a typical lunar impact crater are quite different.

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.

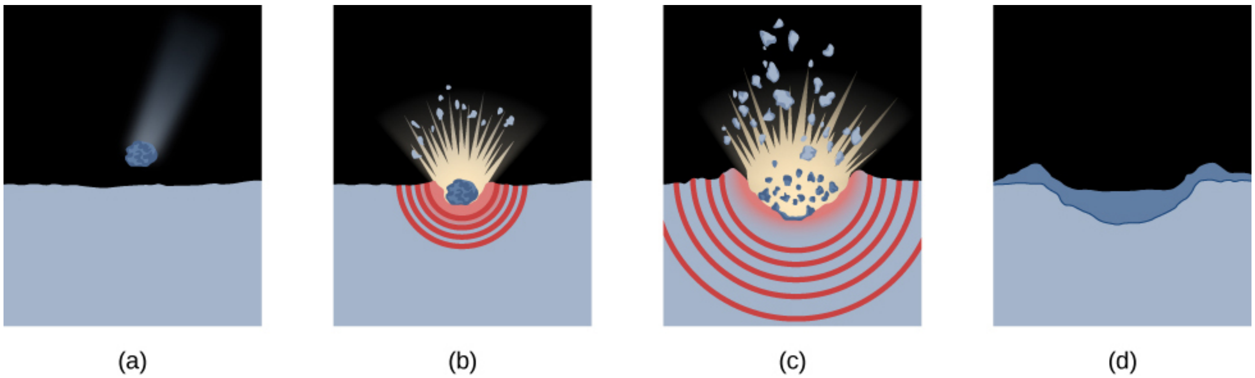


Figure 9.14 Stages in the Formation of an Impact Crater. (a) The impact occurs. (b) The projectile vaporizes and a shock wave spreads through the lunar rock. (c) Ejecta are thrown out of the crater. (d) Most of the ejected material falls back to fill the crater, forming an ejecta blanket.

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.

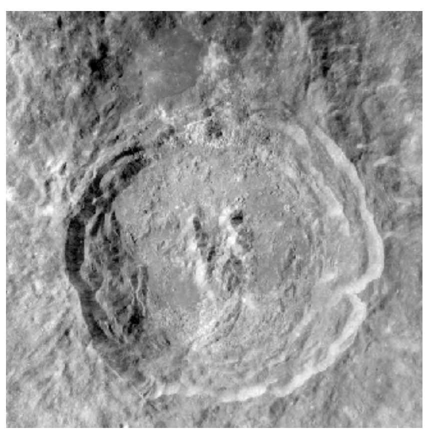


Figure 9.15 Typical Impact Crater. King Crater on the far side of the Moon, a fairly recent lunar crater 75 kilometers in diameter, shows most of the features associated with large impact structures. (credit: NASA/JSC/Arizona State University)

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.

(a) (b)

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.

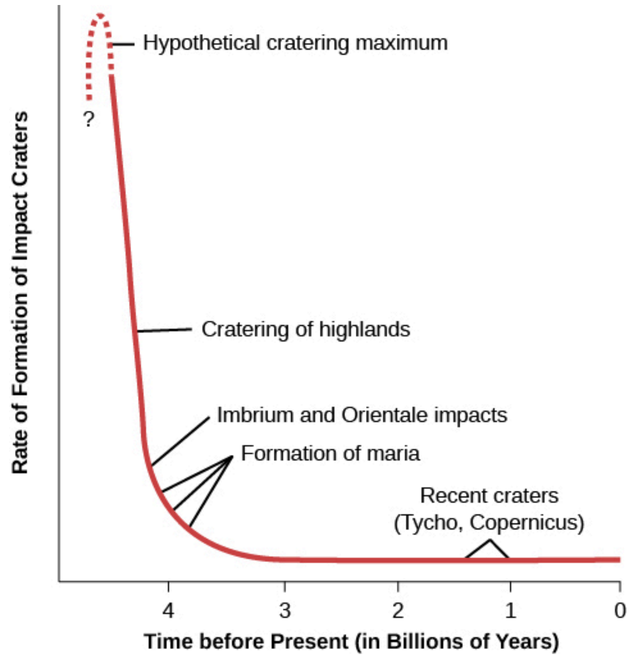


Figure 9.19 Cratering Rates over Time. The number of craters being made on the Moon's surface has varied with time over the past 4.3 billion years.

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.

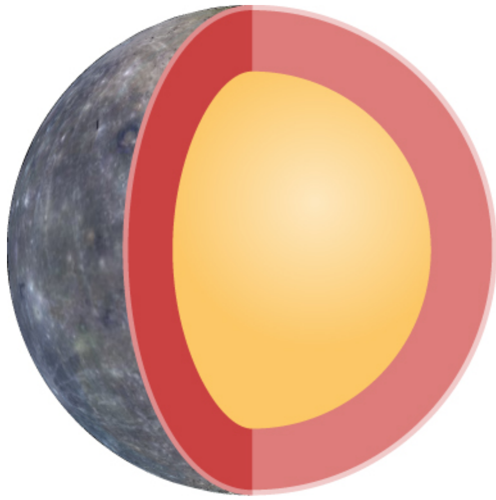


Figure 9.20 Mercury's Internal Structure. The interior of Mercury is dominated by a metallic core about the same size as our Moon.

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.

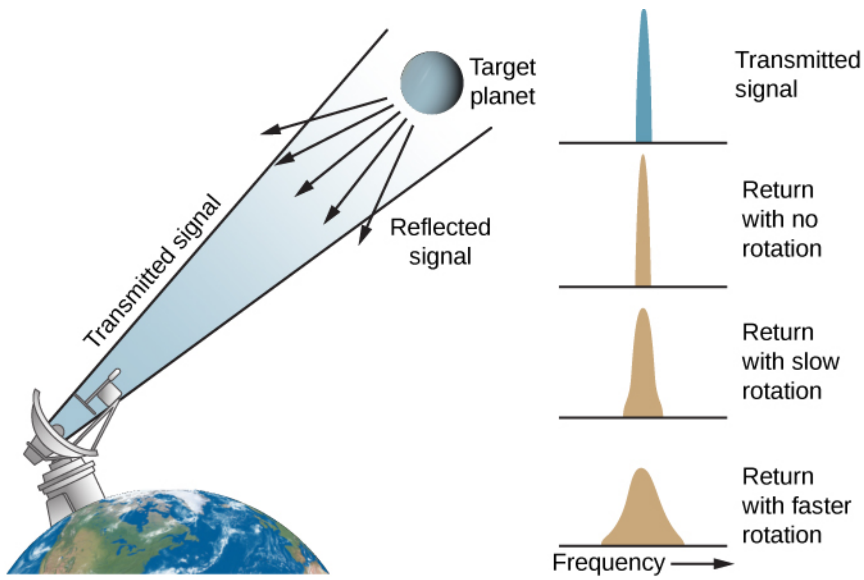


Figure 9.21 Doppler Radar Measures Rotation. When a radar beam is reflected from a rotating planet, the motion of one side of the planet's disk toward us and the other side away from us causes Doppler shifts in the reflected signal. The effect is to cause both a redshift and a blueshift, widening the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

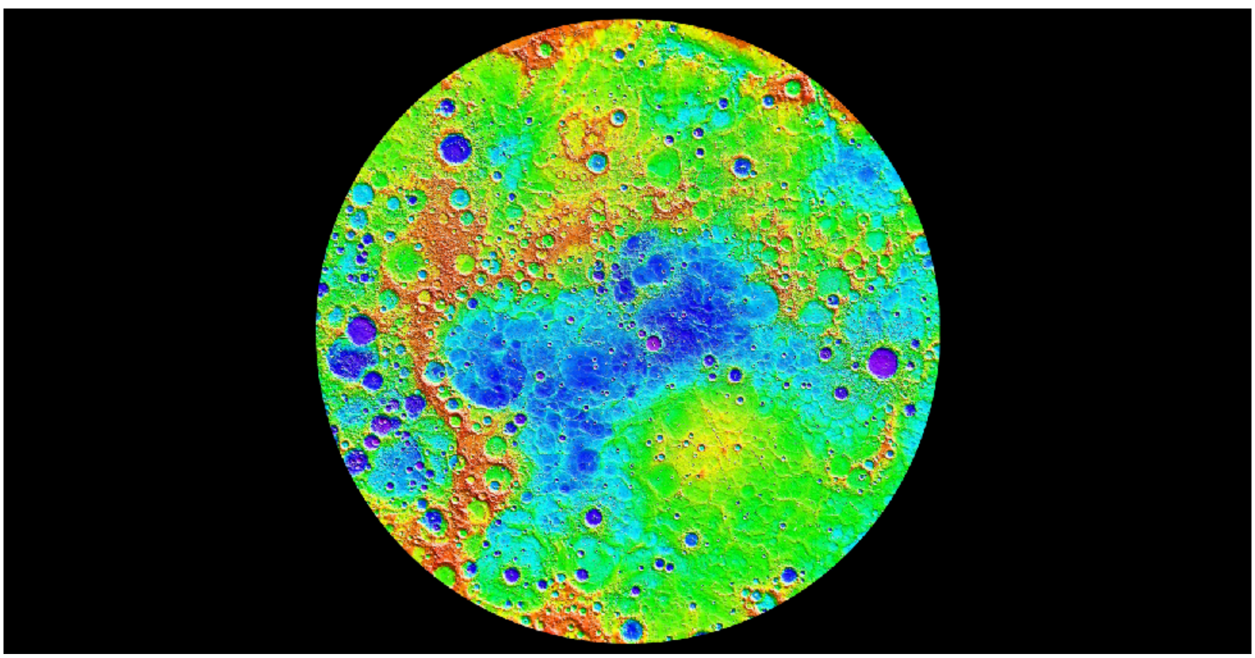


Figure 9.22 Mercury's Topography. The topography of Mercury's northern hemisphere is mapped in great detail from MESSENGER data. The lowest regions are shown in purple and blue, and the highest regions are shown in red. The difference in elevation between the lowest and highest regions shown here is 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)

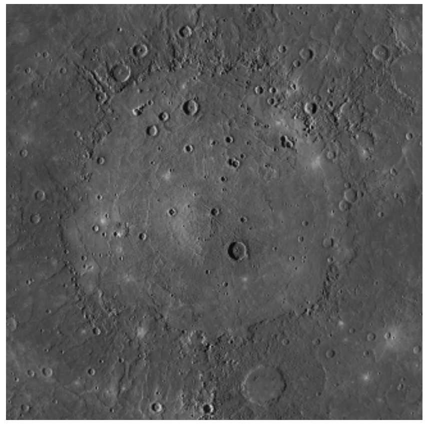


Figure 9.23 Caloris Basin. This partially flooded impact basin is the largest known structural feature on Mercury. The smooth plains in the interior of the basin have an area of almost two million square kilometers. Compare this photo with **Figure 9.11**, the Orientale Basin on the Moon. (credit: NASA/Johns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

Articles

The Moon

Bakich, Michael. “Asia’s New Assault on the Moon.” *Astronomy* (August 2009): 50. The Japanese Selene and Chinese Chang’e 1 missions.

Beatty, J. “NASA Slams the Moon.” *Sky & Telescope* (February 2010): 28. The impact of the LCROSS mission on the Moon and what we learned from it.

Bell, T. “Warning: Dust Ahead.” *Astronomy* (March 2006): 46. What we know about lunar dust and the problems it can cause.

Dorminey, B. “Secrets beneath the Moon’s Surface.” *Astronomy* (March 2011): 24. A nice timeline of the Moon’s evolution and the story of how we are finding out more about its internal structure.

Jayawardhana, R. “Deconstructing the Moon.” *Astronomy* (September 1998): 40. An update on the giant impact hypothesis for forming the Moon.

Register, B. “The Fate of the Moon Rocks.” *Astronomy* (December 1985): 15. What was done with the rocks the astronauts brought back from the Moon.

Schmitt, H. “Exploring Taurus–Littrow: Apollo 17.” *National Geographic* (September 1973). First-person account given by the only scientist to walk on the Moon.

Schmitt, H. “From the Moon to Mars.” *Scientific American* (July 2009): 36. The only scientist to walk on the Moon reflects on the science from Apollo and future missions to Mars.

Schultz, P. “New Clues to the Moon’s Distant Past.” *Astronomy* (December 2011): 34. Summary of results and ideas from the LCROSS and LRO missions.

Shirao, M. “Kayuga’s High Def Highlights.” *Sky & Telescope* (February 2010): 20. Results from the Japanese mission to the Moon, with high definition TV cameras.

Wadhwa, M. “What Are We Learning from the Moon Rocks?” *Astronomy* (June 2013): 54. Very nice discussion of how the rocks tell us about Moon’s composition, age, and origin.

Wood, Charles. “The Moon’s Far Side: Nearly a New World.” *Sky & Telescope* (January 2007): 48. This article compares what we know about the two sides and why they are different.

Zimmerman, R. “How Much Water is on the Moon?” *Astronomy* (January 2014): 50. Results from the LRO’s instruments and good overview of issue.

Mercury

Beatty, J. “Mercury Gets a Second Look.” *Sky & Telescope* (March 2009): 26. The October 2008 MESSENGER mission flyby.

Beatty, J. “Reunion with Mercury.” *Sky & Telescope* (May 2008): 24. The January 2008 MESSENGER encounter with Mercury.

“Mercury: Meet the Planet Nearest the Sun.” *Sky & Telescope* (March 2014): 39. Four-page pictorial introduction, including the new MESSENGER probe full map of the planet provided.

Oberg, J. “Torrid Mercury’s Icy Poles.” *Astronomy* (December 2013): 30. A nice overview of results from MESSENGER mission, including the ice in polar craters.

Sheehan, W., and Dobbins, T. “Mesmerized by Mercury.” *Sky & Telescope* (June 2000): 109. History of Mercury observations and how amateur astronomers can contribute.

Talcott, R. “Surprises from MESSENGER’s Historic Mercury Fly-by.” *Astronomy* (March 2009): 28.

Talcott, R. “Mercury Reveals its Hidden Side.” *Astronomy* (May 2008): 26. Results and image from the MESSENGER mission flyby of January 2008.

Websites

The Moon

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.

Lunar Reconnaissance Orbiter Mission Page: **http://lro.gsfc.nasa.gov/ (http://lro.gsfc.nasa.gov/)** .

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.

Sky & Telescope magazine’s observing guides and articles about the Moon: **http://www.skyandtelescope.com/observing/celestial-objects-to-watch/moon/ (http://www.skyandtelescope.com/observing/celestial-objects-to-watch/moon/)** .

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.

10 EARTHLIKE PLANETS: VENUS AND MARS

Figure 10.1 Spirit Rover on Mars. This May 2004 image shows the tracks made by the Mars Exploration *Spirit* rover on the surface of the red planet. *Spirit* was active on Mars between 2004 and 2010, twenty times longer than its planners had expected. It "drove" over 7.73 kilometers in the process of examining the martian landscape. (credit: modification of work by NASA/JPL/Cornell)

Chapter Outline

Thinking Ahead

The Moon and Mercury are geologically dead. In contrast, the larger terrestrial planets—Earth, Venus, and Mars—are more active and interesting worlds. We have already discussed Earth, and we now turn to Venus and Mars. These are the nearest planets and the most accessible to spacecraft. Not surprisingly, the greatest effort in planetary exploration has been devoted to these fascinating worlds. In the chapter, we discuss some of the results of more than four decades of scientific exploration of Mars and Venus. Mars is exceptionally interesting, with evidence that points to habitable conditions in the past. Even today, we are discovering things about Mars that make it the most likely place where humans might set up a habitat in the future. However, our robot explorers have clearly shown that neither Venus nor Mars has conditions similar to Earth. How did it happen that these three neighboring terrestrial planets have diverged so dramatically in their evolution?

10.1 THE NEAREST PLANETS: AN OVERVIEW

Learning Objectives

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

- Explain why it’s difficult to learn about Venus from Earth-based observation alone
- Describe the history of our interest in Mars before the Space Age
- Compare the basic physical properties of Earth, Mars, and Venus, including their orbits

As you might expect from close neighbors, Mars and Venus are among the brightest objects in the night sky. The average distance of Mars from the Sun is 227 million kilometers (1.52 AU), or about half again as far from the Sun as Earth. Venus’ orbit is very nearly circular, at a distance of 108 million kilometers (0.72 AU) from the Sun. Like Mercury, Venus sometimes appears as an “evening star” and sometimes as a “morning star.” Venus approaches Earth more closely than does any other planet: at its nearest, it is only 40 million kilometers from us. The closest Mars ever gets to Earth is about 56 million kilometers.

Appearance

Venus appears very bright, and even a small telescope reveals that it goes through phases like the Moon. Galileo discovered that Venus displays a full range of phases, and he used this as an argument to show that Venus must circle the Sun and not Earth. The planet’s actual surface is not visible because it is shrouded by dense clouds that reflect about 70% of the sunlight that falls on them, frustrating efforts to study the underlying surface, even with cameras in orbit around the planet (**Figure 10.2**).

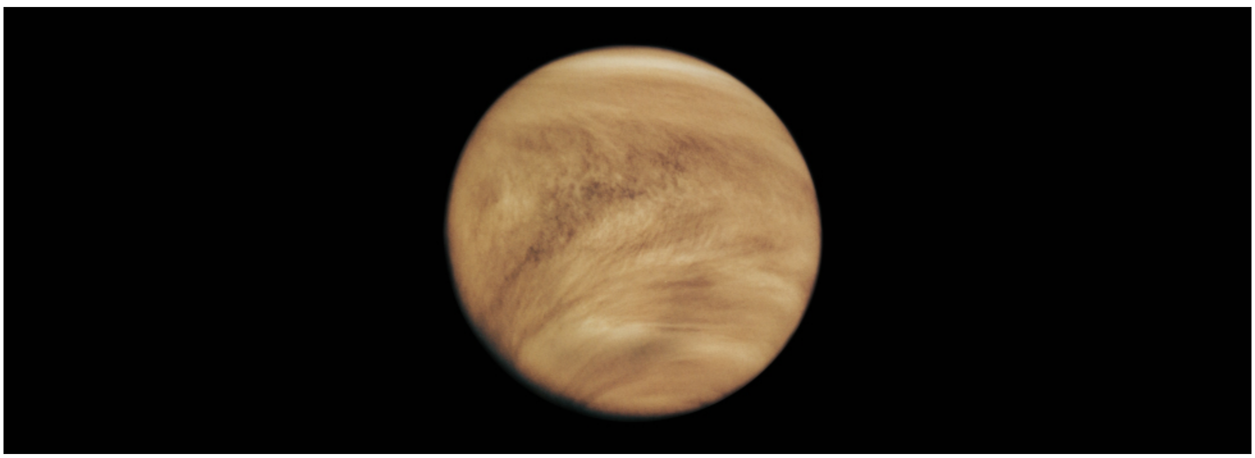


Figure 10.2 Venus as Photographed by the Pioneer Venus Orbiter. This ultraviolet image shows an upper-atmosphere cloud structure that would be invisible at visible wavelengths. Note that there is not even a glimpse of the planet’s surface. (credit: modification of work by NASA)

In contrast, Mars is more tantalizing as seen through a telescope (**Figure 10.3**). The planet is distinctly red, due (as we now know) to the presence of iron oxides in its soil. This color may account for its association with war (and blood) in the legends of early cultures. The best resolution obtainable from telescopes on the ground is about 100 kilometers, or about the same as what we can see on the Moon with the unaided eye. At this resolution, no hint of topographic structure can be detected: no mountains, no valleys, not even impact craters. On the other hand, bright polar ice caps can be seen easily, together with dusky surface markings that sometimes change in outline and intensity from season to season.

