8 Mars

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▲ **About the photo:** Sunset on Mars (photographed by the *Curiosity* rover).

When the first astronauts visit Mars, what will they find? Though an astronaut could not survive without a spacesuit, she would feel more at home on Mars than anywhere else in the solar system. She could stand on a rocky surface, scoop up a gloveful of dirt, and explore extinct volcanoes and ancient canyons.

Sally Ride and Tam O'Shaughnessy, *The Mystery of Mars*

LEARNING OBJECTIVE

Chapter 8 Overview

The idea of a civilization on Mars was once taken so seriously that the term *Martians* became nearly synonymous with alien life. Spacecraft sent to Mars have since shattered this fictional image of a world of cities and sophisticated beings, but the possibility of past or present microbial life on Mars remains a subject of intense scientific investigation.

Substantial evidence suggests that water once flowed on Mars, and it seems likely that Mars once had surface or subsurface environments similar to those in which life thrived on the early Earth. If life arose on Mars (or was transported there on meteorites from the early Earth), we may be able to find its fossil remains. It's even possible that life still survives somewhere on Mars, perhaps underground where volcanic heat can keep some water liquid.

We have not yet reached the point where we can undertake a definitive search for life on Mars, but we are rapidly learning about Mars and its history. In this chapter, we'll explore what we've learned to date and what this knowledge implies about the possibility of life on the red planet.

8.1 Fantasies of Martian Civilization

Shining brightly and noticeably red in the nighttime sky, Mars has long captured the human imagination. Most of our modern understanding of Mars comes from observations by robotic spacecraft (Figure 8.1).

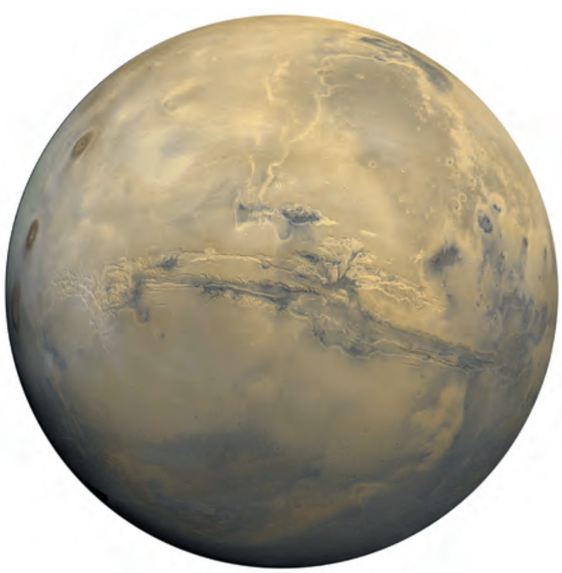


FIGURE 8.1

Mars, photographed by the *Viking* orbiter. The horizontal "gash" across the center is the giant canyon called Valles Marineris.

But interest in life on Mars began much earlier, and for decades was a mainstay of popular culture.

LEARNING OBJECTIVE

Martians!

8.1.1 How did Mars invade popular culture?

The story begins in the late eighteenth century with brother and sister astronomers William and Caroline Herschel.* Though better known for discovering the planet Uranus, the Herschels often observed Mars through their telescopes, noting its polar ice caps and discovering that the length of its day (24 hours 37 minutes) is similar to that of an Earth day. In a talk presented to Britain's Royal Society in 1784, William claimed that Mars possessed an atmosphere and that, consequently, "its inhabitants probably enjoy a situation in many respects similar to our own." With the mention of "inhabitants," the possibility of living beings on the red planet had been broached by a

*William (1738–1822) was more than 11 years older than Caroline (1750–1848) and early in her career treated his sister more like an assistant than a colleague. But Caroline developed into a noted astronomer in her own right, achieving many firsts for women in astronomy, including becoming the first woman to win the Gold Medal of the British Royal Astronomical Society. Among other honors, she was awarded a Gold Medal for Science by the King of Prussia on her 96th birthday.

respected scientist in an academic setting, and Martians were assumed to exist. (It should be noted that William was not overly particular when it came to populating the cosmos. As far as he was concerned, everything in the solar system was inhabited, including the Moon and the Sun.)

During the following century, Mars rose to the top of the astronomical charts. In 1877, Italian astronomer Giovanni Schiaparelli claimed to have seen a network of 79 linear features that he called *canali,* by which he meant the Italian word for "channels." However, it was often translated as "canals," which in English refers only to human-made waterways. Coming amid the excitement that followed the 1869 opening of the Suez Canal, Schiaparelli's discovery soon inspired visions of artificial waterways built by a martian civilization. Schiaparelli himself remained skeptical of such claims, and it's not clear whether he even thought the *canali* contained water. But his work caught the imagination of a young Harvard graduate, Percival Lowell (1855–1916).