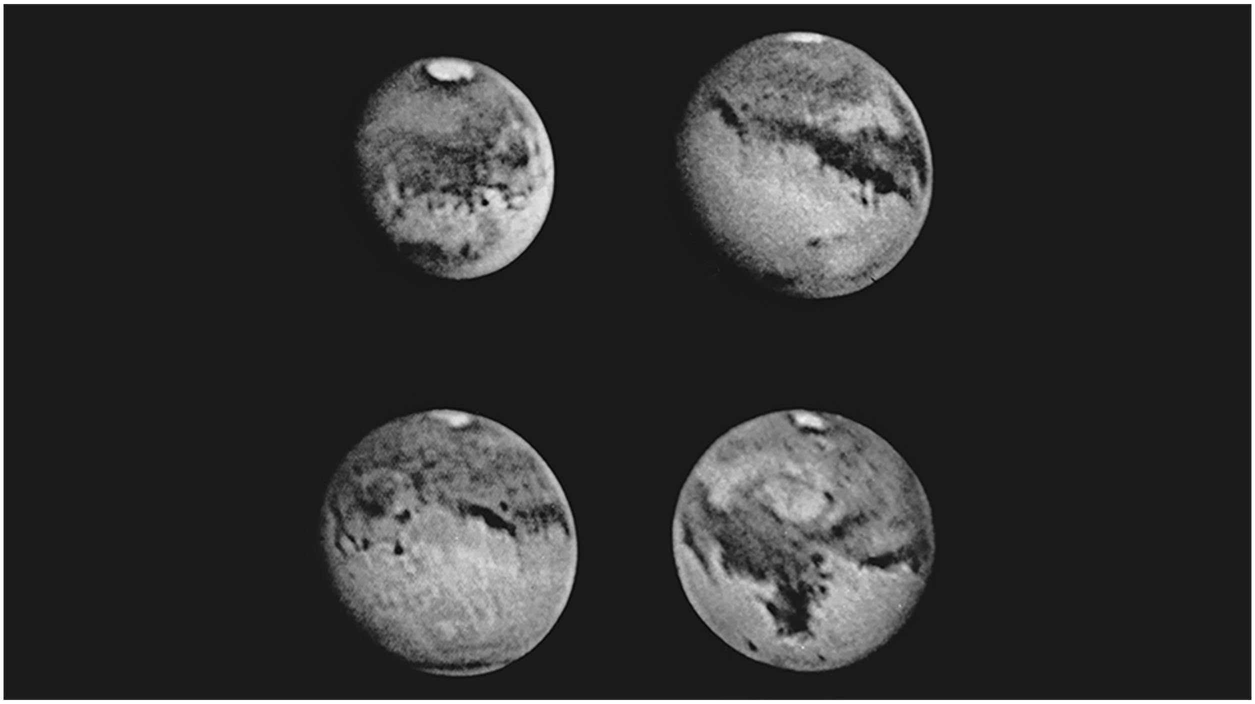


Figure 10.3 Mars as Seen from Earth's Surface. These are among the best Earth-based photos of Mars, taken in 1988 when the planet was exceptionally close to Earth. The polar caps and dark surface markings are evident, but not topographic features. (credit: modification of work by Steve Larson, Lunar and Planetary Laboratory, University of Arizona)

For a few decades around the turn of the twentieth century, some astronomers believed that they saw evidence of an intelligent civilization on Mars. The controversy began in 1877, when Italian astronomer Giovanni Schiaparelli (1835–1910) announced that he could see long, faint, straight lines on Mars that he called *canale*, or channels. In English-speaking countries, the term was mistakenly translated as "canals," implying an artificial origin.

Even before Schiaparelli's observations, astronomers had watched the bright polar caps change size with the seasons and had seen variations in the dark surface features. With a little imagination, it was not difficult to picture the canals as long fields of crops bordering irrigation ditches that brought water from the melting polar ice to the parched deserts of the red planet. (They assumed the polar caps were composed of water ice, which isn't exactly true, as we will see shortly.)

Until has death in 1916, the most effective proponent of intelligent life on Mars was Percival Lowell, a self-made American astronomer and member of the wealthy Lowell family of Boston (see the feature box on **Percival Lowell: Dreaming of an Inhabited Mars**). A skilled author and speaker, Lowell made what seemed to the public to be a convincing case for intelligent Martians, who had constructed the huge canals to preserve their civilization in the face of a deteriorating climate (**Figure 10.4**).

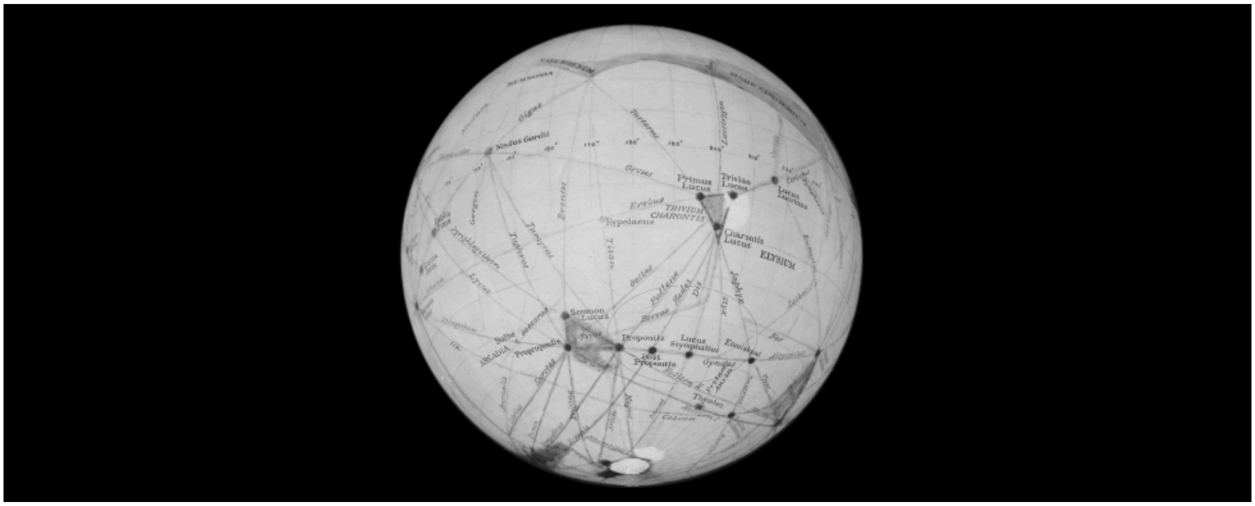


Figure 10.4 Lowell's Mars Globe. One of the remarkable globes of Mars prepared by Percival Lowell, showing a network of dozens of canals, oases, and triangular water reservoirs that he claimed were visible on the red planet.

The argument for a race of intelligent Martians, however, hinged on the reality of the canals, a matter that remained in serious dispute among astronomers. The canal markings were always difficult to study, glimpsed only occasionally because atmospheric conditions caused the tiny image of Mars to shimmer in the telescope. Lowell saw canals everywhere (even a few on Venus), but many other observers could not see them at all and remained unconvinced of their existence. When telescopes larger than Lowell's failed to confirm the presence of canals, the skeptics felt vindicated. Now it is generally accepted that the straight lines were an optical illusion, the result of the human mind's tendency to see order in random features that are glimpsed dimly at the limits of the eye's resolution. When we see small, dim dots of surface markings, our minds tend to connect those dots into straight lines.

VOYAGERS IN ASTRONOMY

Percival Lowell: Dreaming of an Inhabited Mars

Percival Lowell was born into the well-to-do Massachusetts family about whom John Bossidy made the famous toast:

> And this is good old Boston,
> The home of the bean and the cod,
> Where the Lowells talk to the Cabots
> And the Cabots talk only to God.

Percival's brother Lawrence became president of Harvard University, and his sister, Amy, became a distinguished poet. Percival was already interested in astronomy as a boy: he made observations of Mars at age 13. His undergraduate thesis at Harvard dealt with the origin of the solar system, but he did not pursue this interest immediately. Instead, he entered the family business and traveled extensively in Asia. In 1892, however, he decided to dedicate himself to carrying on Schiaparelli's work and solving the mysteries of the martian canals.

In 1894, with the help of astronomers at Harvard but using his own funds, Lowell built an observatory on a high plateau in Flagstaff, Arizona, where he hoped the seeing would be clear enough to show him Mars in unprecedented detail. He and his assistants quickly accumulated a tremendous number of drawings and maps, purporting to show a vast network of martian canals (see **Figure 10.4**). He elaborated his ideas about the inhabitants of the red planet in several books, including *Mars* (1895) and *Mars and Its Canals* (1906), and in hundreds of articles and speeches.

As Lowell put it,

> A mind of no mean order would seem to have presided over the system we see—a mind certainly of considerably more comprehensiveness than that which presides over the various departments of our own public works. Party politics, at all events, have had no part in them; for the system is planet-wide. . . . Certainly what we see hints at the existence of beings who are in advance of, not behind us, in the journey of life.

Lowell’s views captured the public imagination and inspired many novels and stories, the most famous of which was H. G. Wells’ *War of the Worlds* (1897). In this famous “invasion” novel, the thirsty inhabitants of a dying planet Mars (based entirely on Lowell’s ideas) come to conquer Earth with advanced technology.

Although the Lowell Observatory first became famous for its work on the martian canals, both Lowell and the observatory eventually turned to other projects as well. He became interested in the search for a ninth (and then undiscovered) planet in the solar system. In 1930, Pluto was found at the Lowell Observatory, and it is not a coincidence that the name selected for the new planet starts with Lowell’s initials. It was also at the Lowell Observatory that the first measurements were made of the great speed at which galaxies are moving away from us, observations that would ultimately lead to our modern view of an expanding universe.

Lowell (**Figure 10.5**) continued to live at his observatory, marrying at age 53 and publishing extensively. He relished the debate his claims about Mars caused far more than the astronomers on the other side, who often complained that Lowell’s work was making planetary astronomy a less respectable field. At the same time, the public fascination with the planets fueled by Lowell’s work (and its interpreters) may, several generations later, have helped fan support for the space program and the many missions whose results grace the pages of our text.

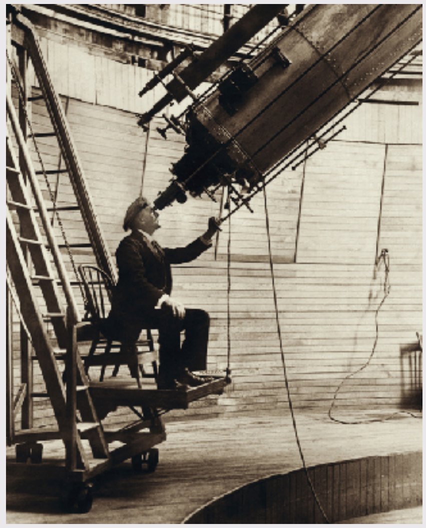


Figure 10.5 Percival Lowell (1855–1916). This 1914 photograph shows Percival Lowell observing Venus with his 24-inch telescope at Flagstaff, Arizona.

LINK TO LEARNING

In October 1938, the Mercury Theater of the Air on radio dramatized *The War of the Worlds* as a series of radio news reports. This **broadcast (https://openstax.org/l/30WarofWorlds)** scared many people into thinking that Lowell's Martians were really invading New Jersey, and caused something of a panic. You can listen to the original radio broadcast if you scroll down to "War of the Worlds."

Rotation of the Planets

Astronomers have determined the rotation period of Mars with great accuracy by watching the motion of permanent surface markings; its sidereal day is 24 hours 37 minutes 23 seconds, just a little longer than the rotation period of Earth. This high precision is not obtained by watching Mars for a single rotation, but by noting how many turns it makes over a long period of time. Good observations of Mars date back more than 200 years, a period during which tens of thousands of martian days have passed. As a result, the rotation period can be calculated to within a few hundredths of a second.

The rotational axis of Mars has a tilt of about 25°, similar to the tilt of Earth's axis. Thus, Mars experiences seasons very much like those on Earth. Because of the longer martian year (almost two Earth years), however, each season there lasts about six of our months.

The situation with Venus is different. Since no surface detail can be seen through Venus' clouds, its rotation period can be found only by bouncing radar signals off the planet (as explained for Mercury in the **Cratered Worlds** chapter). The first radar observations of Venus' rotation were made in the early 1960s. Later, topographical surface features were identified on the planet that showed up in the reflected radar signals. The rotation period of Venus, precisely determined from the motion of such "radar features" across its disk, is 243 days. Even more surprising than how *long* Venus takes to rotate is the fact that it spins in a backward or retrograde direction (east to west).

Stop for a moment and think about how odd this slow rotation makes the calendar on Venus. The planet takes 225 Earth days to orbit the Sun and 243 Earth days to spin on its axis. So the day on Venus (as defined by its spinning once) is longer than the year! As a result, the time the Sun takes to return to the same place in Venus' sky—another way we might define the meaning of a day—turns out to be 117 Earth days. (If you say "See you tomorrow" on Venus, you'll have a long time to wait.) Although we do not know the reason for Venus' slow backward rotation, we can guess that it may have suffered one or more extremely powerful collisions during the formation process of the solar system.

Basic Properties of Venus and Mars

Before discussing each planet individually, let us compare some of their basic properties with each other and with Earth (**Table 10.1**). Venus is in many ways Earth's twin, with a mass 0.82 times the mass of Earth and an almost identical density. The average amount of geological activity has been also relatively high, almost as high as on Earth. On the other hand, with a surface pressure nearly 100 times greater than ours, Venus' atmosphere is not at all like that of Earth. The surface of Venus is also remarkably hot, with a temperature of 730 K (over 850 °F), hotter than the self-cleaning cycle of your oven. One of the major challenges presented by Venus is to understand why the atmosphere and surface environment of this twin have diverged so sharply from those of our own planet.

Properties of Earth, Venus, and Mars

Property	Earth	Venus	Mars
Semimajor axis (AU)	1.00	0.72	1.52
Period (year)	1.00	0.61	1.88
Mass (Earth = 1)	1.00	0.82	0.11
Diameter (km)	12,756	12,102	6,790
Density (g/cm^3)	5.5	5.3	3.9
Surface gravity (Earth = 1)	1.00	0.91	0.38
Escape velocity (km/s)	11.2	10.4	5.0
Rotation period (hours or days)	23.9 h	243 d	24.6 h
Surface area (Earth = 1)	1.00	0.90	0.28
Atmospheric pressure (bar)	1.00	90	0.007

Table 10.1

Mars, by contrast, is rather small, with a mass only 0.11 times the mass of Earth. It is larger than either the Moon or Mercury, however, and, unlike them, it retains a thin atmosphere. Mars is also large enough to have supported considerable geological activity in the distant past. But the most fascinating thing about Mars is that long ago it probably had a thick atmosphere and seas of liquid water—the conditions we associate with development of life. There is even a chance that some form of life persists today in protected environments below the martian surface.

10.2 THE GEOLOGY OF VENUS

Learning Objectives

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

- Describe the general features of the surface of Venus
- Explain what the study of craters on Venus tells us about the age of its surface
- Compare tectonic activity and volcanoes on Venus with those of Earth
- Explain why the surface of Venus is inhospitable to human life

Since Venus has about the same size and composition as Earth, we might expect its geology to be similar. This is partly true, but Venus does not exhibit the same kind of *plate tectonics* as Earth, and we will see that its lack of erosion results in a very different surface appearance.

Spacecraft Exploration of Venus

Nearly 50 spacecraft have been launched to Venus, but only about half were successful. Although the 1962 US Mariner 2 flyby was the first, the Soviet Union launched most of the subsequent missions to Venus. In 1970, Venera 7 became the first probe to land and broadcast data from the surface of Venus. It operated for 23 minutes before succumbing to the high surface temperature. Additional Venera probes and landers followed, photographing the surface and analyzing the atmosphere and soil.

To understand the geology of Venus, however, we needed to make a global study of its surface, a task made very difficult by the perpetual cloud layers surrounding the planet. The problem resembles the challenge facing air traffic controllers at an airport, when the weather is so cloudy or smoggy that they can’t locate the incoming planes visually. The solution is similar in both cases: use a radar instrument to probe through the obscuring layer.

The first global radar map was made by the US Pioneer Venus orbiter in the late 1970s, followed by better maps from the twin Soviet Venera 15 and 16 radar orbiters in the early 1980s. However, most of our information on the geology of Venus is derived from the US *Magellan* spacecraft, which mapped Venus with a powerful *imaging radar*. *Magellan* produced images with a resolution of 100 meters, much better than that of previous missions, yielding our first detailed look at the surface of our sister planet (**Figure 10.6**). (The *Magellan* spacecraft returned more data to Earth than all previous planetary missions combined; each 100 minutes of data transmission from the spacecraft provided enough information, if translated into characters, to fill two 30-volume encyclopedias.)

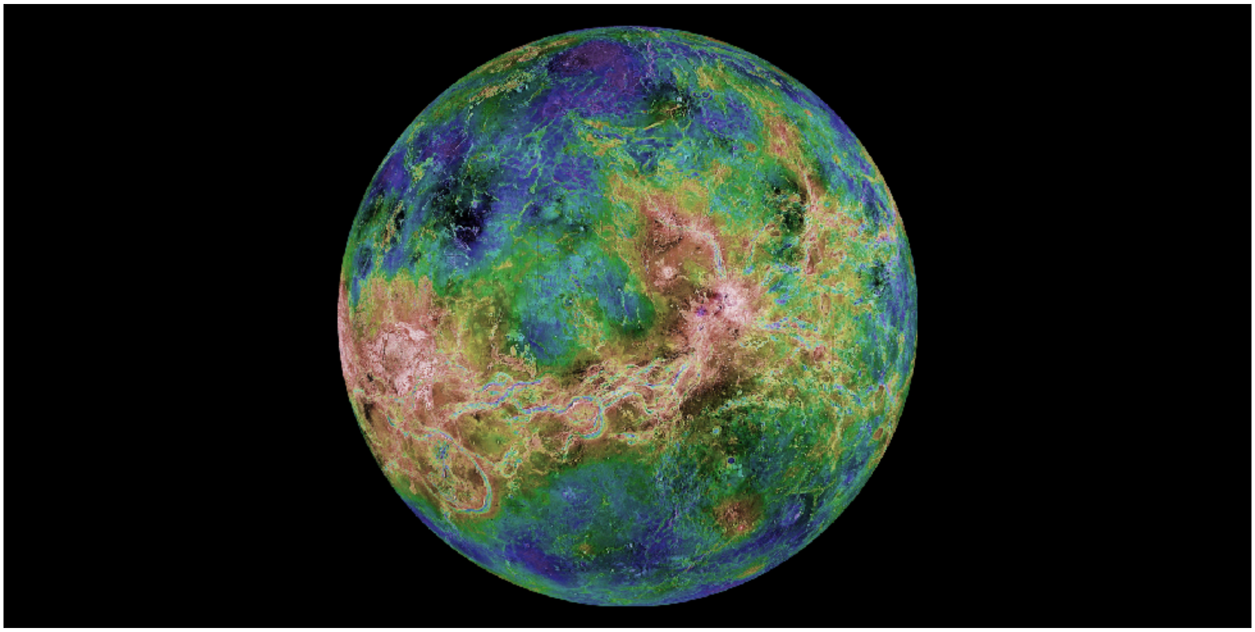


Figure 10.6 Radar Map of Venus. This composite image has a resolution of about 3 kilometers. Colors have been added to indicate elevation, with blue meaning low and brown and white high. The large continent Aphrodite stretches around the equator, where the bright (therefore rough) surface has been deformed by tectonic forces in the crust of Venus. (credit: modification of work by NASA/JPL/USGS)

Consider for a moment how good *Magellan*'s resolution of 100 meters really is. It means the radar images from Venus can show anything on the surface larger than a football field. Suddenly, a whole host of topographic features on Venus became accessible to our view. As you look at the radar images throughout this chapter, bear in mind that these are constructed from radar reflections, not from visible-light photographs. For example, bright features on these radar images are an indication of rough terrain, whereas darker regions are smoother.

Probing Through the Clouds of Venus

The radar maps of Venus reveal a planet that looks much the way Earth might look if our planet's surface were not constantly being changed by erosion and deposition of sediment. Because there is no water or ice on Venus and the surface wind speeds are low, almost nothing obscures or erases the complex geological features produced by the movements of Venus' crust, by volcanic eruptions, and by impact craters. Having finally penetrated below the clouds of Venus, we find its surface to be naked, revealing the history of hundreds of millions of years of geological activity.

About 75% of the surface of Venus consists of lowland lava plains. Superficially, these plains resemble the basaltic ocean basins of Earth, but they were not produced in quite the same way. There is no evidence of subduction zones on Venus, indicating that, unlike Earth, this planet never experienced plate tectonics. Although *convection* (the rising of hot materials) in its mantle generated great stresses in the crust of Venus, they did not start large continental plates moving. The formation of the lava plains of Venus more nearly resembles that of the lunar maria. Both were the result of widespread lava eruptions without the crustal spreading associated with plate tectonics.

Rising above the lowland lava plains are two full-scale continents of mountainous terrain. The largest continent on Venus, called Aphrodite, is about the size of Africa (you can see it stand out in **Figure 10.6**). Aphrodite stretches along the equator for about one-third of the way around the planet. Next in size is the northern highland region Ishtar, which is about the size of Australia. Ishtar contains the highest region on the planet, the Maxwell Mountains, which rise 11 kilometers above the surrounding lowlands. (The Maxwell Mountains are the only feature on Venus named after a man. They commemorate James Clerk Maxwell, whose theory of electromagnetism led to the invention of radar. All other features are named for women, either from history or mythology.)

Craters and the Age of the Venus Surface

One of the first questions astronomers addressed with the high-resolution *Magellan* images was the age of the surface of Venus. Remember that the age of a planetary surface is rarely the age of the world it is on. A young age merely implies an active geology in that location. Such ages can be derived from counting impact craters. **Figure 10.7** is an example of what these craters look like on the Venus radar images. The more densely cratered the surface, the greater its age. The largest crater on Venus (called Mead) is 275 kilometers in diameter, slightly larger than the largest known terrestrial crater (Chicxulub), but much smaller than the lunar impact basins.

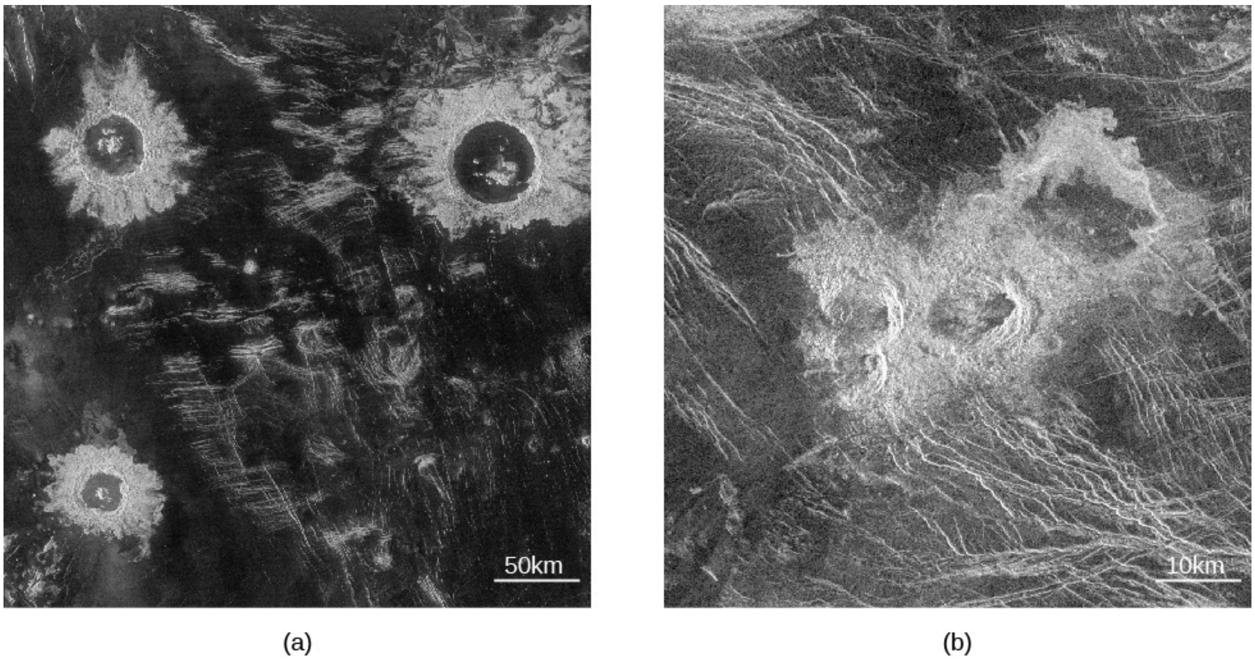


Figure 10.7 Impact Craters on Venus. (a) These large impact craters are in the Lavinia region of Venus. Because they are rough, the crater rims and ejecta appear brighter in these radar images than do the smoother surrounding lava plains. The largest of these craters has a diameter of 50 kilometers. (b) This small, complex crater is named after writer Gertrude Stein. The triple impact was caused by the breaking apart of the incoming asteroid during its passage through the thick atmosphere of Venus. The projectile had an initial diameter of between 1 and 2 kilometers. (credit a: modification of work by NASA/JPL; credit b: modification of work by NASA/JPL)

You might think that the thick atmosphere of Venus would protect the surface from impacts, burning up the projectiles long before they could reach the surface. But this is the case for only smaller projectiles. Crater statistics show very few craters less than 10 kilometers in diameter, indicating that projectiles smaller than about 1 kilometer (the size that typically produces a 10-kilometer crater) were stopped by the atmosphere. Those craters with diameters from 10 to 30 kilometers are frequently distorted or multiple, apparently because the incoming projectile broke apart in the atmosphere before it could strike the ground as shown in the Stein crater in **Figure 10.7**. If we limit ourselves to impacts that produce craters with diameters of 30 kilometers or larger, however, then crater counts are as useful on Venus for measuring surface age as they are on airless bodies such as the Moon.

The large craters in the venusian plains indicate an average surface age that is only between 300 and 600 million years. These results indicate that Venus is indeed a planet with persistent geological activity, intermediate between that of Earth's ocean basins (which are younger and more active) and that of its continents (which are older and less active).

Almost all of the large craters on Venus look fresh, with little degradation or filling in by either lava or windblown dust. This is one way we know that the rates of erosion or sediment deposition are very low. We have the impression that relatively little has happened since the venusian plains were last resurfaced by large-scale volcanic activity. Apparently Venus experienced some sort of planet-wide volcanic convulsion between 300 and 600 million years ago, a mysterious event that is unlike anything in terrestrial history.

Volcanoes on Venus

Like Earth, Venus is a planet that has experienced widespread volcanism. In the lowland plains, volcanic eruptions are the principal way the surface is renewed, with large flows of highly fluid lava destroying old craters and generating a fresh surface. In addition, numerous younger volcanic mountains and other structures are associated with surface hot spots—places where convection in the planet's mantle transports the interior heat to the surface.

The largest individual volcano on Venus, called Sif Mons, is about 500 kilometers across and 3 kilometers high—broader but lower than the Hawaiian volcano Mauna Loa. At its top is a volcanic crater, or *caldera*, about 40 kilometers across, and its slopes show individual lava flows up to 500 kilometers long. Thousands of smaller volcanoes dot the surface, down to the limit of visibility of the *Magellan* images, which correspond to cones or domes about the size of a shopping mall parking lot. Most of these seem similar to terrestrial volcanoes. Other volcanoes have unusual shapes, such as the "pancake domes" illustrated in **Figure 10.8**.

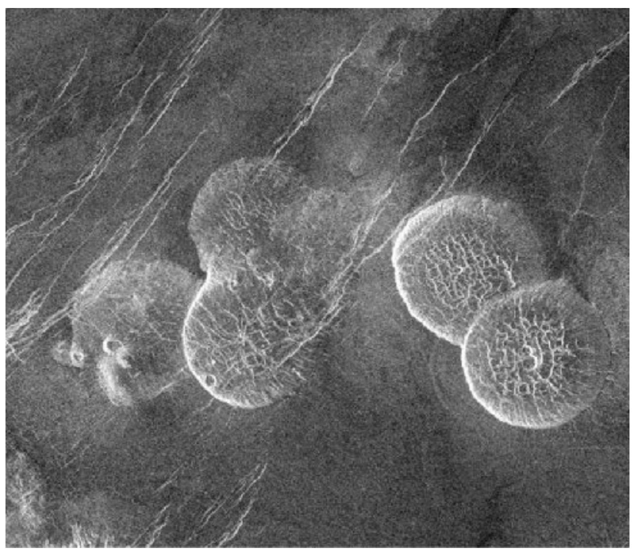


Figure 10.8 Pancake-Shaped Volcanoes on Venus. These remarkable circular domes, each about 25 kilometers across and about 2 kilometers tall, are the result of eruptions of highly viscous (sludgy) lava that spreads out evenly in all directions. (credit: modification of work by NASA/JPL)

All of the volcanism is the result of eruption of lava onto the surface of the planet. But the hot lava rising from the interior of a planet does not always make it to the surface. On both Earth and Venus, this upwelling lava can collect to produce bulges in the crust. Many of the granite mountain ranges on Earth, such as the Sierra Nevada in California, involve such subsurface volcanism. These bulges are common on Venus, where they produce large circular or oval features called *coronae* (singular: corona) (**Figure 10.9**).

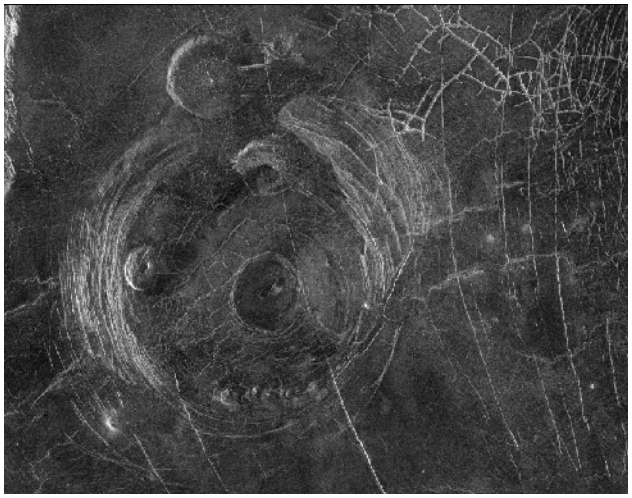


Figure 10.9 The "Miss Piggy" Corona. Fotla Corona is located in the plains to the south of Aphrodite Terra. Curved fracture patterns show where the material beneath has put stress on the surface. A number of pancake and dome volcanoes are also visible. Fotla was a Celtic fertility goddess. Some students see a resemblance between this corona and Miss Piggy of the Muppets (her left ear, at the top of the picture, is the pancake volcano in the upper center of the image). (credit: NASA/JPL)

Tectonic Activity

Convection currents of molten material in the mantle of Venus push and stretch the crust. Such forces are called **tectonic**, and the geological features that result from these forces are called *tectonic features*. On Venus' lowland plains, tectonic forces have broken the lava surface to create remarkable patterns of ridges and cracks (**Figure 10.10**). In a few places, the crust has even torn apart to generate rift valleys. The circular features associated with coronae are tectonic ridges and cracks, and most of the mountains of Venus also owe their existence to tectonic forces.

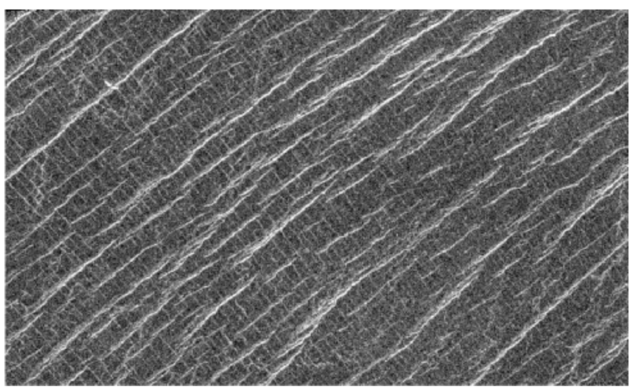


Figure 10.10 Ridges and Cracks. This region of the Lakshmi Plains on Venus has been fractured by tectonic forces to produce a cross-hatched grid of cracks and ridges. Be sure to notice the fainter linear features that run perpendicular to the brighter ones. As this is a radar image, the brightness of the ridges indicates their relative height. This image shows a region about 80 kilometers wide and 37 kilometers high. Lakshmi is a Hindu goddess of prosperity. (credit: modification of work by Magellan Team, JPL, NASA)

The Ishtar continent, which has the highest elevations on Venus, is the most dramatic product of these tectonic forces. Ishtar and its tall Maxwell Mountains resemble the Tibetan Plateau and Himalayan Mountains on Earth. Both are the product of compression of the crust, and both are maintained by the continuing forces of mantle convection.

On Venus' Surface

The successful Venera landers of the 1970s found themselves on an extraordinarily inhospitable planet, with a surface pressure of 90 bars and a temperature hot enough to melt lead and zinc. Despite these unpleasant conditions, the spacecraft were able to photograph their surroundings and collect surface samples for chemical analysis before their instruments gave out. The diffuse sunlight striking the surface was tinted red by the clouds, and the illumination level was equivalent to a heavy overcast on Earth.

The probes found that the rock in the landing areas is igneous, primarily basalts. Examples of the Venera photographs are shown in **Figure 10.11**. Each picture shows a flat, desolate landscape with a variety of rocks, some of which may be ejecta from impacts. Other areas show flat, layered lava flows. There have been no further landings on Venus since the 1970s.

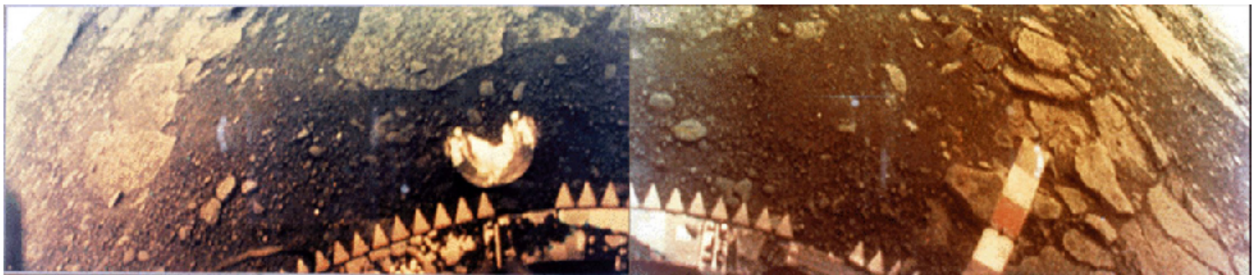


Figure 10.11 Surface of Venus. These views of the surface of Venus are from the Venera 13 spacecraft. Everything is orange because the thick atmosphere of Venus absorbs the bluer colors of light. The horizon is visible in the upper corner of each image. (credit: NASA)

10.3 THE MASSIVE ATMOSPHERE OF VENUS

Learning Objectives

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

- Describe the general composition and structure of the atmosphere on Venus
- Explain how the greenhouse effect has led to high temperatures on Venus

The thick atmosphere of Venus produces the high surface temperature and shrouds the surface in a perpetual red twilight. Sunlight does not penetrate directly through the heavy clouds, but the surface is fairly well lit by diffuse light (about the same as the light on Earth under a heavy overcast). The weather at the bottom of this deep atmosphere remains perpetually hot and dry, with calm winds. Because of the heavy blanket of clouds and atmosphere, one spot on the surface of Venus is similar to any other as far as weather is concerned.

Composition and Structure of the Atmosphere

The most abundant gas on Venus is carbon dioxide (CO_2), which accounts for 96% of the atmosphere. The second most common gas is nitrogen. The predominance of carbon dioxide over nitrogen is not surprising when you recall that Earth's atmosphere would also be mostly carbon dioxide if this gas were not locked up in marine sediments (see the discussion of Earth's atmosphere in **Earth as a Planet**).

Table 10.2 compares the compositions of the atmospheres of Venus, Mars, and Earth. Expressed in this way, as percentages, the proportions of the major gases are very similar for Venus and Mars, but in total quantity, their atmospheres are dramatically different. With its surface pressure of 90 bars, the venusian atmosphere is more than 10,000 times more massive than its martian counterpart. Overall, the atmosphere of Venus is very dry; the absence of water is one of the important ways that Venus differs from Earth.

Atmospheric Composition of Earth, Venus, and Mars

Gas	Earth	Venus	Mars
Carbon dioxide (CO_2)	0.03%	96%	95.3%
Nitrogen (N_2)	78.1%	3.5%	2.7%
Argon (Ar)	0.93%	0.006%	1.6%
Oxygen (O_2)	21.0%	0.003%	0.15%
Neon (Ne)	0.002%	0.001%	0.0003%

Table 10.2

The atmosphere of Venus has a huge troposphere (region of convection) that extends up to at least 50 kilometers above the surface (Figure 10.12). Within the troposphere, the gas is heated from below and circulates slowly, rising near the equator and descending over the poles. Being at the base of the atmosphere of Venus is something like being a kilometer or more below the ocean surface on Earth. There, the mass of water evens out temperature variations and results in a uniform environment—the same effect the thick atmosphere has on Venus.

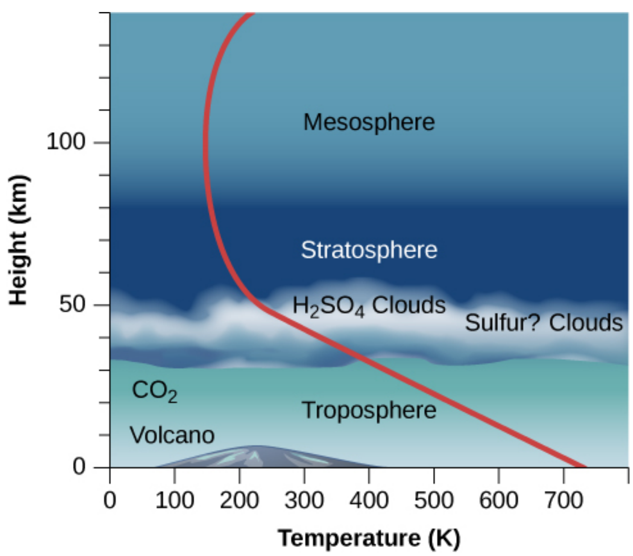


Figure 10.12 Venus' Atmosphere. The layers of the massive atmosphere of Venus shown here are based on data from the Pioneer and Venera entry probes. Height is measured along the left axis, the bottom scale shows temperature, and the red line allows you to read off the temperature at each height. Notice how steeply the temperature rises below the clouds, thanks to the planet's huge greenhouse effect.

In the upper troposphere, between 30 and 60 kilometers above the surface, a thick cloud layer is composed primarily of sulfuric acid droplets. Sulfuric acid (H_2SO_4) is formed from the chemical combination of sulfur dioxide (SO_2) and water (H_2O). In the atmosphere of Earth, sulfur dioxide is one of the primary gases emitted by volcanoes, but it is quickly diluted and washed out by rainfall. In the dry atmosphere of Venus, this unpleasant substance is apparently stable. Below 30 kilometers, the Venus atmosphere is clear of clouds.

Surface Temperature on Venus

The high surface temperature of Venus was discovered by radio astronomers in the late 1950s and confirmed by the Mariner and Venera probes. How can our neighbor planet be so hot? Although Venus is somewhat closer to the Sun than is Earth, its surface is hundreds of degrees hotter than you would expect from the extra sunlight it receives. Scientists wondered what could be heating the surface of Venus to a temperature above 700 K. The answer turned out to be the *greenhouse effect*.

The greenhouse effect works on Venus just as it does on Earth, but since Venus has so much more CO_2—almost a million times more—the effect is much stronger. The thick CO_2 acts as a blanket, making it very difficult for the infrared (heat) radiation from the ground to get back into space. As a result, the surface heats up. The energy balance is only restored when the planet is radiating as much energy as it receives from the Sun, but this can happen only when the temperature of the lower atmosphere is very high. One way of thinking of greenhouse heating is that it must raise the surface temperature of Venus until this energy balance is achieved.

Has Venus always had such a massive atmosphere and high surface temperature, or might it have evolved to such conditions from a climate that was once more nearly earthlike? The answer to this question is of particular interest to us as we look at the increasing levels of CO_2 in Earth's atmosphere. As the greenhouse effect becomes stronger on Earth, are we in any danger of transforming our own planet into a hellish place like Venus?