Lowell, whose degree was in mathematics, came from a wealthy and distinguished New England family. His brother Abbott became famous as a president of Harvard, and his sister Amy gained fame as a poet. After spending a few years as a businessman and as a traveler in the Far East, Percival Lowell turned to astronomy. Impassioned by his belief in the martian canals and enabled by his wealth, Lowell commissioned the building of an observatory in Flagstaff, Arizona. He chose Flagstaff because he thought its dry air and high altitude would limit the blurring caused by Earth's atmosphere, making it easier for him to map the martian canals. The Lowell Observatory opened in 1894 and is still operating today.

Over the next two decades, Lowell mapped close to 200 canals that he claimed to see on Mars, publishing his first book about them in 1895. He assumed Mars's polar caps were made of water ice like Earth's, so he imagined that the canals were built to carry water from the poles to agricultural areas and thirsty cities nearer the equator. From there it was a short leap to imagine the Martians as an old civilization on a dying planet. The global network of canals convinced Lowell that the Martians were citizens of a single, global nation. Such ideas provided the "scientific" basis for H. G. Wells's novel *The War of the Worlds,* published in 1898 (Figure 8.2). Public belief in Martians became so widespread that, decades later, a 1938 radio broadcast of *The War of the Worlds* created a famous panic as many people thought an invasion was actually under way. (The radio voice was that of Orson Welles, no relation to H. G. Wells.)

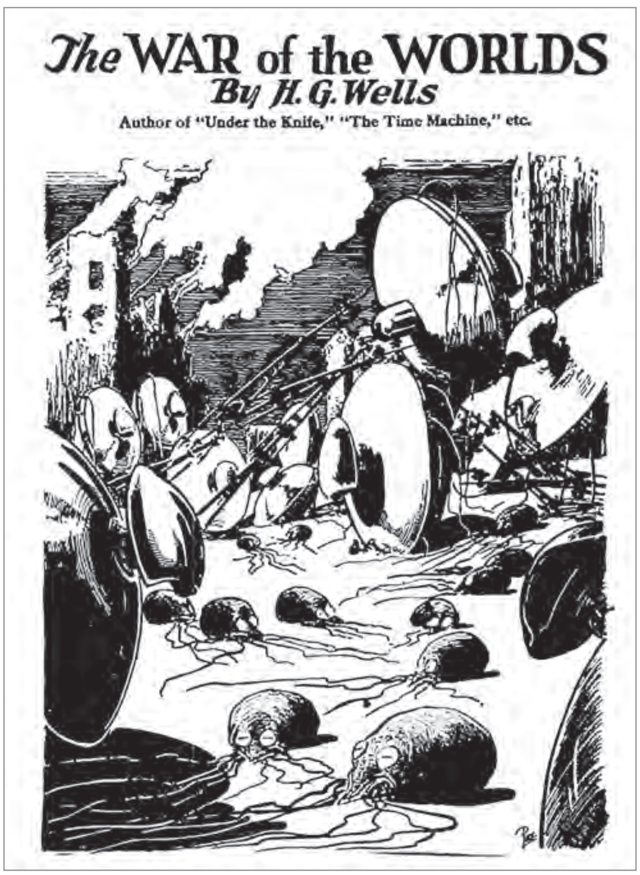


FIGURE 8.2
The cover of the original edition of *The War of the Worlds.*

Think About It Think of as many popular references to a civilization of "Martians" as you can; be sure to consider novels, movies, television shows, advertisements, and music. Do these references tell us anything about the influence of science on the public imagination? Defend your opinion.

Lowell was an effective advocate for the canals, but they do not really exist. Even in his own time, other scientists shot holes through most of Lowell's claims. One notable problem was that most other astronomers did not see any canals either by eye or in photographs, even when using telescopes larger than Lowell's. Lowell's basic assumptions and interpretations also came under fire. Writing in 1907, Alfred Russel Wallace (the co-discoverer with Darwin of evolution by natural selection [Section 5.1]) used physical arguments to suggest that Mars is too cold for liquid water to flow. He also pointed out that Lowell's canals followed straight-line paths for hundreds or thousands of miles, while real canals would be built to follow natural contours of topography (for example, to go around mountains). In summarizing this argument, Wallace wrote that "[a network of canals,] as Mr. Lowell describes, would be the work of a body of madmen rather than of intelligent beings."*

*Excerpted in K. Zahnle, "Decline and Fall of the Martian Empire," *Nature,* vol. 412, July 12, 2001.

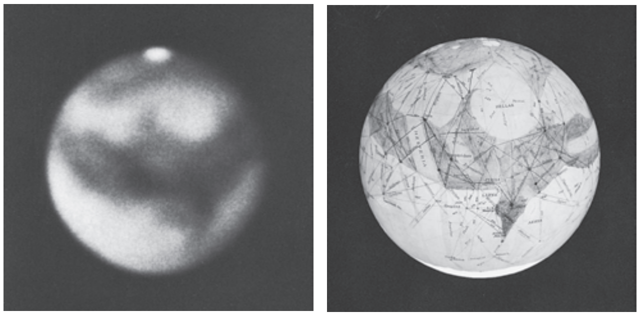


FIGURE 8.3
Can you see how the markings on Mars in the telescopic photo on the left might have resembled the geometrical features in the drawing by Percival Lowell on the right? Try squinting your eyes.