Let us try to reconstruct the possible evolution of Venus from an earthlike beginning to its present state. Venus may once have had a climate similar to that of Earth, with moderate temperatures, water oceans, and much of its CO_2 dissolved in the ocean or chemically combined with the surface rocks. Then we allow for modest additional heating—by gradual increase in the energy output of the Sun, for example. When we calculate how Venus' atmosphere would respond to such effects, it turns out that even a small amount of extra heat can lead to increased evaporation of water from the oceans and the release of gas from surface rocks.

This in turn means a further increase in the atmospheric CO_2 and H_2O, gases that would amplify the greenhouse effect in Venus' atmosphere. That would lead to still more heat near Venus' surface and the release of further CO_2 and H_2O. Unless some other processes intervene, the temperature thus continues to rise. Such a situation is called the **runaway greenhouse effect**.

We want to emphasize that the runaway greenhouse effect is not just a large greenhouse effect; it is an evolutionary *process*. The atmosphere evolves from having a small greenhouse effect, such as on Earth, to a situation where greenhouse warming is a major factor, as we see today on Venus. Once the large greenhouse conditions develop, the planet establishes a new, much hotter equilibrium near its surface.

Reversing the situation is difficult because of the role water plays. On Earth, most of the CO_2 is either chemically bound in the rocks of our crust or dissolved by the water in our oceans. As Venus got hotter and hotter, its oceans evaporated, eliminating that safety valve. But the water vapor in the planet's atmosphere will not last forever in the presence of ultraviolet light from the Sun. The light element hydrogen can escape from the atmosphere, leaving the oxygen behind to combine chemically with surface rock. The loss of water is therefore an irreversible process: once the water is gone, it cannot be restored. There is evidence that this is just what happened to the water once present on Venus.

We don't know if the same runaway greenhouse effect could one day happen on Earth. Although we are uncertain about the point at which a stable greenhouse effect breaks down and turns into a runaway greenhouse effect, Venus stands as clear testament to the fact that a planet cannot continue heating indefinitely without a major change in its oceans and atmosphere. It is a conclusion that we and our descendants will surely want to pay close attention to.

10.4 THE GEOLOGY OF MARS

Learning Objectives

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

- Discuss the main missions that have explored Mars
- Explain what we have learned from examination of meteorites from Mars
- Describe the various features found on the surface of Mars
- Compare the volcanoes and canyons on Mars with those of Earth
- Describe the general conditions on the surface of Mars

Mars is more interesting to most people than Venus because it is more hospitable. Even from the distance of Earth, we can see surface features on Mars and follow the seasonal changes in its polar caps (**Figure 10.13**). Although the surface today is dry and cold, evidence collected by spacecraft suggests that Mars once had blue skies and lakes of liquid water. Even today, it is the sort of place we can imagine astronauts visiting and perhaps even setting up permanent bases.

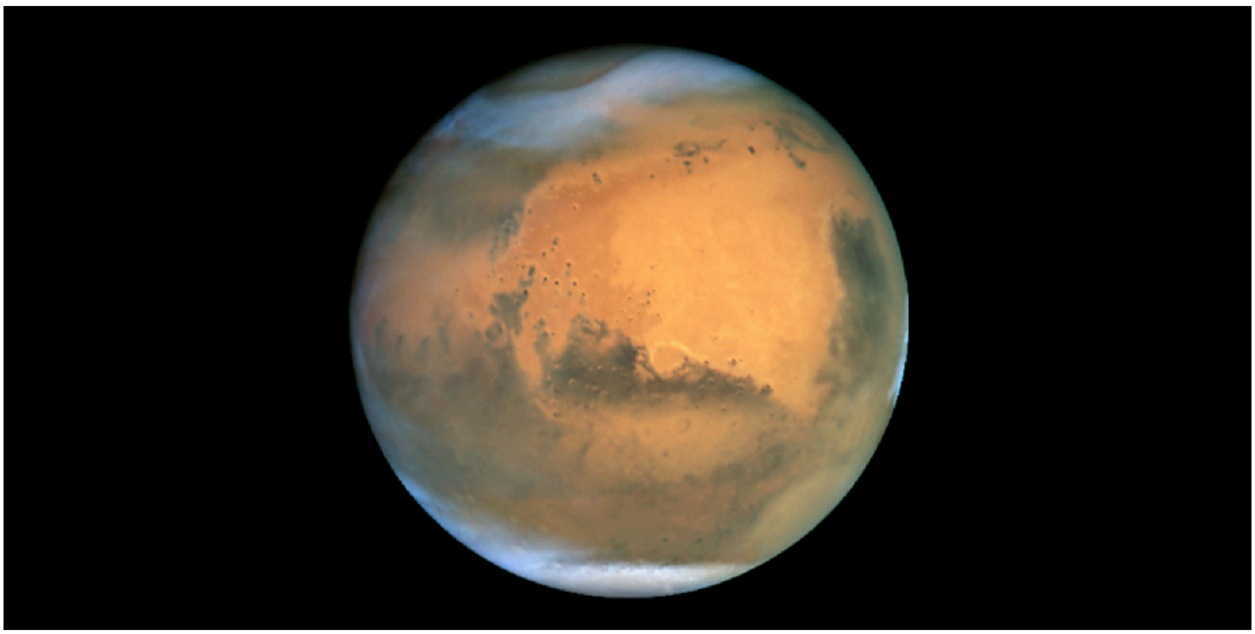


Figure 10.13 Mars Photographed by the Hubble Space Telescope. This is one of the best photos of Mars taken from our planet, obtained in June 2001 when Mars was only 68 million kilometers away. The resolution is about 20 kilometers—much better than can be obtained with ground-based telescopes but still insufficient to reveal the underlying geology of Mars. (credit: modification of work by NASA and the Hubble Heritage Team (STScI/AURA))

Spacecraft Exploration of Mars

Mars has been intensively investigated by spacecraft. More than 50 spacecraft have been launched toward Mars, but only about half were fully successful. The first visitor was the US Mariner 4, which flew past Mars in 1965 and transmitted 22 photos to Earth. These pictures showed an apparently bleak planet with abundant impact craters. In those days, craters were unexpected; some people who were romantically inclined still hoped to see canals or something like them. In any case, newspaper headlines sadly announced that Mars was a "dead planet."

In 1971, NASA's Mariner 9 became the first spacecraft to orbit another planet, mapping the entire surface of Mars at a resolution of about 1 kilometer and discovering a great variety of geological features, including volcanoes, huge canyons, intricate layers on the polar caps, and channels that appeared to have been cut by running water. Geologically, Mars didn't look so dead after all.

The twin Viking spacecraft of the 1970s were among the most ambitious and successful of all planetary missions. Two *orbiters* surveyed the planet and served to relay communications for two *landers* on the surface. After an exciting and sometimes frustrating search for a safe landing spot, the Viking 1 lander touched down on the surface of Chryse Planitia (the Plains of Gold) on July 20, 1976, exactly 7 years after Neil Armstrong's historic first step on the Moon. Two months later, Viking 2 landed with equal success in another plain farther north, called Utopia. The landers photographed the surface with high resolution and carried out complex experiments searching for evidence of life, while the orbiters provided a global perspective on Mars geology.

Mars languished unvisited for two decades after Viking. Two more spacecraft were launched toward Mars, by NASA and the Russian Space Agency, but both failed before reaching the planet.

The situation changed in the 1990s as NASA began a new exploration program using spacecraft that were smaller and less expensive than Viking. The first of the new missions, appropriately called Pathfinder, landed the first wheeled, solar-powered rover on the martian surface on July 4, 1997 (**Figure 10.14**). An orbiter called *Mars Global Surveyor* (MGS) arrived a few months later and began high-resolution photography of the entire surface over more than one martian year. The most dramatic discovery by this spacecraft, which is still operating, was evidence of gullies apparently cut by surface water, as we will discuss later. These missions were followed in 2003 by the NASA *Mars Odyssey* orbiter, and the ESA *Mars Express* orbiter, both carrying high-resolution cameras. A gamma-ray spectrometer on *Odyssey* discovered a large amount of subsurface hydrogen (probably in the form of frozen water). Subsequent orbiters included the NASA *Mars Reconnaissance Orbiter* to evaluate future landing sites, MAVEN to study the upper atmosphere, and India's *Mangalayaan*, also focused on study of Mars' thin layers of air. Several of these orbiters are also equipped to communicate with landers and rovers on the surface and serve as data relays to Earth.

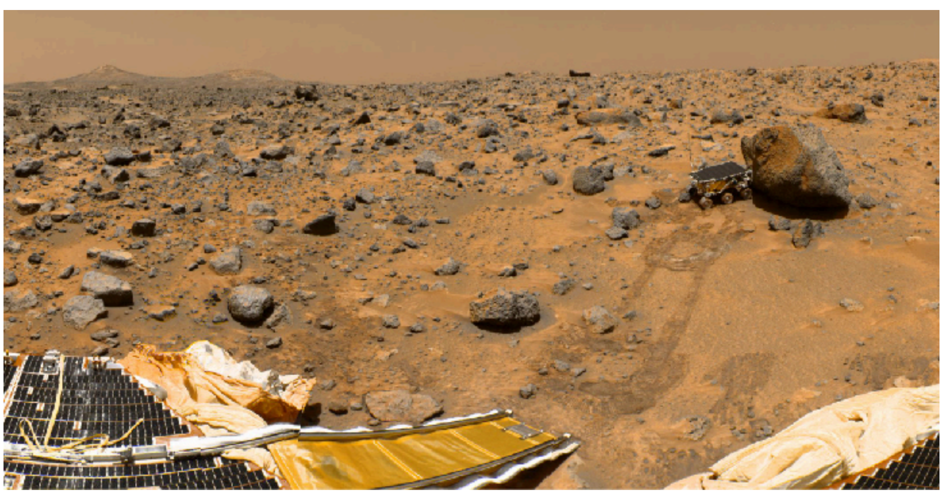


Figure 10.14 Surface View from Mars Pathfinder. The scene from the Pathfinder lander shows a windswept plain, sculpted long ago when water flowed out of the martian highlands and into the depression where the spacecraft landed. The *Sojourner* rover, the first wheeled vehicle on Mars, is about the size of a microwave oven. Its flat top contains solar cells that provided electricity to run the vehicle. You can see the ramp from the lander and the path the rover took to the larger rock that the mission team nicknamed "Yogi." (credit: NASA/JPL)

In 2003, NASA began a series of highly successful Mars landers. Twin Mars Exploration Rovers (MER), named *Spirit* and *Opportunity*, have been successful far beyond their planned lifetimes. The design goal for the rovers was 600 meters of travel; in fact, they have traveled jointly more than 50 kilometers. After scouting around its rim, *Opportunity* drove down the steep walls into an impact crater called Victoria, then succeeded with some difficulty in climbing back out to resume its route (Figure 10.15). Dust covering the rovers' solar cells caused a drop in power, but when a seasonal dust storm blew away the dust, the rovers resumed full operation. In order to survive winter, the rovers were positioned on slopes to maximize solar heating and power generation. In 2006, *Spirit* lost power on one of its wheels, and subsequently became stuck in the sand, where it continued operation as a fixed ground station. Meanwhile, in 2008, *Phoenix* (a spacecraft "reborn" of spare parts from a previous Mars mission that had failed) landed near the edge of the north polar cap, at latitude 68°, and directly measured water ice in the soil.

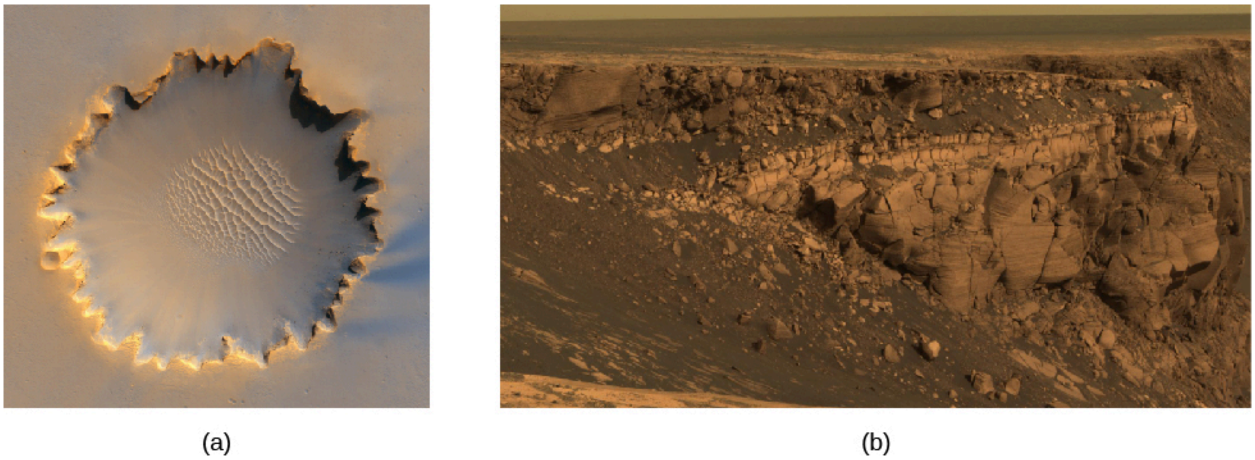


Figure 10.15 Victoria Crater. (a) This crater in Meridiani Planum is 800 meters wide, making it slightly smaller than Meteor crater on Earth. Note the dune field in the interior. (b) This image shows the view from the *Opportunity* rover as it scouted the rim of Victoria crater looking for a safe route down into the interior. (credit a: modification of work by NASA/JPL-Caltech/University of Arizona/Cornell/Phio State University; credit b: modification of work by NASA/JPL/Cornell)

In 2011, NASA launched its largest (and most expensive) Mars mission since Viking (see Figure 10.1). The 1-ton rover *Curiosity*, the size of a subcompact car, has plutonium-powered electrical generators, so that it is not dependent on sunlight for power. *Curiosity* made a pinpoint landing on the floor of Gale crater, a site selected for its complex geology and evidence that it had been submerged by water in the past. Previously, Mars landers had been sent to flat terrains with few hazards, as required by their lower targeting accuracy. The scientific goals of *Curiosity* include investigations of climate and geology, and assessment of the habitability of past and present Mars environments. It does not carry a specific life detection instrument, however. So far, scientists have not been able to devise a simple instrument that could distinguish living from nonliving materials on Mars.

LINK TO LEARNING

The *Curiosity* rover required a remarkably complex landing sequence and NASA made a **video (https://openstax.org/l/30Curiosityrove)** about it called "7 Minutes of Terror" that went viral on the Internet.

A dramatic **video summary (https://openstax.org/l/30MarsSurface)** of the first two years of *Curiosity*'s exploration of the martian surface can be viewed as well.

Martian Samples

Much of what we know of the Moon, including the circumstances of its origin, comes from studies of lunar samples, but spacecraft have not yet returned martian samples to Earth for laboratory analysis. It is with great interest, therefore, that scientists have discovered that samples of martian material are nevertheless already here on Earth, available for study. These are all members of a rare class of *meteorites* (**Figure 10.16**)—rocks that have fallen from space.

Figure 10.16 Martian Meteorite. This fragment of basalt, ejected from Mars in a crater-forming impact, eventually arrived on Earth's surface. (credit: NASA)

How would rocks have escaped from Mars? Many impacts have occurred on the red planet, as shown by its heavily cratered surface. Fragments blasted from large impacts can escape from Mars, whose surface gravity is only 38% of Earth's. A long time later (typically a few million years), a very small fraction of these fragments collide with Earth and survive their passage through our atmosphere, just like other meteorites. (We'll discuss meteorites in more detail in the chapter on **Cosmic Samples and the Origin of the Solar System**.) By the way, rocks from the Moon have also reached our planet as meteorites, although we were able to demonstrate their lunar origin only by comparison with samples returned by the Apollo missions

Most of the martian meteorites are volcanic basalts; most of them are also relatively young—about 1.3 billion years old. We know from details of their composition that they are not from Earth or the Moon. Besides, there was no volcanic activity on the Moon to form them as recently as 1.3 billon years ago. It would be very difficult for ejecta from impacts on Venus to escape through its thick atmosphere. By the process of elimination, the only reasonable origin seems to be Mars, where the Tharsis volcanoes were active at that time.

The martian origin of these meteorites was confirmed by the analysis of tiny gas bubbles trapped inside several of them. These bubbles match the atmospheric properties of Mars as first measured directly by Viking. It appears that some atmospheric gas was trapped in the rock by the shock of the impact that ejected it from Mars and started it on its way toward Earth.

One of the most exciting results from analysis of these martian samples has been the discovery of both water and organic (carbon-based) compounds in them, which suggests that Mars may once have had oceans and perhaps even life on its surface. As we have already hinted, there is other evidence for the presence of flowing water on Mars in the remote past, and even extending to the present.

In this and the following sections, we will summarize the picture of Mars as revealed by all these exploratory missions and by about 40 samples from Mars.

Global Properties of Mars

Mars has a diameter of 6790 kilometers, just over half the diameter of Earth, giving it a total surface area very nearly equal to the continental (land) area of our planet. Its overall density of 3.9 g/cm^3 suggests a composition consisting primarily of silicates but with a small metal core. The planet has no global magnetic field, although there are areas of strong surface magnetization that indicate that there was a global field billions of years ago. Apparently, the red planet has no liquid material in its core today that would conduct electricity.

Thanks to the *Mars Global Surveyor*, we have mapped the entire planet, as shown in **Figure 10.17**. A laser altimeter on board made millions of separate measurements of the surface topography to a precision of a few meters—good enough to show even the annual deposition and evaporation of the polar caps. Like Earth, the Moon, and Venus, the surface of Mars has continental or highland areas as well as widespread volcanic plains. The total range in elevation from the top of the highest mountain (Olympus Mons) to the bottom of the deepest basin (Hellas) is 31 kilometers.

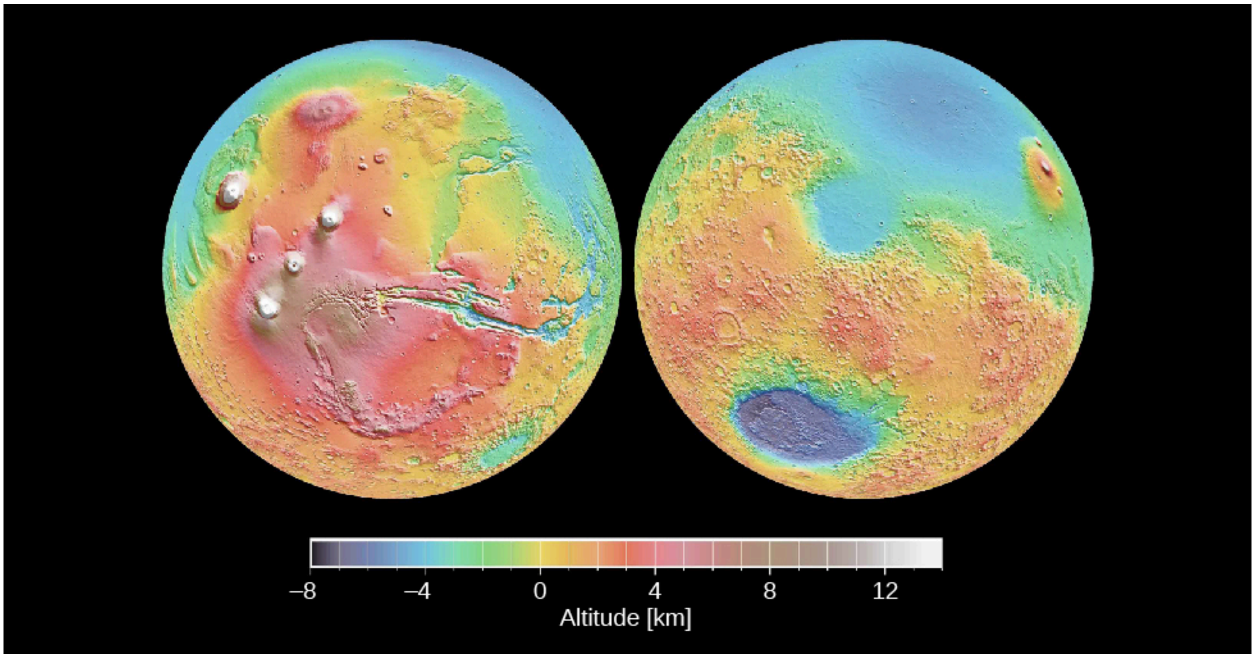


Figure 10.17 Mars Map from Laser Ranging. These globes are highly precise topographic maps, reconstructed from millions of individual elevation measurements made with the *Mars Global Surveyor*. Color is used to indicate elevation. The hemisphere on the left includes the Tharsis bulge and Olympus Mons, the highest mountain on Mars; the hemisphere on the right includes the Hellas basin, which has the lowest elevation on Mars. (credit: modification of work by NASA/JPL)

Approximately half the planet consists of heavily cratered highland terrain, found primarily in the southern hemisphere. The other half, which is mostly in the north, contains younger, lightly cratered volcanic plains at an average elevation about 5 kilometers lower than the highlands. Remember that we saw a similar pattern on Earth, the Moon, and Venus. A geological division into older highlands and younger lowland plains seems to be characteristic of all the terrestrial planets except Mercury.

Lying across the north-south division of Mars is an uplifted continent the size of North America. This is the 10-kilometer-high Tharsis bulge, a volcanic region crowned by four great volcanoes that rise still higher into the martian sky.

Volcanoes on Mars

The lowland plains of Mars look very much like the lunar maria, and they have about the same density of impact craters. Like the lunar maria, they probably formed between 3 and 4 billion years ago. Apparently, Mars experienced extensive volcanic activity at about the same time the Moon did, producing similar basaltic lavas.

The largest volcanic mountains of Mars are found in the Tharsis area (you can see them in **Figure 10.17**), although smaller volcanoes dot much of the surface. The most dramatic volcano on Mars is Olympus Mons (Mount Olympus), with a diameter larger than 500 kilometers and a summit that towers more than 20 kilometers above the surrounding plains—three times higher than the tallest mountain on Earth (**Figure 10.18**). The volume of this immense volcano is nearly 100 times greater than that of Mauna Loa in Hawaii. Placed on

Earth's surface, Olympus would more than cover the entire state of Missouri.

Figure 10.18 Olympus Mons. The largest volcano on Mars, and probably the largest in the solar system, is Olympus Mons, illustrated in this computer-generated rendering based on data from the *Mars Global Surveyor's* laser altimeter. Placed on Earth, the base of Olympus Mons would completely cover the state of Missouri; the caldera, the circular opening at the top, is 65 kilometers across, about the size of Los Angeles. (credit: NASA/Corbis)

Images taken from orbit allow scientists to search for impact craters on the slopes of these volcanoes in order to estimate their age. Many of the volcanoes show a fair number of such craters, suggesting that they ceased activity a billion years or more ago. However, Olympus Mons has very, very few impact craters. Its present surface cannot be more than about 100 million years old; it may even be much younger. Some of the fresh-looking lava flows might have been formed a hundred years ago, or a thousand, or a million, but geologically speaking, they are quite young. This leads geologists to the conclusion that Olympus Mons possibly remains intermittently active today—something future Mars land developers may want to keep in mind.

Martian Cracks and Canyons

The Tharsis bulge has many interesting geological features in addition to its huge volcanoes. In this part of the planet, the surface itself has bulged upward, forced by great pressures from below, resulting in extensive tectonic cracking of the crust. Among the most spectacular tectonic features on Mars are the canyons called the Valles Marineris (or Mariner Valleys, named after Mariner 9, which first revealed them to us), which are shown in **Figure 10.19**. They extend for about 5000 kilometers (nearly a quarter of the way around Mars) along the slopes of the Tharsis bulge. If it were on Earth, this canyon system would stretch all the way from Los Angeles to Washington, DC. The main canyon is about 7 kilometers deep and up to 100 kilometers wide, large enough for the Grand Canyon of the Colorado River to fit comfortably into one of its side canyons.

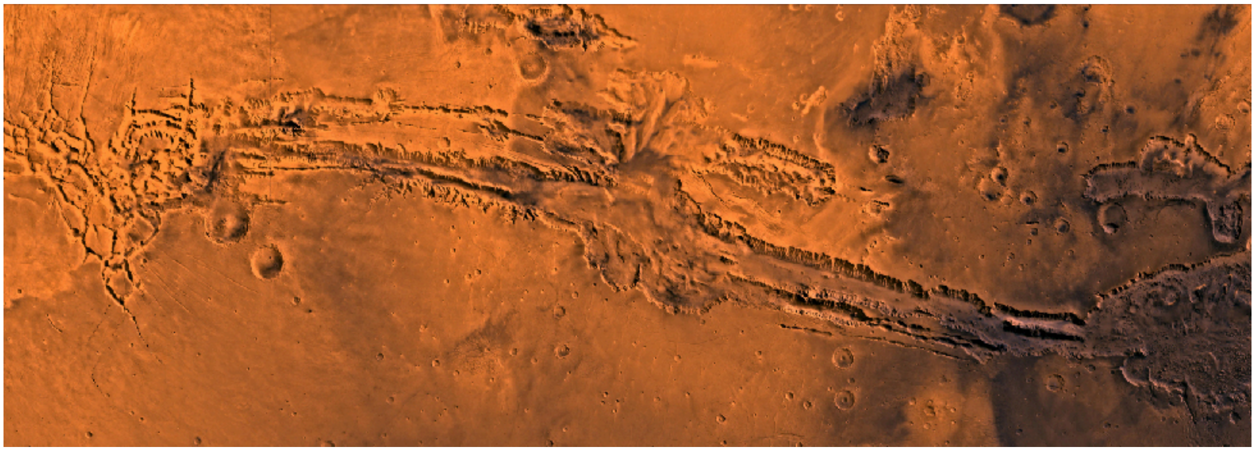


Figure 10.19 Heavily Eroded Canyonlands on Mars. This image shows the Valles Marineris canyon complex, which is 3000 kilometers wide and 8 kilometers deep. (credit: NASA/JPL/USGS)

LINK TO LEARNING

An excellent **4-minute video tour (https://openstax.org/l/30VallesMariner)** of Valles Marineris, narrated by planetary scientist Phil Christensen, is available for viewing.

The term “canyon” is somewhat misleading here because the Valles Marineris canyons have no outlets and were not cut by running water. They are basically tectonic cracks, produced by the same crustal tensions that caused the Tharsis uplift. However, water has played a later role in shaping the canyons, primarily by seeping from deep springs and undercutting the cliffs. This undercutting led to landslides that gradually widened the original cracks into the great valleys we see today (**Figure 10.20**). Today, the primary form of erosion in the canyons is probably wind.

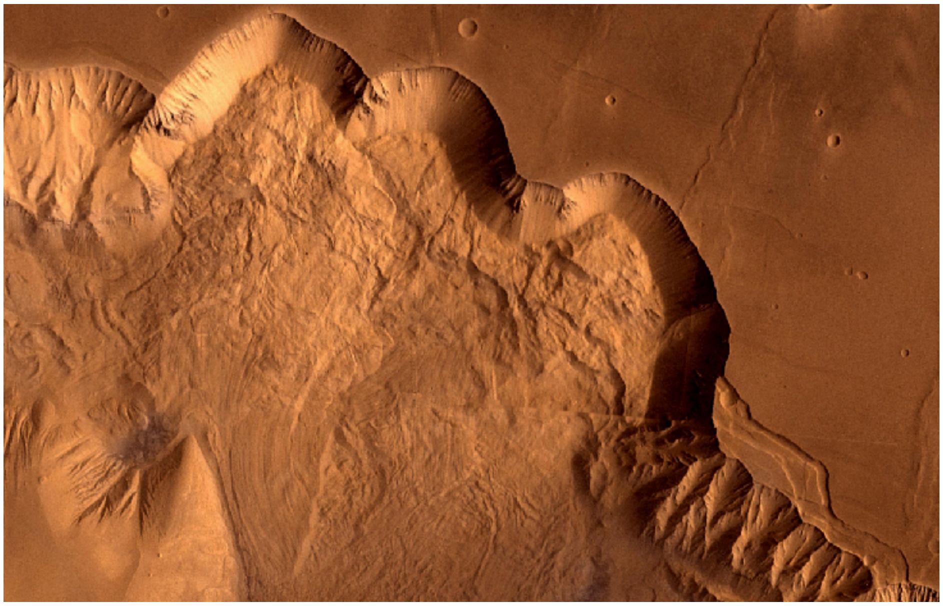


Figure 10.20 Martian Landslides. This Viking orbiter image shows Ophir Chasma, one of the connected valleys of the Valles Marineris canyon system. Look carefully and you can see enormous landslides whose debris is piled up underneath the cliff wall, which tower up to 10 kilometers above the canyon floor. (credit: modification of work by NASA/JPL/USGS)

While the Tharsis bulge and Valles Marineris are impressive, in general, we see fewer tectonic structures on Mars than on Venus. In part, this may reflect a lower general level of geological activity, as would be expected for a smaller planet. But it is also possible that evidence of widespread faulting has been buried by wind-deposited sediment over much of Mars. Like Earth, Mars may have hidden part of its geological history under a cloak of soil.

The View on the Martian Surface

The first spacecraft to land successfully on Mars were Vikings 1 and 2 and Mars Pathfinder. All sent back photos that showed a desolate but strangely beautiful landscape, including numerous angular rocks interspersed with dune like deposits of fine-grained, reddish soil (Figure 10.21).

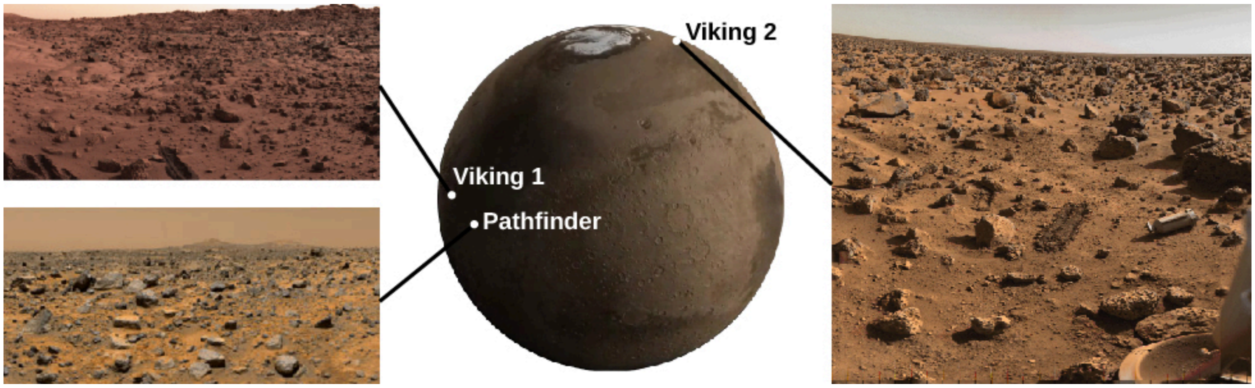


Figure 10.21 Three Martian Landing Sites. The Mars landers Viking 1 in Chryse, Pathfinder in Ares Valley, and Viking 2 in Utopia, all photographed their immediate surroundings. It is apparent from the similarity of these three photos that each spacecraft touched down on a flat, windswept plain littered with rocks ranging from tiny pebbles up to meter-size boulders. It is probable that most of Mars looks like this on the surface. (credit "Viking 1": modification of work by Van der Hoorn/NASA; credit "Pathfinder": modification of work by NASA; credit "Viking 2": modification of work by NASA; credit Mars: modification of work by NASA/Goddard Space Flight Center)

All three of these landers were targeted to relatively flat, lowland terrain. Instruments on the landers found that the soil consisted of clays and iron oxides, as had long been expected from the red color of the planet. All the rocks measured appeared to be of volcanic origin and roughly the same composition. Later landers were targeted to touch down in areas that apparently were flooded sometime in the past, where sedimentary rock layers, formed in the presence of water, are common. (Although we should note that nearly all the planet is blanketed in at least a thin layer of wind-blown dust).

The Viking landers included weather stations that operated for several years, providing a perspective on martian weather. The temperatures they measured varied greatly with the seasons, due to the absence of moderating oceans and clouds. Typically, the summer maximum at Viking 1 was 240 K (–33 °C), dropping to 190 K (–83 °C) at the same location just before dawn. The lowest air temperatures, measured farther north by Viking 2, were about 173 K (–100 °C). During the winter, Viking 2 also photographed water frost deposits on the ground (**Figure 10.22**). We make a point of saying "water frost" here because at some locations on Mars, it gets cold enough for carbon dioxide (dry ice) to freeze out of the atmosphere as well.

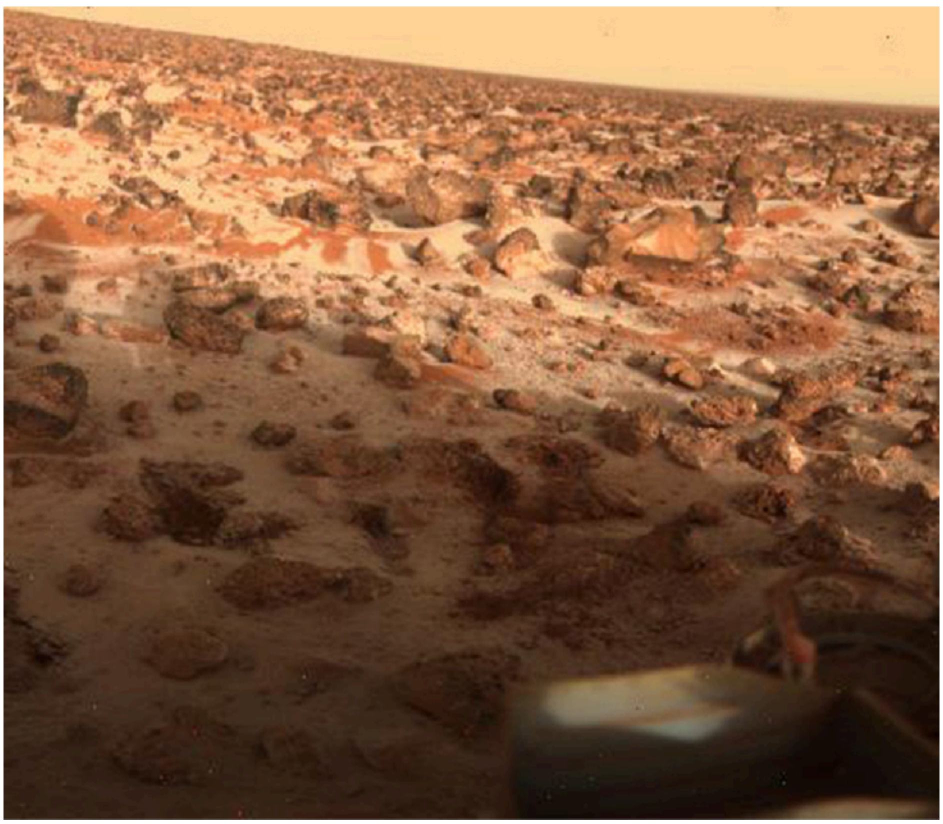


Figure 10.22 Water Frost in Utopia. This image of surface frost was photographed at the Viking 2 landing site during late winter. (credit: NASA/JPL)

Most of the winds measured on Mars are only a few kilometers per hour. However, Mars is capable of great windstorms that can shroud the entire planet with windblown dust. Such high winds can strip the surface of some of its loose, fine dust, leaving the rock exposed. The later rovers found that each sunny afternoon the atmosphere became turbulent as heat rose off the surface. This turbulence generated dust devils, which play an important role in lifting the fine dust into the atmosphere. As the dust devils strip off the top layer of light dust and expose darker material underneath, they can produce fantastic patterns on the ground (**Figure 10.23**).

Wind on Mars plays an important role in redistributing surface material. **Figure 10.23** shows a beautiful area of dark sand dunes on top of lighter material. Much of the material stripped out of the martian canyons has been dumped in extensive dune fields like this, mostly at high latitudes.

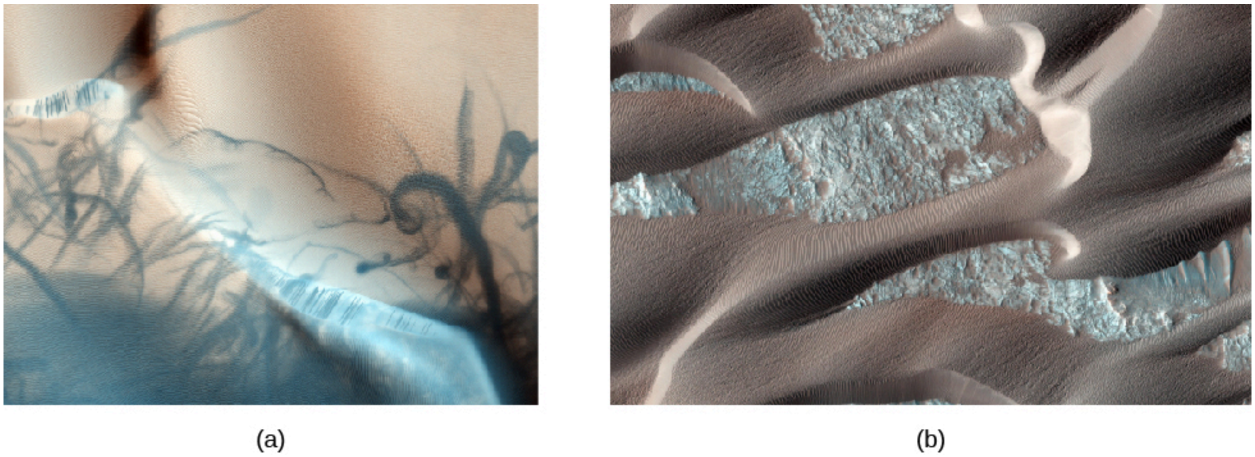


Figure 10.23 Dust Devil Tracks and Sand Dunes. (a) This high-resolution photo from the *Mars Global Surveyor* shows the dark tracks of several dust devils that have stripped away a thin coating of light-colored dust. This view is of an area about 3 kilometers across. Dust devils are one of the most important ways that dust gets redistributed by the martian winds. They may also help keep the solar panels of our rovers free of dust. (b) These windblown sand dunes on Mars overlay a lighter sandy surface. Each dune in this high-resolution view is about 1 kilometer across. (credit a: modification of work by NASA/JPL/University of Arizona; credit b: modification of work by NASA/JPL-Caltech/University of Arizona)

10.5 WATER AND LIFE ON MARS

Learning Objectives

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

- Describe the general composition of the atmosphere on Mars
- Explain what we know about the polar ice caps on Mars and how we know it
- Describe the evidence for the presence of water in the past history of Mars
- Summarize the evidence for and against the possibility of life on Mars

Of all the planets and moons in the solar system, Mars seems to be the most promising place to look for life, both fossil microbes and (we hope) some forms of life deeper underground that still survive today. But where (and how) should we look for life? We know that the one requirement shared by all life on Earth is liquid water. Therefore, the guiding principle in assessing habitability on Mars and elsewhere has been to "follow the water." That is the perspective we take in this section, to follow the water on the red planet and hope it will lead us to life.

Atmosphere and Clouds on Mars

The atmosphere of Mars today has an average surface pressure of only 0.007 bar, less than 1% that of Earth. (This is how thin the air is about 30 kilometers above Earth's surface.) Martian air is composed primarily of carbon dioxide (95%), with about 3% nitrogen and 2% argon. The proportions of different gases are similar to those in the atmosphere of Venus (see **Table 10.2**), but a lot less of each gas is found in the thin air on Mars.

While winds on Mars can reach high speeds, they exert much less force than wind of the same velocity would on Earth because the atmosphere is so thin. The wind is able, however, to loft very fine dust particles, which can sometimes develop planet-wide dust storms. It is this fine dust that coats almost all the surface, giving Mars its distinctive red color. In the absence of surface water, wind erosion plays a major role in sculpting the martian surface (**Figure 10.24**).