What was Lowell seeing? In a few cases, his canals correspond to real features on Mars. For example, the canal he claimed to see most often (which he called *Agathodaemon*) coincides with the location of the huge canyon network now known as Valles Marineris (see Figure 8.1). A few other canals also roughly follow the contours of real features on Mars, but most of the canals were pure fantasy. Figure 8.3 compares a telescopic photo of Mars with one of Lowell's maps of the same regions. You can probably see how the dark and light regions match up in the photo and the drawing, but seeing any canals requires a vivid imagination. (Some scholars speculate that the particular optics of his telescope caused Lowell to map images of blood vessels on his own retina as some of the canals.)

Lowell's story illustrates both the pitfalls and the triumphs of modern science. The pitfall is that individual scientists, no matter how upstanding and dedicated, may still bring personal biases to bear on their scientific work. In Lowell's case, he was so convinced of the existence of canals and Martians that he simply ignored all evidence to the contrary. But the story's ending shows why modern science ultimately is so successful. Despite Lowell's stature, other scientists did not accept his claims on faith. Instead, they sought to confirm his observations and to test his underlying assumptions. They found that Lowell's claims fell short on all counts. As a result, Lowell became an increasingly isolated voice as he continued to advocate a viewpoint that was clearly wrong.

8.2 A Modern Portrait of Mars

The public debate about martian canals and cities was not entirely put to rest until NASA began sending spacecraft to Mars. In 1965, NASA's *Mariner 4* spacecraft flew to within 6000 miles of the martian surface, transmitting a few dozen low-resolution images of the landscape below. Mars's surface was littered

FIGURE 8.4
The surface of Mars photographed by the *Viking 2* lander in 1979, showing a thin coating of ice on the rocks and soil. The inset shows a working model (actually, a spare spacecraft) of the *Viking* landers, identical to those that landed on Mars, on display at the National Air and Space Museum in Washington, D.C.

with craters, not canals, and measurements of the atmospheric pressure and temperature made from the spacecraft indicated a cold, dry planet seemingly incapable of supporting life.

Nevertheless, all was not lost when it came to the potential for life on Mars. There was no evidence of any intelligent beings, but the thin atmosphere and the polar caps left open the possibility of the existence of microbes or perhaps even some primitive plants or animals. On July 20, 1976, seven years to the day after Neil Armstrong's history-making walk on the Moon and nearly a century since Schiaparelli's description of *canali,* the thin skies above Mars were pierced by a NASA space probe. The *Viking 1* lander touched down on the Chryse Planitia, a sprawling, rock-strewn plain about 1300 kilometers north of the martian equator. Two months later, *Viking 2* landed on the other side of the planet. Meanwhile, two *Viking* orbiters began studying the planet from above.

When the *Viking* landers' cameras opened their eyes in the frigid martian air, they found a bleak landscape with red dust and scattered rocks. No creatures stared back at the cameras, and no plants were huddled in the weak sunlight. For months the images continued to come in, but the view scarcely changed. Nothing grew other than some occasional patches of frost, and nothing moved other than windblown dust (Figure 8.4). Though neither lander could move from the spot where it had settled, each had a robotic

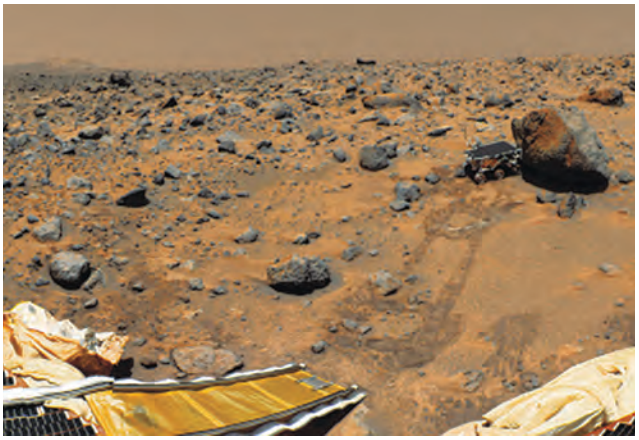


FIGURE 8.5
The view from the *Pathfinder* lander (partially visible in the foreground); the scattered rocks were probably carried to the site by an ancient flood. The little rover, *Sojourner,* is at the upper right, studying a rock that scientists named Yogi.