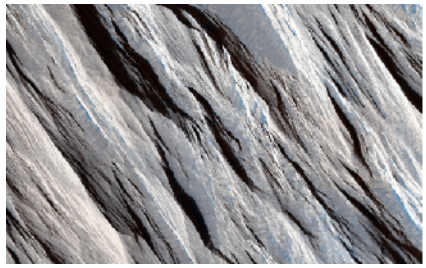


Figure 10.24 Wind Erosion on Mars. These long straight ridges, called yardangs, are aligned with the dominant wind direction. This is a high-resolution image from the *Mars Reconnaissance Orbiter* and is about 1 kilometer wide. (credit: NASA/JPL-Caltech/University of Arizona)

LINK TO LEARNING

The issue of how strong the winds on Mars can be plays a big role in the **2015 hit movie The Martian (https://openstax.org/l/30TheMartian)** in which the main character is stranded on Mars after being buried in the sand in a windstorm so great that his fellow astronauts have to leave the planet so their ship is not damaged. Astronomers have noted that the martian winds could not possibly be as forceful as depicted in the film. In most ways, however, the depiction of Mars in this movie is remarkably accurate.

Although the atmosphere contains small amounts of water vapor and occasional clouds of water ice, liquid water is not stable under present conditions on Mars. Part of the problem is the low temperatures on the planet. But even if the temperature on a sunny summer day rises above the freezing point, the low pressure means that liquid water still cannot exist on the surface, except at the lowest elevations. At a pressure of less than 0.006 bar, the boiling point is as low or lower than the freezing point, and water changes directly from solid to vapor without an intermediate liquid state (as does "dry ice," carbon dioxide, on Earth). However, salts dissolved in water lower its freezing point, as we know from the way salt is used to thaw roads after snow and ice forms during winter on Earth. Salty water is therefore sometimes able to exist in liquid form on the martian surface, under the right conditions.

Several types of clouds can form in the martian atmosphere. First there are dust clouds, discussed above. Second are water-ice clouds similar to those on Earth. These often form around mountains, just as happens on our planet. Finally, the CO_2 of the atmosphere can itself condense at high altitudes to form hazes of dry ice crystals. The CO_2 clouds have no counterpart on Earth, since on our planet temperatures never drop low enough (down to about 150 K or about –125 °C) for this gas to condense.

The Polar Caps

Through a telescope, the most prominent surface features on Mars are the bright polar caps, which change with the seasons, similar to the seasonal snow cover on Earth. We do not usually think of the winter snow in northern latitudes as a part of our polar caps, but seen from space, the thin winter snow merges with Earth's thick, permanent ice caps to create an impression much like that seen on Mars (**Figure 10.25**).

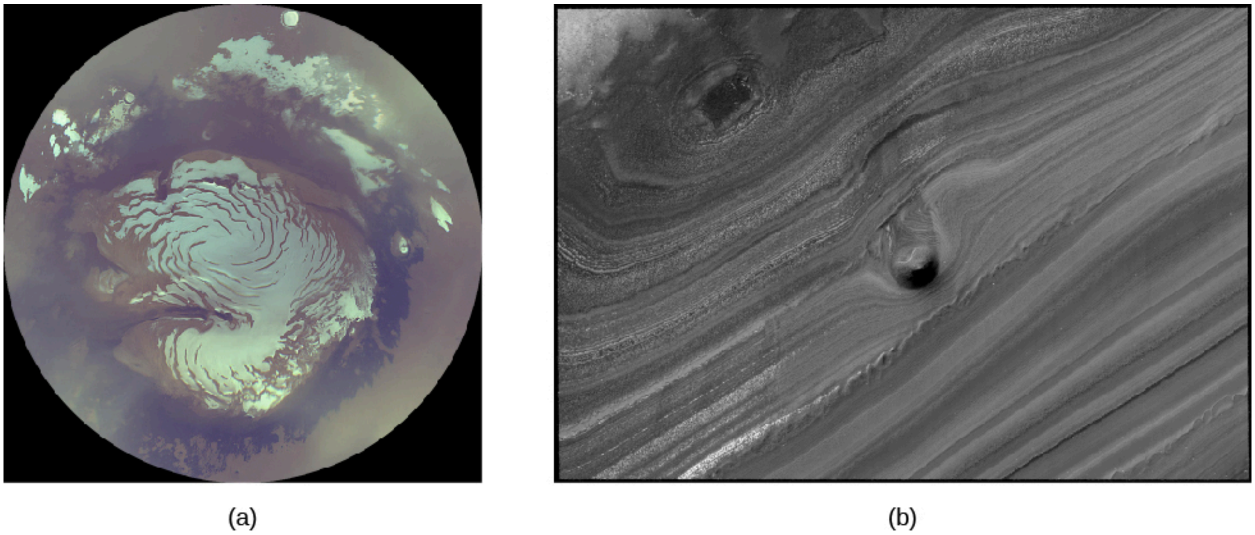


Figure 10.25 Martian North Polar Cap. (a) This is a composite image of the north pole in summer, obtained in October 2006 by the *Mars Reconnaissance Orbiter*. It shows the mostly water-ice residual cap sitting atop light, tan-colored, layered sediments. Note that although the border of this photo is circular, it shows only a small part of the planet. (b) Here we see a small section of the layered terrain near the martian north pole. There is a mound about 40 meters high that is sticking out of a trough in the center of the picture. (credit a: modification of work by NASA/JPL/MSSS; credit b: modification of work by NASA/JPL-Caltech/University of Arizona)

The *seasonal caps* on Mars are composed not of ordinary snow but of frozen CO_2 (dry ice). These deposits condense directly from the atmosphere when the surface temperature drops below about 150 K. The caps develop during the cold martian winters and extend down to about 50° latitude by the start of spring.

Quite distinct from these thin seasonal caps of CO_2 are the *permanent* or *residual caps* that are always present near the poles. The southern permanent cap has a diameter of 350 kilometers and is composed of frozen CO_2 deposits together with a great deal of water ice. Throughout the southern summer, it remains at the freezing point of CO_2, 150 K, and this cold reservoir is thick enough to survive the summer heat intact.

The northern permanent cap is different. It is much larger, never shrinking to a diameter less than 1000 kilometers, and is composed of water ice. Summer temperatures in the north are too high for the frozen CO_2 to be retained. Measurements from the *Mars Global Surveyor* have established the exact elevations in the north polar region of Mars, showing that it is a large basin about the size of our own Arctic Ocean basin. The ice cap itself is about 3 kilometers thick, with a total volume of about 10 million km^3 (similar to that of Earth's Mediterranean Sea). If Mars ever had extensive liquid water, this north polar basin would have contained a shallow sea. There is some indication of ancient shorelines visible, but better images will be required to verify this suggestion.

Images taken from orbit also show a distinctive type of terrain surrounding the permanent polar caps, as shown in **Figure 10.25**. At latitudes above 80° in both hemispheres, the surface consists of recent layered deposits that cover the older cratered ground below. Individual layers are typically ten to a few tens of meters thick, marked by alternating light and dark bands of sediment. Probably the material in the polar deposits includes dust carried by wind from the equatorial regions of Mars.

What do these terraced layers tell us about Mars? Some cyclic process is depositing dust and ice over periods of time. The time scales represented by the polar layers are tens of thousands of years. Apparently the martian climate experiences periodic changes at intervals similar to those between ice ages on Earth. Calculations indicate that the causes are probably also similar: the gravitational pull of the other planets produces variations in Mars' orbit and tilt as the great clockwork of the solar system goes through its paces.

The *Phoenix* spacecraft landed near the north polar cap in summer (**Figure 10.26**). Controllers knew that it would not be able to survive a polar winter, but directly measuring the characteristics of the polar region was deemed important enough to send a dedicated mission. The most exciting discovery came when the spacecraft tried to dig a shallow trench under the spacecraft. When the overlying dust was stripped off, they saw bright white material, apparently some kind of ice. From the way this ice sublimated over the next few days, it was clear that it was frozen water.

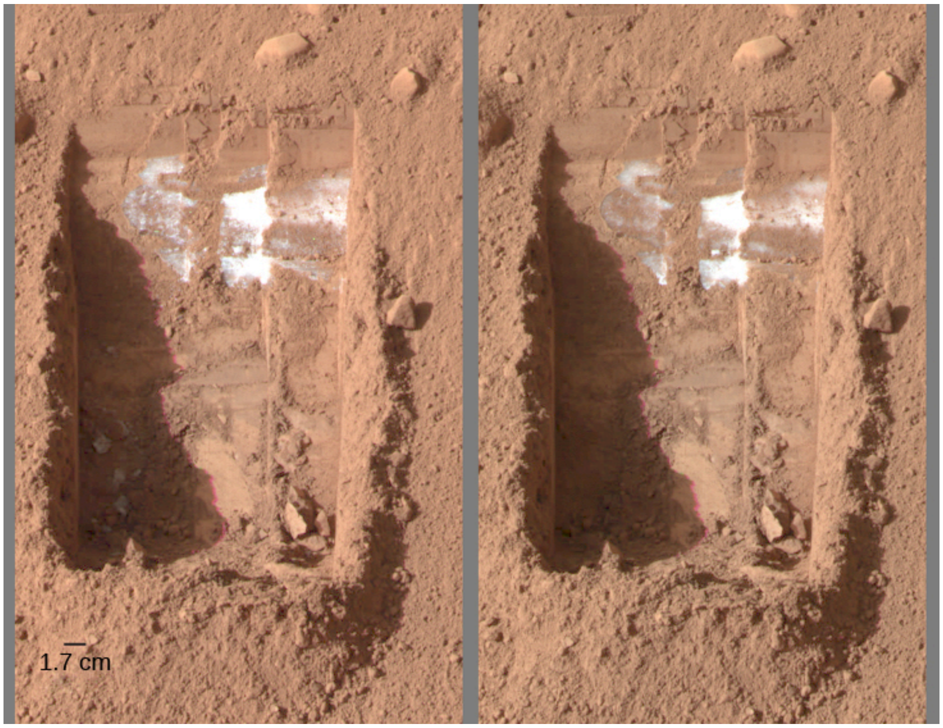


Figure 10.26 Evaporating Ice on Mars. We see a trench dug by the *Phoenix* lander in the north polar region four martian days apart in June 2008. If you look at the shadowed region in the bottom left of the trench, you can see three spots of ice in the left image which have sublimated away in the right image. (credit: modification of work by NASA/JPL-Caltech/University of Arizona/Texas A&M University)

EXAMPLE 10.1

Comparing the Amount of Water on Mars and Earth

It is interesting to estimate the amount of water (in the form of ice) on Mars and to compare this with the amount of water on Earth. In each case, we can find the total volume of a layer on a sphere by multiplying the area of the sphere ($4\pi R^2$) by the thickness of the layer. For Earth, the ocean water is equivalent to a layer 3 km thick spread over the entire planet, and the radius of Earth is 6.378×10^6 m (see **Appendix F**). For Mars, most of the water we are sure of is in the form of ice near the poles. We can calculate the amount of ice in one of the residual polar caps if it is (for example) 2 km thick and has a radius of 400 km (the area of a circle is πR^2).

Solution

The volume of Earth's water is therefore the area $4\pi R^2$

$$4\pi\left(6.378 \times 10^6\ \text{m}\right)^2 = 5.1 \times 10^{14}\ \text{m}^2$$

multiplied by the thickness of 3000 m:

$$5.1 \times 10^{14}\ \text{m}^2 \times 3000\ \text{m} = 1.5 \times 10^{18}\ \text{m}^3$$

This gives 1.5 × 10^{18} m^3 of water. Since water has a density of 1 ton per cubic meter (1000 kg/m^3), we can calculate the mass:

$$1.5 \times 10^{18}\ \text{m}^3 \times 1\ \text{ton/m}^3 = 1.5 \times 10^{18}\ \text{tons}$$

For Mars, the ice doesn't cover the whole planet, only the caps; the polar cap area is

$$\pi R^2 = \pi(4 \times 10^5\ \text{m})^2 = 5 \times 10^{11}\ \text{m}^2$$

(Note that we converted kilometers to meters.)

The volume = area × height, so we have:

$$(2 \times 10^3\ \text{m})(5 \times 10^{11}\ \text{m}^2) = 1 \times 10^{15}\ \text{m}^3 = 10^{15}\ \text{m}^3$$

Therefore, the mass is:

$$10^{15}\ \text{m}^3 \times 1\ \text{ton/m}^3 = 10^{15}\ \text{tons}$$

This is about 0.1% that of Earth's oceans.

Check Your Learning

A better comparison might be to compare the amount of ice in the Mars polar ice caps to the amount of ice in the Greenland ice sheet on Earth, which has been estimated as 2.85 × 10^{15} m^3. How does this compare with the ice on Mars?

Answer:

The Greenland ice sheet has about 2.85 times as much ice as in the polar ice caps on Mars. They are about the same to the nearest power of 10.

Channels and Gullies on Mars

Although no bodies of liquid water exist on Mars today, evidence has accumulated that rivers flowed on the red planet long ago. Two kinds of geological features appear to be remnants of ancient watercourses, while a third class—smaller gullies—suggests intermittent outbreaks of liquid water even today. We will examine each of these features in turn.

In the highland equatorial plains, there are multitudes of small, sinuous (twisting) channels—typically a few meters deep, some tens of meters wide, and perhaps 10 or 20 kilometers long (**Figure 10.27**). They are called runoff channels because they look like what geologists would expect from the surface runoff of ancient rain storms. These runoff channels seem to be telling us that the planet had a very different climate long ago. To estimate the age of these channels, we look at the cratering record. Crater counts show that this part of the planet is more cratered than the lunar maria but less cratered than the lunar highlands. Thus, the runoff channels are probably older than the lunar maria, presumably about 4 billion years old.

The second set of water-related features we see are *outflow channels* (**Figure 10.27**) are much larger than the runoff channels. The largest of these, which drain into the Chryse basin where Pathfinder landed, are 10 kilometers or more wide and hundreds of kilometers long. Many features of these outflow channels have convinced geologists that they were carved by huge volumes of running water, far too great to be produced by ordinary rainfall. Where could such floodwater have come from on Mars?

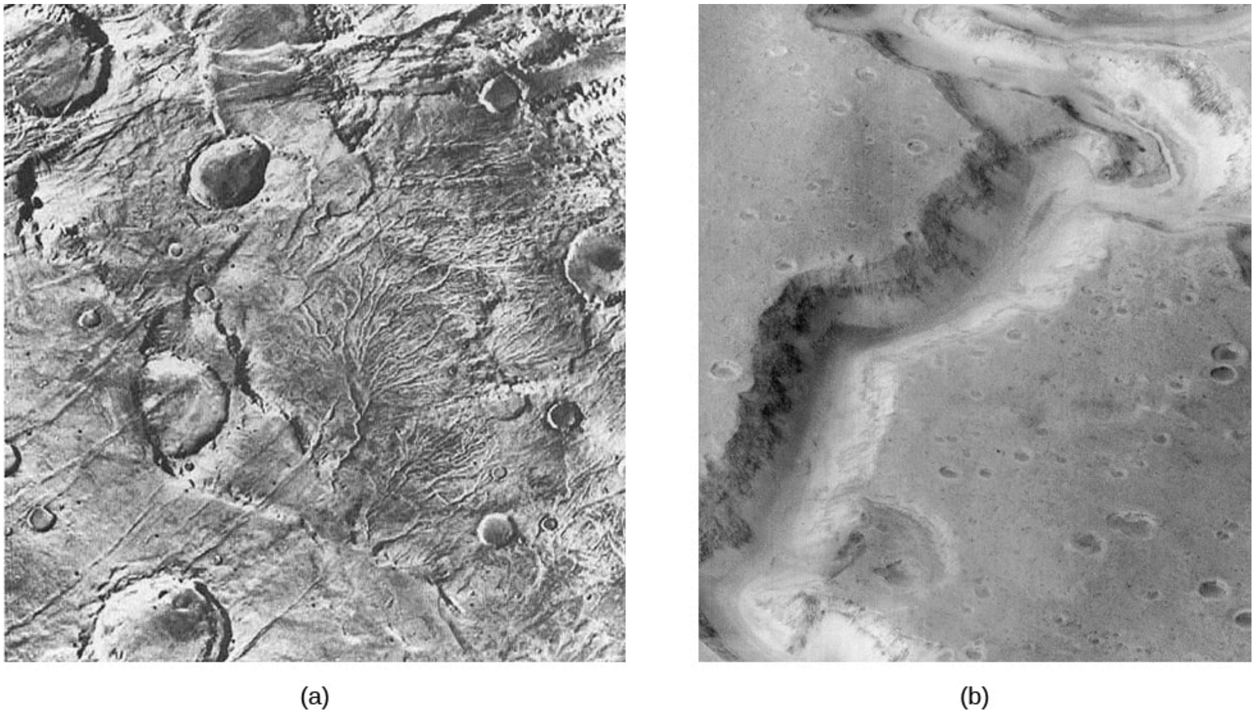


Figure 10.27 Runoff and Outflow Channels. (a) These runoff channels in the old martian highlands are interpreted as the valleys of ancient rivers fed by either rain or underground springs. The width of this image is about 200 kilometers. (b) This intriguing channel, called Nanedi Valles, resembles Earth riverbeds in some (but not all) ways. The tight curves and terraces seen in the channel certainly suggest the sustained flow of a fluid like water. The channel is about 2.5 kilometers across. (credit a: modification of work by Jim Secosky/NASA; credit b: modification of work by Jim Secosky/NASA)

As far we can tell, the regions where the outflow channels originate contained abundant water frozen in the soil as permafrost. Some local source of heating must have released this water, leading to a period of rapid and catastrophic flooding. Perhaps this heating was associated with the formation of the volcanic plains on Mars, which date back to roughly the same time as the outflow channels.

Note that neither the runoff channels nor the outflow channels are wide enough to be visible from Earth, nor do they follow straight lines. They could not have been the "canals" Percival Lowell imagined seeing on the red planet.

The third type of water feature, the smaller *gullies*, was discovered by the *Mars Global Surveyor* (**Figure 10.28**). The *Mars Global Surveyor's* camera images achieved a resolution of a few meters, good enough to see something as small as a truck or bus on the surface. On the steep walls of valleys and craters at high latitudes, there are many erosional features that look like gullies carved by flowing water. These gullies are very young: not only are there no superimposed impact craters, but in some instances, the gullies seem to cut across recent wind-deposited dunes. Perhaps there is liquid water underground that can occasionally break out to produce short-lived surface flows before the water can freeze or evaporate.

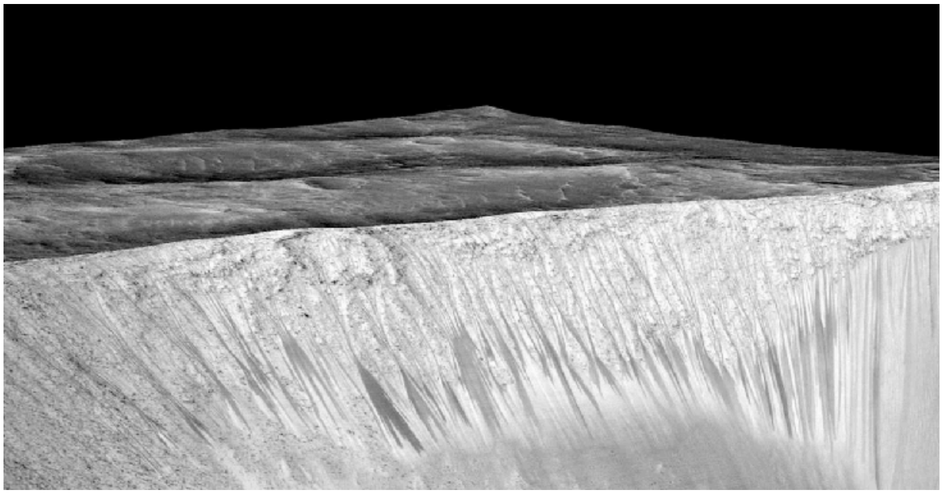


Figure 10.28 Gullies on the Wall of Garni Crater. This high-resolution image is from the *Mars Reconnaissance Orbiter*. The dark streaks, which are each several hundred meters long, change in a seasonal pattern that suggests they are caused by the temporary flow of surface water. (credit: NASA/JPL-Caltech/University of Arizona)

The gullies also have the remarkable property of changing regularly with the martian seasons. Many of the dark streaks (visible in **Figure 10.28**) elongate within a period of a few days, indicating that something is flowing downhill—either water or dark sediment. If it is water, it requires a continuing source, either from the atmosphere or from springs that tap underground water layers (aquifers.) Underground water would be the most exciting possibility, but this explanation seems inconsistent with the fact that many of the dark streaks start at high elevations on the walls of craters.