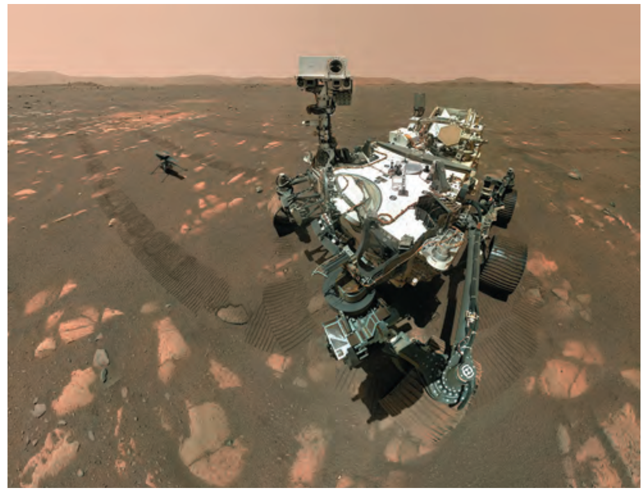


FIGURE 8.6
This self-portrait, assembled from dozens of individual images, shows the *Perseverance* rover and *Ingenuity* helicopter on Mars on April 6, 2021.

arm with which it collected soil for some onboard experiments designed to look for microbes (see Section 8.4).

The *Viking* orbiters and landers provided a wealth of scientific data about Mars. But they also left many questions unanswered, and the scientific community was itching for follow-up missions. Unfortunately, budgetary and political considerations, along with the failure of two Russian missions to Mars (*Phobos 1* and *2*) and one American mission (*Mars Observer*), all conspired to stop spacecraft exploration of Mars for some 20 years. The long mission drought did not end until July 4, 1997, with the landing of *Pathfinder* and its little rover, *Sojourner* (Figure 8.5). Named for Sojourner Truth, an African American heroine of the Civil War era, the rover could travel only a few tens of meters—just enough for it to check the chemical compositions of nearby rocks.

As of 2022, a total of 10 robotic landers or rovers had reached Mars successfully (Table 8.1), along with more than a dozen orbiters, eight of which were still operational (Table 8.2); several more missions should be launched before 2025. NASA's most recent rover, *Perseverance*, also carried a small helicopter named *Ingenuity* to Mars (Figure 8.6), where it successfully became humanity's first aircraft to make a powered, controlled flight on another world. By combining data from these missions with past data, we are

TABLE 8.1 Successful and Upcoming Mars Landers/Rovers

Mission	*Agency*	*Type*	*Landing Year*
Viking 1	NASA	lander	1976
Viking 2	NASA	lander	1976
Pathfinder/ Sojourner	NASA	lander/rover	1997
Spirit	NASA	rover	2004
Opportunity	NASA	rover	2004
Phoenix	NASA	lander	2008
Curiosity	NASA	rover	2012
InSight	NASA	lander	2018
Tianwen-1/ Zurong	China	lander/rover	2021
Perseverance/ Ingenuity	NASA	lander/helicopter	2021
ExoMars	ESA/Russia	lander/rover	2025*

*Originally planned as a joint 2022 launch of the European Space Agency's *Rosalind Franklin* rover and Russia's *Kazachok* lander, but delayed by war as this book goes to press.

TABLE 8.2 Operational (as of 2022) and Upcoming Mars Orbiters

Mission	*Agency*	*Arrival Year*
Mars Odyssey	NASA	2001
Mars Express	ESA	2003
Mars Reconnaissance Orbiter	NASA	2006
Mangalyaan	India	2014
MAVEN	NASA	2014
ExoMars Trace Gas Orbiter	ESA	2016
Hope	United Arab Emirates	2021
Tianwen-1 Orbiter	China	2021
MMX	Japan	2025*
EscaPADE	NASA	2025*
Mangalyaan 2	India	2025*

*Planned; Japan's *MMX* will also attempt to collect a sample from Phobos and return it to Earth.

beginning to put together a realistic portrait of the past and present habitability of Mars.

LEARNING OBJECTIVE
Mars Today

8.2.1 What is Mars like today?

The present-day surface of Mars may look much like some deserts or volcanic plains on Earth, but its thin atmosphere makes the conditions quite different. Table 8.3 summarizes basic Mars data and presents Earth data for comparison. The low atmospheric pressure—less than 1% of that on Earth's surface—means the air is so thin that a visiting astronaut could not survive outside for more than a few minutes without a pressurized space suit. The atmosphere consists mostly of carbon dioxide, but the total amount of gas is so small that it creates only a weak greenhouse effect. As a result, the temperature is usually well below freezing, with a global average of about −50°C (−58°F). The lack of oxygen means we could not breathe the thin air, and it also explains why Mars lacks an ozone layer (recall that ozone, O_3, is made of oxygen). The lack of ozone allows much of the Sun's damaging ultraviolet radiation to pass unhindered to the surface.