Additional evidence that the dark streaks (called by the scientists *recurring slope lineae*) are caused by water was found in 2015 when spectra were obtained of the dark streaks (**Figure 10.29**). These showed the presence of hydrated salts produced by the evaporation of salty water. If the water is salty, it could remain liquid long enough to flow downstream for distances of a hundred meters or more, before it either evaporates or soaks into the ground. However, this discovery still does not identify the ultimate source of the water.

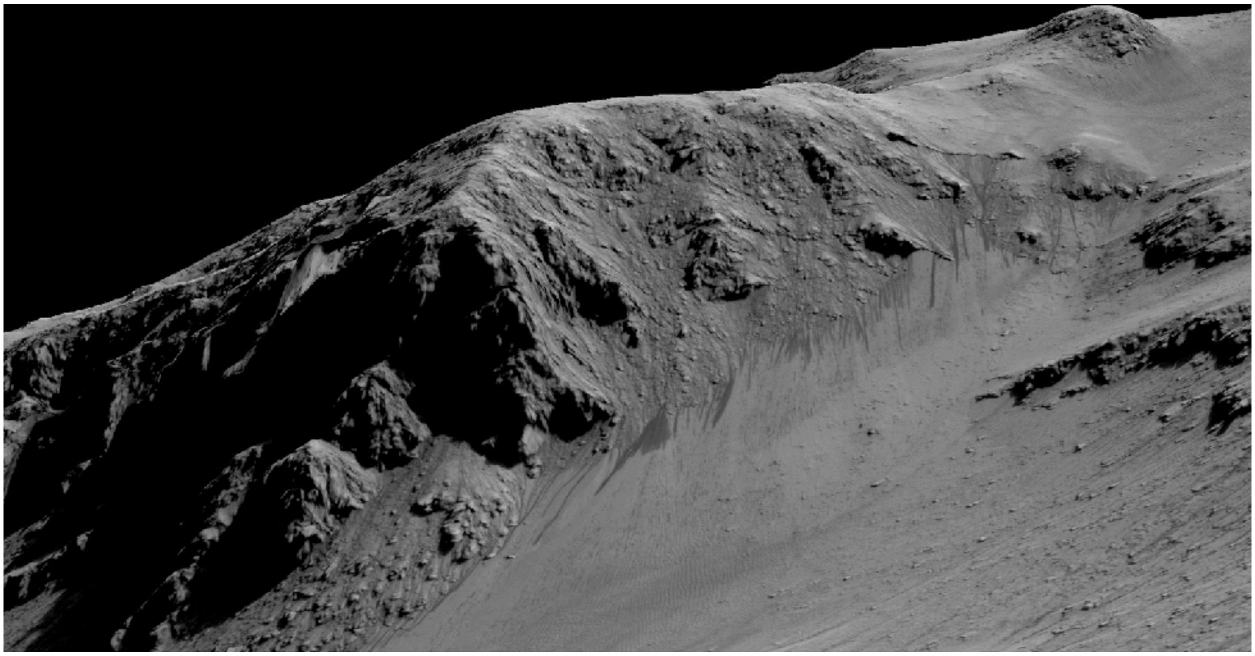


Figure 10.29 Evidence for Liquid Water on Mars. The dark streaks in Horowitz crater, which move downslope, have been called recurring slope lineae. The streaks in the center of the image go down the wall of the crater for about a distance of 100 meters. Spectra taken of this region indicate that these are locations where salty liquid water flows on or just below the surface of Mars. (The vertical dimension is exaggerated by a factor of 1.5 compared to horizontal dimensions.) (credit: NASA/JPL-Caltech/University of Arizona)

Ancient Lakes and Glaciers

The rovers (*Spirit*, *Opportunity*, and *Curiosity*) that have operated on the surface of Mars have been used to hunt for additional evidence of water. They could not reach the most interesting sites, such as the gullies, which are located on steep slopes. Instead, they explored sites that might be dried-out lake beds, dating back to a time when the climate on Mars was warmer and the atmosphere thicker—allowing water to be liquid on the surface.

Spirit was specifically targeted to explore what looked like an ancient lake-bed in Gusev crater, with an outflow channel emptying into it. However, when the spacecraft landed, it found that the former lakebed had been covered by thin lava flows, blocking the rover from access to the sedimentary rocks it had hoped to find. However, *Opportunity* had better luck. Peering at the walls of a small crater, it detected layered sedimentary rock. These rocks contained chemical evidence of evaporation, suggesting there had been a shallow salty lake in that location. In these sedimentary rocks were also small spheres that were rich in the mineral hematite, which forms only in watery environments. Apparently this very large basin had once been underwater.

LINK TO LEARNING

The small spherical rocks were nicknamed “blueberries” by the science team and the discovery of a whole “berry-bowl” of them was announced in this **interesting news release (https://openstax.org/l/30berrybowl)** from NASA.

The *Curiosity* rover landed inside Gale crater, where photos taken from orbit also suggested past water erosion. It discovered numerous sedimentary rocks, some in the form of mudstones from an ancient lakebed; it also found indications of rocks formed by the action of shallow water at the time the sediment formed (**Figure**

10.30).

Even today there is evidence of large quantities of ice just below the surface of Mars. In the mid-latitudes, high-resolution photos from orbit have revealed glaciers covered with dirt and dust. In some cliffs, the ice is observed directly (see Figure 10.30). These glaciers are thought to have formed during warm periods, when the atmospheric pressure was greater and snow and ice could precipitate. They also suggest readily available frozen water that could support future human exploration of the planet.

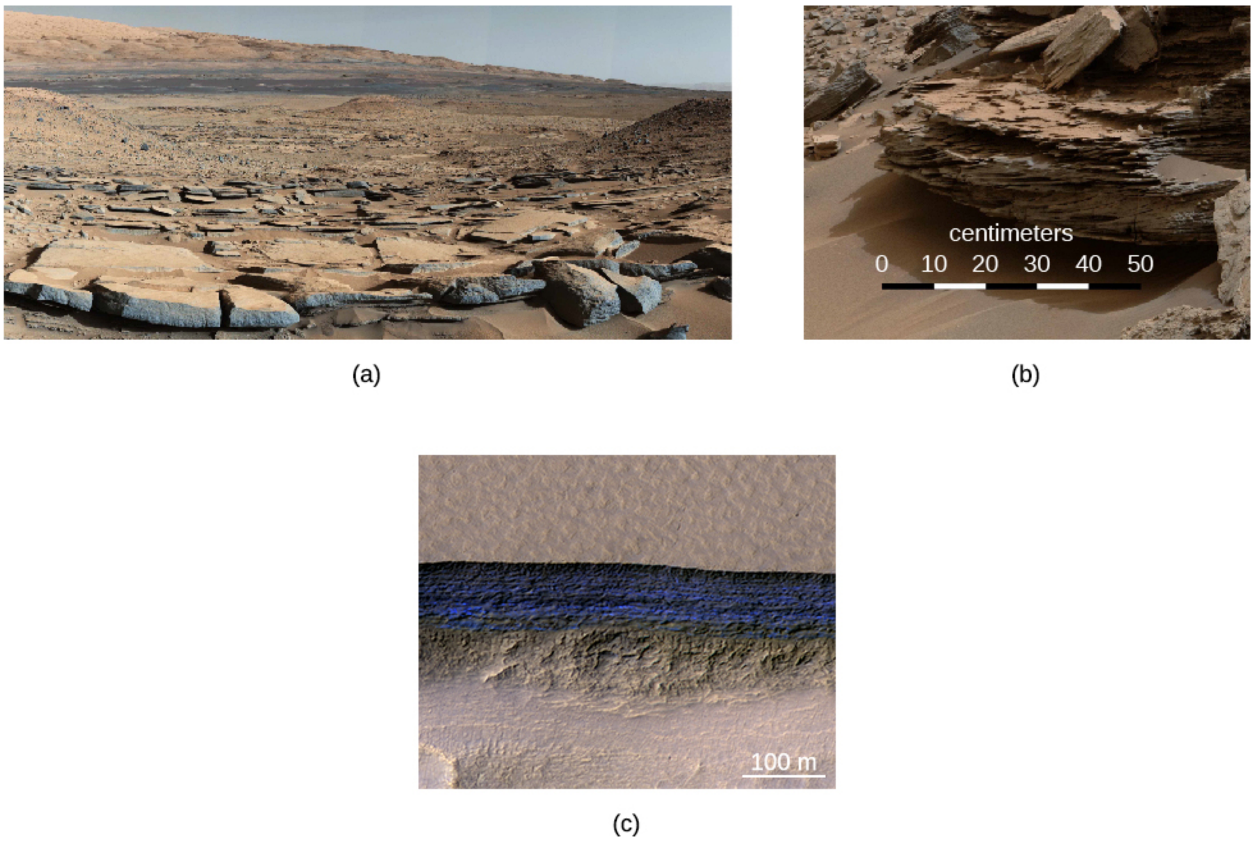


Figure 10.30 Gale Crater and Underground Ice Deposits. (a) This scene, photographed by the *Curiosity* rover, shows an ancient lakebed of cracked mudstones. (b) Geologists working with the *Curiosity* rover interpret this image of cross-bedded sandstone in Gale crater as evidence of liquid water passing over a loose bed of sediment at the time this rock formed. (c) Ice bands a hundred meters tall are visible in blue in a cliff-face on Mars, suggesting large deposits of frozen water buried just a few meters below the surface. Note that the blue color has been exaggerated in this photo, taken by the Mars Reconnaissance Orbiter spacecraft. (credit a: modification of work by NASA/JPL-Caltech/MSSS; credit b: modification of work by NASA/JPL-Caltech/MSSS; credit c: modification of work by NASA/JPL-Caltech/UA/USGS)

MAKING CONNECTIONS

Astronomy and Pseudoscience: The “Face on Mars”

People like human faces. We humans have developed great skill in recognizing people and interpreting facial expressions. We also have a tendency to see faces in many natural formations, from clouds to the man in the Moon. One of the curiosities that emerged from the Viking orbiters’ global mapping of Mars was the discovery of a strangely shaped mesa in the Cydonia region that resembled a human face. Despite later rumors of a cover-up, the “Face on Mars” was, in fact, recognized by Viking scientists and included in one of the early mission press releases. At the low resolution and oblique lighting under which the Viking image was obtained, the mile-wide mesa had something of a Sphinx-like appearance.

Unfortunately, a small band of individuals decided that this formation was an artificial, carved sculpture of a human face placed on Mars by an ancient civilization that thrived there hundreds of thousands of years ago. A band of “true believers” grew around the face and tried to deduce the nature of the “sculptors” who made it. This group also linked the face to a variety of other pseudoscientific phenomena such as crop circles (patterns in fields of grain, mostly in Britain, now known to be the work of pranksters).

Members of this group accused NASA of covering up evidence of intelligent life on Mars, and they received a great deal of help in publicizing their perspective from tabloid media. Some of the believers picketed the Jet Propulsion Laboratory at the time of the failure of the *Mars Observer* spacecraft, circulating stories that the “failure” of the *Mars Observer* was itself a fake, and that its true (secret) mission was to photograph the face.

The high-resolution *Mars Observer* camera (MOC) was reflown on the *Mars Global Surveyor* mission, which arrived at Mars in 1997. On April 5, 1998, in Orbit 220, the MOC obtained an oblique image of the face at a resolution of 4 meters per pixel, a factor-of-10 improvement in resolution over the Viking image. Another image in 2001 had even higher resolution. Immediately released by NASA, the new images showed a low mesa-like hill cut crossways by several roughly linear ridges and depressions, which were misidentified in the 1976 photo as the eyes and mouth of a face. Only with an enormous dose of imagination can any resemblance to a face be seen in the new images, demonstrating how dramatically our interpretation of geology can change with large improvements in resolution. The original and the higher resolution images can be seen in **Figure 10.31**.

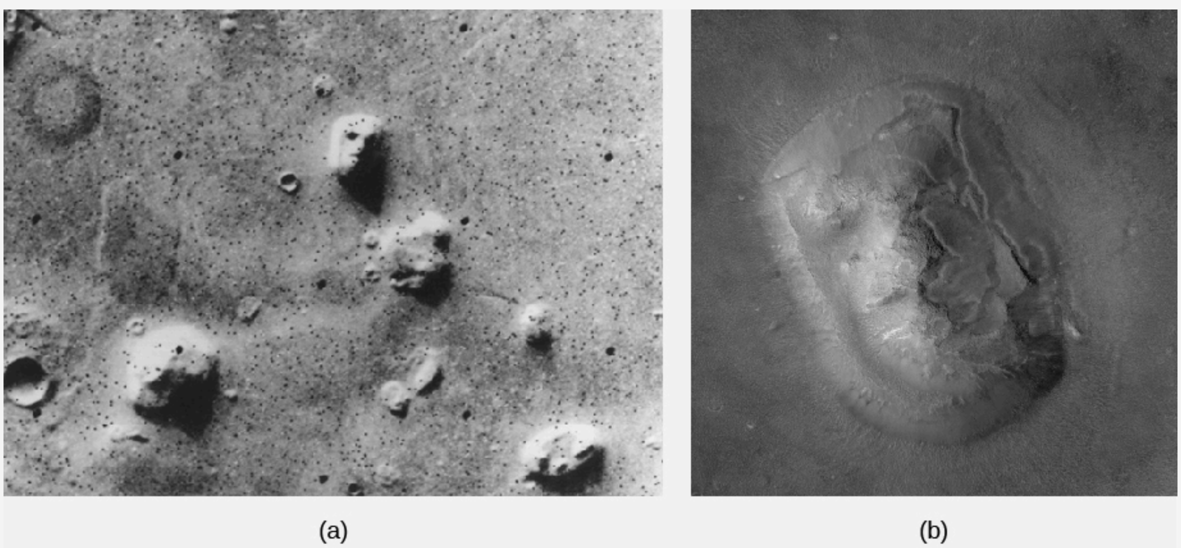


Figure 10.31 Face on Mars. The so-called “Face on Mars” is seen (a) in low resolution from Viking (the “face” is in the upper part of the picture) and (b) with 20 times better resolution from the *Mars Global Surveyor*. (credit a: modification of work NASA/JPL; credit b: modification of work by NASA/JPL/MSSS)

After 20 years of promoting pseudoscientific interpretations and various conspiracy theories, can the “Face on Mars” believers now accept reality? Unfortunately, it does not seem so. They have accused NASA of faking the new picture. They also suggest that the secret mission of the *Mars Observer* included a nuclear bomb used to destroy the face before it could be photographed in greater detail by the *Mars Global Surveyor*.

Space scientists find these suggestions incredible. NASA is spending increasing sums for research on life in the universe, and a major objective of current and upcoming Mars missions is to search for evidence of past microbial life on Mars. Conclusive evidence of extraterrestrial life would be one of the great discoveries of science and incidentally might well lead to increased funding for NASA. The idea that NASA or other government agencies would (or could) mount a conspiracy to suppress such welcome evidence is truly bizarre.

Alas, the “Face on Mars” story is only one example of a whole series of conspiracy theories that are kept before the public by dedicated believers, by people out to make a fast buck, and by irresponsible media attention. Others include the “urban legend” that the Air Force has the bodies of extraterrestrials at a secret base, the widely circulated report that UFOs crashed near Roswell, New Mexico (actually it was a balloon carrying scientific instruments to find evidence of Soviet nuclear tests), or the notion that alien astronauts helped build the Egyptian pyramids and many other ancient monuments because our ancestors were too stupid to do it alone.

In response to the increase in publicity given to these “fiction science” ideas, a group of scientists, educators, scholars, and magicians (who know a good hoax when they see one) have formed the Committee for Skeptical Inquiry. Two of the original authors of your book are active on the committee. For more information about its work delving into the rational explanations for paranormal claims, see their excellent magazine, *The Skeptical Inquirer*, or check out their website at www.csicop.org/.

Climate Change on Mars

The evidence about ancient rivers and lakes of water on Mars discussed so far suggests that, billions of years ago, martian temperatures must have been warmer and the atmosphere must have been more substantial than it is today. But what could have changed the climate on Mars so dramatically?

We presume that, like Earth and Venus, Mars probably formed with a higher surface temperature thanks to the greenhouse effect. But Mars is a smaller planet, and its lower gravity means that atmospheric gases could escape more easily than from Earth and Venus. As more and more of the atmosphere escaped into space, the temperature on the surface gradually fell.

Eventually Mars became so cold that most of the water froze out of the atmosphere, further reducing its ability to retain heat. The planet experienced a sort of *runaway refrigerator effect*, just the opposite of the runaway greenhouse effect that occurred on Venus. Probably, this loss of atmosphere took place within less than a billion years after Mars formed. The result is the cold, dry Mars we see today.

Conditions a few meters below the martian surface, however, may be much different. There, liquid water (especially salty water) might persist, kept warm by the internal heat of Mars or the insulating layers solid and rock. Even on the surface, there may be ways to change the martian atmosphere temporarily.

Mars is likely to experience long-term climate cycles, which may be caused by the changing orbit and tilt of the planet. At times, one or both of the polar caps might melt, releasing a great deal of water vapor into the atmosphere. Perhaps an occasional impact by a comet might produce a temporary atmosphere that is thick enough to permit liquid water on the surface for a few weeks or months. Some have even suggested that future technology might allow us to *terraform* Mars—that is, to engineer its atmosphere and climate in ways that might make the planet more hospitable for long-term human habitation.

The Search for Life on Mars

If there was running water on Mars in the past, perhaps there was life as well. Could life, in some form, remain in the martian soil today? Testing this possibility, however unlikely, was one of the primary objectives of the Viking landers in 1976. These landers carried miniature biological laboratories to test for microorganisms in the martian soil. Martian soil was scooped up by the spacecraft's long arm and placed into the experimental chambers, where it was isolated and incubated in contact with a variety of gases, radioactive isotopes, and nutrients to see what would happen. The experiments looked for evidence of *respiration* by living animals, *absorption* of *nutrients* offered to organisms that might be present, and an *exchange of gases* between the soil and its surroundings for any reason whatsoever. A fourth instrument pulverized the soil and analyzed it carefully to determine what organic (carbon-bearing) material it contained.

The Viking experiments were so sensitive that, had one of the spacecraft landed anywhere on Earth (with the possible exception of Antarctica), it would easily have detected life. But, to the disappointment of many scientists and members of the public, no life was detected on Mars. The soil tests for absorption of nutrients and gas exchange did show some activity, but this was most likely caused by chemical reactions that began as water was added to the soil and had nothing to do with life. In fact, these experiments showed that martian soil seems much more chemically active than terrestrial soils because of its exposure to solar ultraviolet radiation (since Mars has no ozone layer).

The organic chemistry experiment showed no trace of organic material, which is apparently destroyed on the martian surface by the sterilizing effect of this ultraviolet light. While the possibility of life on the surface has not been eliminated, most experts consider it negligible. Although Mars has the most earthlike environment of any planet in the solar system, the sad fact is that nobody seems to be home today, at least on the surface.

However, there is no reason to think that life could not have begun on Mars about 4 billion years ago, at the same time it started on Earth. The two planets had very similar surface conditions then. Thus, the attention of scientists has shifted to the search for *fossil* life on Mars. One of the primary questions to be addressed by future spacecraft is whether Mars once supported its own life forms and, if so, how this martian life compared with that on our own planet. Future missions will include the return of martian samples selected from sedimentary rocks at sites that once held water and thus perhaps ancient life. The most powerful searches for martian life (past or present) will thus be carried out in our laboratories here on Earth.