Nevertheless, martian conditions are much less extreme than those on the Moon (mainly because of the moderating effects of the atmosphere), and it's easy to imagine future astronauts living and working in airtight research stations while occasionally donning space suits for outdoor excursions. Martian surface gravity is about 38% of that on Earth, so everyone and everything would weigh about 38% of Earth weight. Astronauts could walk around easily even while wearing space suits with heavy backpacks. It would also probably be easy to adapt to patterns of day and night, since the martian day (which Mars scientists called a "sol") is only about 40 minutes longer than an Earth day.

THE LACK OF SURFACE LIQUID WATER The low atmospheric pressure explains one of the key facts relevant to the search for life on Mars: There are no lakes, rivers, or even puddles of liquid water on the surface of Mars today. We know this not only because we've studied most of the surface in reasonable detail but also because the surface conditions do not allow it. In most places and at most times, Mars is so cold that any liquid water would immediately freeze into ice. Even when the temperature rises above freezing, as it often does at midday near the equator, the air pressure is so low that liquid water would quickly evaporate. In other words, liquid water is *unstable* on Mars today: If you put on a space suit and took a cup of water outside your pressurized spaceship, the water would almost immediately either freeze or evaporate away, or some combination of both (Figure 8.7). However, as we'll discuss shortly, Mars almost certainly had liquid water in the past, and still has ample water ice and some water vapor and perhaps even pockets of liquid water underground.

LEARNING OBJECTIVE
Seasonal Changes on Mars

MARTIAN SEASONS AND WINDS Recall that Earth has seasons because of the tilt of our planet's axis

TABLE 8.3 Basic Data for Mars and Earth

Characteristic	*Mars*	*Earth*
Average distance from Sun	227.9 million km (1.52 AU)	149.6 million km (1 AU)
Perihelion distance	206 million km	147.1 million km
Aphelion distance	249 million km	152.1 million km
Orbital period (Earth years)	1.881 yr	1 yr
Equatorial radius	3397 km	6378 km
Mass (Earth masses)	0.107	1
Rotation period	24 hr 37 min	23 hr 56 min
Axis tilt	25°	23.5°
Surface gravity (Earth units)	0.38	1
Atmospheric composition	95% CO_2, 2.7% N_2, 1.6% argon	77% N_2, 21% O_2, 1% argon, 0.4% H_2O (average), 0.04% CO_2
Average surface temperature	−50°C	15°C
Average surface pressure	0.007 bar*	1 bar

*1 bar ≈ sea level pressure on Earth

(Figure 8.8). Earth's axis remains pointed in the same direction (toward the north star, Polaris) throughout the year, which means the Northern and Southern Hemispheres are angled toward the Sun on opposite sides of Earth's orbit. It is summer when your hemisphere is angled toward the Sun, and winter when it is angled away.

Mars's axis tilt today is only slightly greater than Earth's (25° versus 23.5°), so Mars has seasons for the same basic reason. However, the martian seasons differ from Earth seasons in two important ways. First, because the martian year is nearly twice as long as an Earth year, each season lasts nearly twice as long on Mars. Second, while Earth's nearly circular orbit means that tilt is the only significant factor in our seasons, Mars's more elliptical orbit puts Mars significantly closer to the Sun during its southern hemisphere summer and farther from the Sun during its southern hemisphere winter (Figure 8.9). Mars's southern hemisphere therefore has more extreme seasons (shorter and warmer summers, longer and colder winters) than its northern hemisphere. (The seasons differ in length because planets move faster near perihelion and slower near aphelion, in accord with Kepler's second law [Section 2.2].)

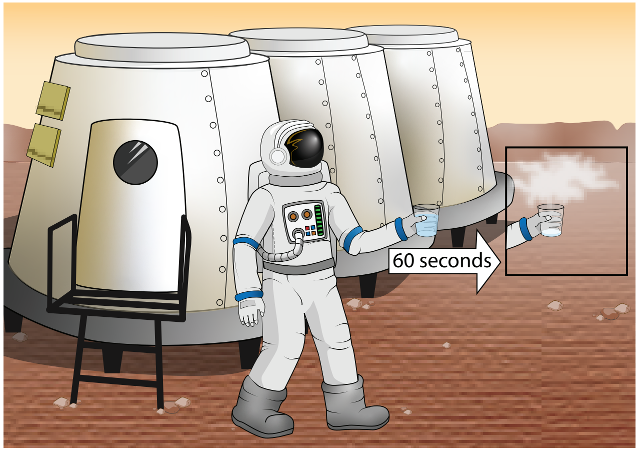


FIGURE 8.7
This illustration shows what would happen if you could take a cup of water outside on Mars. All the liquid water would quickly freeze or evaporate (or a combination of both).