MAKING CONNECTIONS

Planetary Protection

When scientists begin to search for life on another planet, they must make sure that we do not contaminate the other world with life carried from Earth. At the very beginning of spacecraft exploration on Mars, an international agreement specified that all landers were to be carefully sterilized to avoid accidentally transplanting terrestrial microbes to Mars. In the case of Viking, we know the sterilization was successful. Viking's failure to detect martian organisms also implies that these experiments did not detect hitchhiking terrestrial microbes.

As we have learned more about the harsh conditions on the martian surface, the sterilization requirements have been somewhat relaxed. It is evident that no terrestrial microbes could grow on the martian surface, with its low temperature, absence of water, and intense ultraviolet radiation. Microbes from Earth might survive in a dormant, dried state, but they cannot grow and proliferate on Mars.

The problem of contaminating Mars will become more serious, however, as we begin to search for life below the surface, where temperatures are higher and no ultraviolet light penetrates. The situation will be even more daunting if we consider human flights to Mars. Any humans will carry with them a multitude of terrestrial microbes of all kinds, and it is hard to imagine how we can effectively keep the two biospheres isolated from each other if Mars has indigenous life. Perhaps the best situation could be one in which the two life-forms are so different that each is effectively invisible to the other—not recognized on a chemical level as living or as potential food.

The most immediate issue of public concern is not with the contamination of Mars but with any dangers associated with returning Mars samples to Earth. NASA is committed to the complete biological isolation of returned samples until they are demonstrated to be safe. Even though the chances of contamination are extremely low, it is better to be safe than sorry.

Most likely there is no danger, even if there is life on Mars and alien microbes hitch a ride to Earth inside some of the returned samples. In fact, Mars is sending samples to Earth all the time in the form of the Mars meteorites. Since some of these microbes (if they exist) could probably survive the trip to Earth inside their rocky home, we may have been exposed many times over to martian microbes. Either they do not interact with our terrestrial life, or in effect our planet has already been inoculated against such alien bugs.

LINK TO LEARNING

More than any other planet, Mars has inspired science fiction writers over the years. You can find scientifically reasonable stories about Mars in a subject index of such stories online. If you click on **Mars (https://openstax.org/l/30MarsStories)** as a topic, you will find stories by a number of space scientists, including William Hartmann, Geoffrey Landis, and Ludek Pesek.

10.6 DIVERGENT PLANETARY EVOLUTION

Learning Objectives

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

- Compare the planetary evolution of Venus, Earth, and Mars

Venus, Mars, and our own planet Earth form a remarkably diverse triad of worlds. Although all three orbit in roughly the same inner zone around the Sun and all apparently started with about the same chemical mix of silicates and metals, their evolutionary paths have diverged. As a result, Venus became hot and dry, Mars became cold and dry, and only Earth ended up with what we consider a hospitable climate.

We have discussed the runaway greenhouse effect on Venus and the runaway refrigerator effect on Mars, but we do not understand exactly what started these two planets down these separate evolutionary paths. Was Earth ever in danger of a similar fate? Or might it still be diverted onto one of these paths, perhaps due to stress on the atmosphere generated by human pollutants? One of the reasons for studying Venus and Mars is to seek insight into these questions.

Some people have even suggested that if we understood the evolution of Mars and Venus better, we could possibly reverse their evolution and restore more earthlike environments. While it seems unlikely that humans could ever make either Mars or Venus into a replica of Earth, considering such possibilities is a useful part of our more general quest to understand the delicate environmental balance that distinguishes our planet from its two neighbors. In **Cosmic Samples and the Origin of the Solar System**, we return to the comparative study of the terrestrial planets and their divergent evolutionary histories.

CHAPTER 10 REVIEW

KEY TERMS

runaway greenhouse effect the process by which the greenhouse effect, rather than remaining stable or being lessened through intervention, continues to grow at an increasing rate

tectonic geological features that result from stresses and pressures in the crust of a planet; tectonic forces can lead to earthquakes and motion of the crust

SUMMARY

10.1 The Nearest Planets: An Overview

Venus, the nearest planet, is a great disappointment through the telescope because of its impenetrable cloud cover. Mars is more tantalizing, with dark markings and polar caps. Early in the twentieth century, it was widely believed that the “canals” of Mars indicated intelligent life there. Mars has only 11% the mass of Earth, but Venus is nearly our twin in size and mass. Mars rotates in 24 hours and has seasons like Earth; Venus has a retrograde rotation period of 243 days. Both planets have been extensively explored by spacecraft.

10.2 The Geology of Venus

Venus has been mapped by radar, especially with the *Magellan* spacecraft. Its crust consists of 75% lowland lava plains, numerous volcanic features, and many large coronae, which are the expression of subsurface volcanism. The planet has been modified by widespread tectonics driven by mantle convection, forming complex patterns of ridges and cracks and building high continental regions such as Ishtar. The surface is extraordinarily inhospitable, with pressure of 90 bars and temperature of 730 K, but several Russian Venera landers investigated it successfully.

10.3 The Massive Atmosphere of Venus

The atmosphere of Venus is 96% CO_2. Thick clouds at altitudes of 30 to 60 kilometers are made of sulfuric acid, and a CO_2 greenhouse effect maintains the high surface temperature. Venus presumably reached its current state from more earthlike initial conditions as a result of a runaway greenhouse effect, which included the loss of large quantities of water.

10.4 The Geology of Mars

Most of what we know about Mars is derived from spacecraft: highly successful orbiters, landers, and rovers. We have also been able to study a few martian rocks that reached Earth as meteorites. Mars has heavily cratered highlands in its southern hemisphere, but younger, lower volcanic plains over much of its northern half. The Tharsis bulge, as big as North America, includes several huge volcanoes; Olympus Mons is more than 20 kilometers high and 500 kilometers in diameter. The Valles Marineris canyons are tectonic features widened by erosion. Early landers revealed only barren, windswept plains, but later missions have visited places with more geological (and scenic) variety. Landing sites have been selected in part to search for evidence of past water.

10.5 Water and Life on Mars

The martian atmosphere has a surface pressure of less than 0.01 bar and is 95% CO_2. It has dust clouds, water clouds, and carbon dioxide (dry ice) clouds. Liquid water on the surface is not possible today, but there is subsurface permafrost at high latitudes. Seasonal polar caps are made of dry ice; the northern residual cap is water ice, whereas the southern permanent ice cap is made predominantly of water ice with a covering of carbon dioxide ice. Evidence of a very different climate in the past is found in water erosion features: both runoff channels and outflow channels, the latter carved by catastrophic floods. Our rovers, exploring ancient lakebeds and places where sedimentary rock has formed, have found evidence for extensive surface water in the past. Even more exciting are the gullies that seem to show the presence of flowing salty water on the surface today, hinting at near-surface aquifers. The Viking landers searched for martian life in 1976, with negative results, but life might have flourished long ago. We have found evidence of water on Mars, but following the water has not yet led us to life on that planet.

10.6 Divergent Planetary Evolution

Earth, Venus, and Mars have diverged in their evolution from what may have been similar beginnings. We need to understand why if we are to protect the environment of Earth.

FOR FURTHER EXPLORATION

Articles

Venus

Dorminey, B. “Cool Science on a Hot World.” *Astronomy* (February 2006): 46. Five-page overview of Venus and the Venus Express mission plans.

Kargel, J. “Rivers of Venus.” *Sky & Telescope* (August 1997): 32. On lava channels.

Robertson, D. “Parched Planet.” *Sky & Telescope* (April 2008): 26. Overview of our understanding of the planet.

Robinson, C. “Magellan Reveals Venus.” *Astronomy* (February 1995): 32.

Stofan, E. “The New Face of Venus.” *Sky & Telescope* (August 1993): 22.

Zimmerman, R. “Taking Venus by Storm.” *Astronomy* (October 2008): 66. On results from the Venus Express mission.

Mars

Albee, A. “The Unearthly Landscapes of Mars.” *Scientific American* (June 2003): 44. Results from the Mars Global Surveyor and Mars Odyssey missions and an overview.

Bell, J. “A Fresh Look at Mars.” *Astronomy* (August 2015): 28. Nice summary of recent spacecraft results and how they are revising our understanding of Mars.

Bell, J. “Uncovering Mars’ Secret Past.” *Sky & Telescope* (July 2009): 22. How rovers and orbiters are helping us to understand Mars history and the role of water.

Bell, J. “The Red Planet’s Watery Past.” *Scientific American* (December 2006): 62. Rovers are furnishing proof that ancient Mars was wet.

Burnham, R. “Red Planet Rendezvous.” *Astronomy* (May 2006): 68. About Mariner Valley and a flyover film constructed from many still images.

Christensen, P. “The Many Faces of Mars.” *Scientific American* (July 2005): 32. Results from the Rover mission; evidence that Mars was once wet in places.

Lakdawalla, E. “The History of Water on Mars.” *Sky & Telescope* (September 2013): 16. Clear review of our current understanding of the role of water on Mars in different epochs.

Malin, M. “Visions of Mars.” *Sky & Telescope* (April 1999): 42. A geological tour of the red planet, with new Mars

Global Surveyor images.

McEwen, A. “Mars in Motion.” *Scientific American* (May 2013): 58. On gullies and other surface changes.

McKay, C. & Garcia, V. “How to Search for Life on Mars.” *Scientific American* (June 2014): 44. Experiments future probes could perform.

Naeye, R. “Europe’s Eye on Mars.” *Sky & Telescope* (December 2005): 30. On the Mars Express mission and the remarkable close-up images it is sending.

Talcott, R. “Seeking Ground Truth on Mars.” *Astronomy* (October 2009): 34. How rovers and orbiters are helping scientists understand the red planet’s surface.

Websites

European Space Agency Mars Express Page: **http://www.esa.int/Our_Activities/Space_Science/Mars_Express (http://www.esa.int/Our_Activities/Space_Science/Mars_Express)** .

European Space Agency Venus Express Page: **http://www.esa.int/Our_Activities/Space_Science/Venus_Express (http://www.esa.int/Our_Activities/Space_Science/Venus_Express)** .

High Resolution Imaging Science Experiment: **http://hirise.lpl.arizona.edu/ (http://hirise.lpl.arizona.edu/)** .

Jet Propulsion Lab Mars Exploration Page: **http://mars.jpl.nasa.gov/ (http://mars.jpl.nasa.gov/)** .

Mars Globe HD app: **https://itunes.apple.com/us/app/mars-globe-hd/id376020224?mt=8 (https://itunes.apple.com/us/app/mars-globe-hd/id376020224?mt=8)** .

Mars Rover 360° Panorama: **http://www.360cities.net/image/curiosity-rover-martian-solar-day-2#171.10,26.50,70.0 (http://www.360cities.net/image/curiosity-rover-martian-solar-day-2#171.10,26.50,70.0)** . Interactive.

NASA Center for Mars Exploration: **http://www.nasa.gov/mission_pages/mars/main/index.html (http://www.nasa.gov/mission_pages/mars/main/index.html)** .

NASA Solar System Exploration Mars Page: **http://solarsystem.nasa.gov/planets/mars (http://solarsystem.nasa.gov/planets/mars)** .

NASA Solar System Exploration Venus Page: **http://solarsystem.nasa.gov/planets/venus (http://solarsystem.nasa.gov/planets/venus)** .

NASA’s apps about Mars for phones and tablets can be found at: **http://mars.nasa.gov/mobile/info/ (http://mars.nasa.gov/mobile/info/)** .

NASA’s Magellan Mission to Venus: **http://www2.jpl.nasa.gov/magellan/ (http://www2.jpl.nasa.gov/magellan/)** .

Russian (Soviet) Venus Missions and Images: **http://mentallandscape.com/C_CatalogVenus.htm (http://mentallandscape.com/C_CatalogVenus.htm)** .

Venus Atlas app: **https://itunes.apple.com/us/app/venus-atlas/id317310503?mt=8 (https://itunes.apple.com/us/app/venus-atlas/id317310503?mt=8)** .

Venus Express Results Article: **http://www.mpg.de/798302/F002_Focus_026-033.pdf (http://www.mpg.de/798302/F002_Focus_026-033.pdf)** .

Videos

50 Years of Mars Exploration: **http://www.jpl.nasa.gov/video/details.php?id=1395**

(http://www.jpl.nasa.gov/video/details.php?id=1395) . NASA's summary of all missions through *MAVEN*; good quick overview (4:08).

Being a Mars Rover: What It's Like to be an Interplanetary Explorer: **https://www.youtube.com/watch?v=nRpCOEsPD54 (https://www.youtube.com/watch?v=nRpCOEsPD54)** . 2013 talk by Dr. Lori Fenton about what it's like on the surface of Mars (1:07:24).

Magellan Maps Venus: **http://www.bbc.co.uk/science/space/solarsystem/space_missions/magellan_probe#p005y07s (http://www.bbc.co.uk/science/space/solarsystem/space_missions/magellan_probe#p005y07s)** . BBC clip with Dr. Ellen Stofan on the radar images of Venus and what they tell us (3:06).

Our *Curiosity*: **https://www.youtube.com/watch?v=XczKXWvokm4 (https://www.youtube.com/watch?v=XczKXWvokm4)** . Mars *Curiosity* rover 2-year anniversary video narrated by Neil deGrasse Tyson and Felicia Day (6:01).

Planet Venus: The Deadliest Planet, Venus Surface and Atmosphere: **https://www.youtube.com/watch?v=HqFVxWfVtoo (https://www.youtube.com/watch?v=HqFVxWfVtoo)** . Quick tour of Venus' atmosphere and surface (2:04).

Planetary Protection and Hitchhikers in the Solar System: The Danger of Mingling Microbes: **https://www.youtube.com/watch?v=6iGC3uO7jBI (https://www.youtube.com/watch?v=6iGC3uO7jBI)** . 2009 talk by Dr. Margaret Race on preventing contamination between worlds (1:28:50).

COLLABORATIVE GROUP ACTIVITIES

A. Your group has been asked by high NASA officials to start planning the first human colony on Mars. Begin by making a list of what sorts of things humans would need to bring along to be able to survive for years on the surface of the red planet.

B. As a publicity stunt, the mayor of Venus, Texas (there really is such a town), proposes that NASA fund a mission to Venus with humans on board. Clearly, the good mayor neglected to take an astronomy course in college. Have your group assemble a list of as many reasons as possible why it is unlikely that humans will soon land on the surface of Venus.

C. Even if humans would have trouble surviving on the surface of Venus, this does not mean we could not learn a lot more about our veiled sister planet. Have your group brainstorm a series of missions (pretend cost is no object) that would provide us with more detailed information about Venus' atmosphere, surface, and interior.

D. Sometime late in the twenty-first century, when travel to Mars has become somewhat routine, a very wealthy couple asks you to plan a honeymoon tour of Mars that includes the most spectacular sights on the red planet. Constitute your group as the Percival Lowell Memorial Tourist Agency, and come up with a list of not-to-be missed tourist stops on Mars.

E. In the popular book and film, called *The Martian*, the drama really begins when our hero is knocked over and loses consciousness as he is half buried by an intense wind storm on Mars. Given what you have learned about Mars' atmosphere in this chapter, have your group discuss how realistic that scenario is. (By the way, the author of the book has himself genially acknowledged in interviews and talks that this is a reasonable question to ask.)

F. Astronomers have been puzzled and annoyed about the extensive media publicity that was given the small group of "true believers" who claimed the "Face on Mars" was not a natural formation (see the **Astronomy and Pseudoscience: The "Face on Mars"** feature box). Have your group make a list of the reasons many of the media were so enchanted by this story. What do you think astronomers could or should do to get the skeptical, scientific perspective about such issues before the public?

G. Your group is a special committee of scientists set up by the United Nations to specify how any Mars samples should be returned to Earth so that possible martian microbes do not harm Earth life. What precautions would you recommend, starting at Mars and going all the way to the labs that analyze the martian samples back on Earth?

H. Have your group brainstorm about Mars in popular culture. How many movies, songs or other music, and products can you think of connected with Mars? What are some reasons that Mars would be a popular theme for filmmakers, songwriters, and product designers?

EXERCISES

Review Questions

1. List several ways that Venus, Earth, and Mars are similar, and several ways they are different.

2. Compare the current atmospheres of Earth, Venus, and Mars in terms of composition, thickness (and pressure at the surface), and the greenhouse effect.

3. How might Venus' atmosphere have evolved to its present state through a runaway greenhouse effect?

4. Describe the current atmosphere on Mars. What evidence suggests that it must have been different in the past?

5. Explain the runaway refrigerator effect and the role it may have played in the evolution of Mars.

6. What evidence do we have that there was running (liquid) water on Mars in the past? What evidence is there for water coming out of the ground even today?

7. What evidence is there that Venus was volcanically active about 300–600 million years ago?

8. Why is Mars red?

9. What is the composition of clouds on Mars?

10. What is the composition of the polar caps on Mars?

11. Describe two anomalous features of the rotation of Venus and what might account for them.

12. How was the *Mars Odyssey* spacecraft able to detect water on Mars without landing on it?

Thought Questions

13. What are the advantages of using radar imaging rather than ordinary cameras to study the topography of Venus? What are the relative advantages of these two approaches to mapping Earth or Mars?

14. Venus and Earth are nearly the same size and distance from the Sun. What are the main differences in the geology of the two planets? What might be some of the reasons for these differences?

15. Why is there so much more carbon dioxide in the atmosphere of Venus than in that of Earth? Why so much more carbon dioxide than on Mars?

16. If the Viking missions were such a rich source of information about Mars, why have we sent the Pathfinder, *Global Surveyor*, and other more recent spacecraft to Mars? Make a list of questions about Mars that still puzzle astronomers.

17. Compare Mars with Mercury and the Moon in terms of overall properties. What are the main similarities and differences?

18. Contrast the mountains on Mars and Venus with those on Earth and the Moon.

19. We believe that all of the terrestrial planets had similar histories when it comes to impacts from space. Explain how this idea can be used to date the formation of the martian highlands, the martian basins, and the Tharsis volcanoes. How certain are the ages derived for these features (in other words, how do we check the ages we derive from this method)?

20. Is it likely that life ever existed on either Venus or Mars? Justify your answer in each case.

21. Suppose that, decades from now, NASA is considering sending astronauts to Mars and Venus. In each case, describe what kind of protective gear they would have to carry, and what their chances for survival would be if their spacesuits ruptured.

22. We believe that Venus, Earth, and Mars all started with a significant supply of water. Explain where that water is now for each planet.

23. One source of information about Mars has been the analysis of meteorites from Mars. Since no samples from Mars have ever been returned to Earth from any of the missions we sent there, how do we know these meteorites are from Mars? What information have they revealed about Mars?

24. The runaway greenhouse effect and its inverse, the runaway refrigerator effect, have led to harsh, uninhabitable conditions on Venus and Mars. Does the greenhouse effect always cause climate changes leading to loss of water and life? Give a reason for your answer.

25. In what way is the high surface temperature of Venus relevant to concerns about global warming on Earth today?

26. What is a dust devil? Would you expect to feel more of a breeze from a dust devil on Mars or on Earth? Explain.

27. Near the martian equator, temperatures at the same spot can vary from an average of –135 °C at night to an average of 30 °C during the day. How can you explain such a wide difference in temperature compared to that on Earth?

Figuring For Yourself

28. Estimate the amount of water there could be in a global (planet-wide) region of subsurface permafrost on Mars (do the calculations for two permafrost thicknesses, 1 and 10 km, and a concentration of ice in the permafrost of 10% by volume). Compare the two results you get with the amount of water in Earth's oceans calculated in **Example 10.1**.

29. At its nearest, Venus comes within about 41 million km of Earth. How distant is it at its farthest?

30. If you weigh 150 lbs. on the surface of Earth, how much would you weigh on Venus? On Mars?

31. Calculate the relative land area—that is, the amount of the surface not covered by liquids—of Earth, the Moon, Venus, and Mars. (Assume that 70% of Earth is covered with water.)

32. The closest approach distance between Mars and Earth is about 56 million km. Assume you can travel in a spaceship at 58,000 km/h, which is the speed achieved by the New Horizons space probe that went to Pluto and is the fastest speed so far of any space vehicle launched from Earth. How long would it take to get to Mars at the time of closest approach?