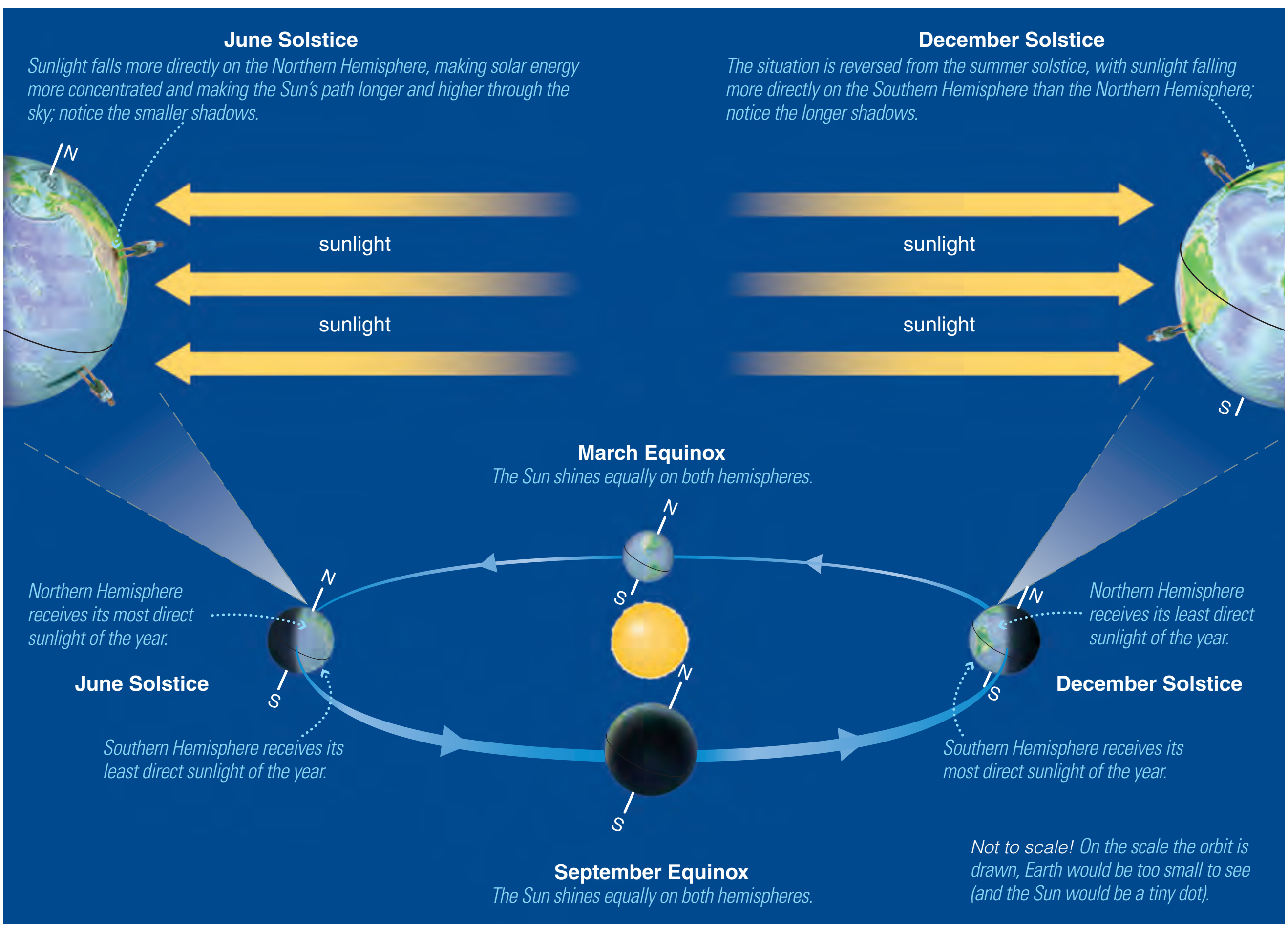


FIGURE 8.8
Earth's seasons are caused by the tilt of the axis. Notice that the axis points in the same direction (toward Polaris) throughout the year, which means the Northern Hemisphere is tipped toward the Sun on one side of the orbit and away from the Sun on the other side. The same is true for the Southern Hemisphere, but on opposite sides of the orbit.

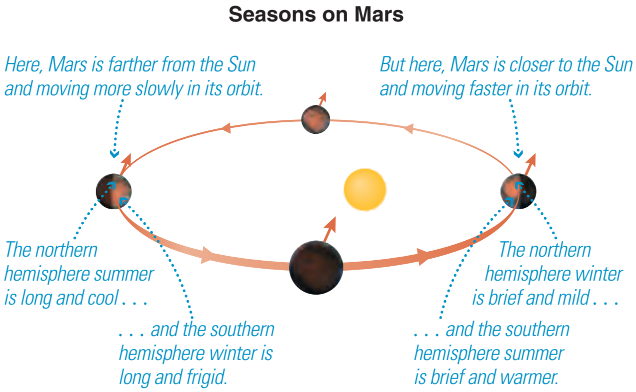


FIGURE 8.9
The ellipticity of Mars's orbit makes seasons more extreme in the southern hemisphere than in the northern hemisphere.

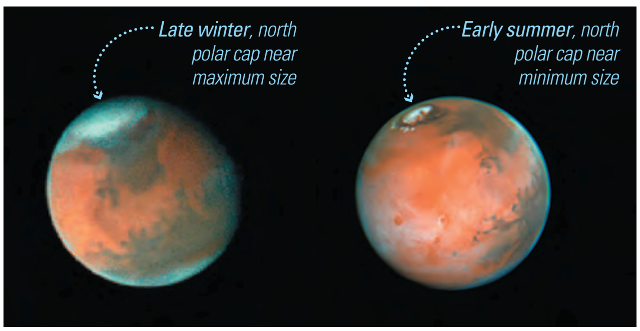


FIGURE 8.10
These images from the Hubble Space Telescope show the dramatic change in the size of the north polar ice cap with the martian seasons. (Mars is oriented slightly differently in the two photos.)

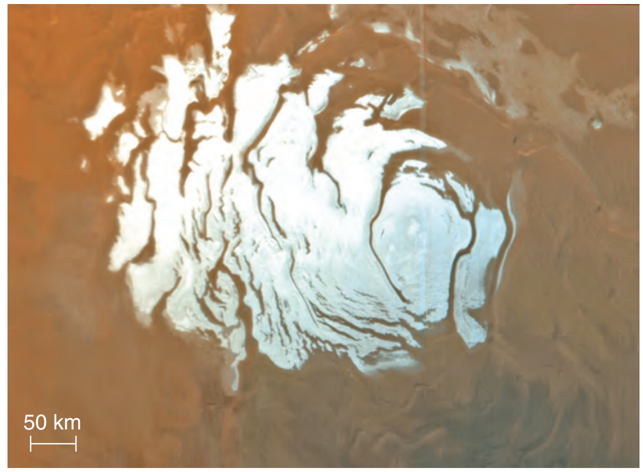


FIGURE 8.11
This image, from *Mars Global Surveyor,* shows the residual south polar cap during summer. A layer of frozen carbon dioxide around 8 meters thick overlies a much thicker cap of water ice. In winter, the whole area shown in the image is covered in CO_2 frost.

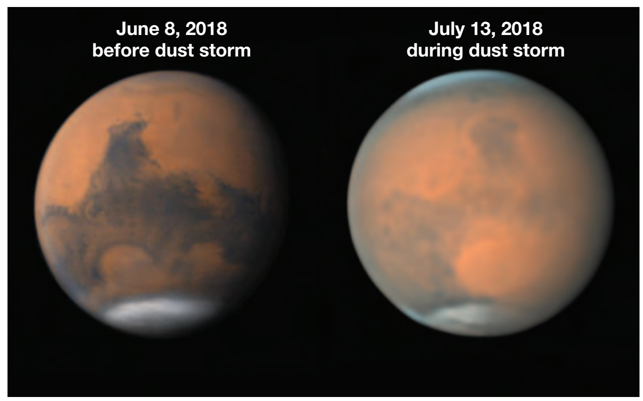


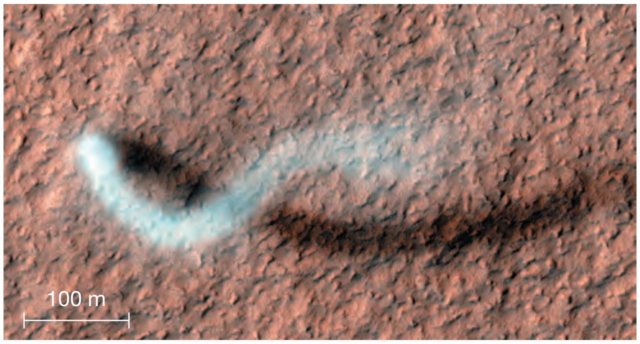
FIGURE 8.12
These two images contrast the appearance of the same face of Mars in the absence (left) and presence (right) of a global dust storm.

Seasonal changes lead to several major features of martian weather. Temperatures at the winter pole drop so low (about −130°C) that carbon dioxide condenses into "dry ice" at the polar cap; that is why the polar caps are so much larger in winter than in summer (Figure 8.10). Meanwhile, frozen carbon dioxide at the summer pole vaporizes into carbon dioxide gas,* and by the peak of summer only a residual cap of water ice remains (Figure 8.11). The atmospheric pressure therefore increases at the summer pole and decreases at the winter pole. Overall, as much as one-third of the total carbon dioxide of the martian atmosphere moves seasonally between the north and south polar caps.

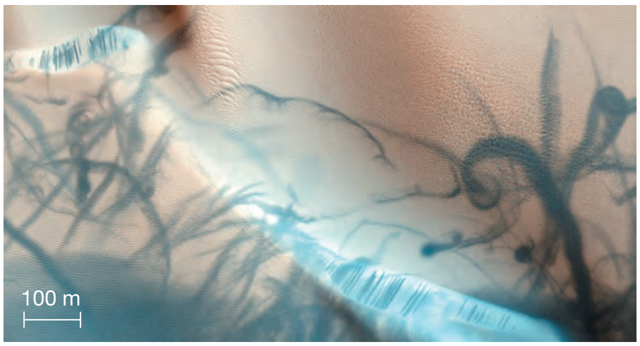
The strong winds associated with the cycling of carbon dioxide gas can initiate huge dust storms, particularly when the more extreme summer approaches in the southern hemisphere (Figure 8.12). At times, the martian surface becomes almost completely hidden by airborne dust. As the dust settles out, it can change the surface appearance over vast areas (for example, by covering dark regions with brighter dust); such changes fooled astronomers of the past into thinking they were seeing seasonal changes in vegetation.

Martian winds can also spawn *dust devils,* swirling winds that you may have seen over desert sands or dry dirt on Earth. Dust devils look much like miniature tornadoes, but they rise up from the ground rather than coming down from the sky. The air in a dust devil is heated from below by the sunlight-warmed ground; it swirls because of the way the rising air interacts with prevailing winds. Dust devils on Mars are especially common during summer in either hemisphere. While many are quite small, some can be far larger than their counterparts on Earth (Figure 8.13).

*Note that dry ice vaporizes directly from solid phase into gas phase, a process technically called *sublimation*. On Mars, the low atmospheric pressure means water ice sublimates directly into gas in the same way. If you are not familiar with dry ice sublimation, it is easy to obtain some dry ice at many grocery stores and watch this phenomenon for yourself, or you can find videos online.



a This image shows a dust devil in action, along with its shadow, as seen from orbit. The length of the shadow tells us that the dust devil extended to an altitude of at least 800 meters.



b This orbital image looks down on a set of tracks left behind by dust devils that moved across martian sand dunes. The dunes generally appear light in color because they are covered by reddish dust deposited by recent dust storms. The underlying sand is darker in color, so we see dark tracks where dust devils have swept the dust away.

FIGURE 8.13

Dust devils are common on Mars. Both images are from the *Mars Reconnaissance Orbiter.*

COLOR OF THE MARTIAN SKY Martian winds and dust storms leave Mars with perpetually dusty air, which helps explain the colors of the martian sky. The air on Mars is so thin that, without the suspended dust, the sky would be essentially black even in daytime. However, light scattered by the suspended dust tends to give the sky a yellow-brown color. Different hues can occur as the amount of suspended dust varies, and in the mornings and evenings. For example, the martian sunset photo that opens this chapter shows the scene approximately as it would look to the human eye (but with slightly exaggerated colors).

It's worth noting that the colors you see in spacecraft images are not necessarily what you would see with your eyes if you were actually on Mars. Spacecraft cameras carry many filters, some beyond the red or blue limits of human vision, and scientists must make choices in deciding exactly how to digitally "colorize" images from the cameras. Getting the color "right"—meaning how it would look to the human eye—can therefore be quite difficult. Moreover, the color choice isn't always intended to show what the eye might see, but instead to better bring out important features in the image, such as small differences in rock colors. For this reason, you may even see images from Mars that show a blue sky (look ahead to Figure 8.22, for example), though your eye would see it differently.

LEARNING OBJECTIVE
Geological Features of Mars

8.2.2 What are the major geological features of Mars?

The surface of Mars may be desolate and barren today, but it was not always so. Many surface features appear to have been shaped by liquid water, leading scientists to conclude that Mars must once have had a much more hospitable climate. Before we discuss the evidence for surface water and ideas about the climate history of Mars, it's useful to get our bearings by looking at the large-scale geographic features of the planet.

A MAP OF MARS Figure 8.14 shows the full surface of Mars, with the poles at the top and bottom and the equator running horizontally across the middle (in much the same way that an atlas shows the full globe of Earth). Study the map briefly, and familiarize yourself with major features such as the polar caps, the Tharsis Bulge, Valles Marineris, and the large impact crater known as Hellas Basin. You should also recognize many smaller impact craters, particularly in the southern hemisphere, and numerous large volcanoes—including Olympus Mons—which you can identify by their dome shapes and central calderas (the "craters" in the tops of volcanoes). To understand the scale of these features, recall that Mars is about half as large in diameter as Earth, so its surface area is about one-fourth that of Earth (surface area is proportional to the square of the radius). Because water covers about three-fourths of Earth's surface, we conclude that the total land area of Mars is about the same as the total *land* area of Earth.

Think About It Any flat map of a round world will distort some features; the map projection in Figure 8.14 (a *Mollweide projection*) allows *areas* of different features to be accurately compared. Find a similar projection of Earth and display it so that it is scaled correctly relative to Figure 8.14 (that is, twice as long and wide). Compare the sizes of various Mars features to the sizes of familiar features on Earth.

DIFFERING SURFACE REGIONS One of the most striking features in Figure 8.14 is the dramatic difference in terrain between the northern and southern hemispheres. The southern hemisphere is heavily scarred

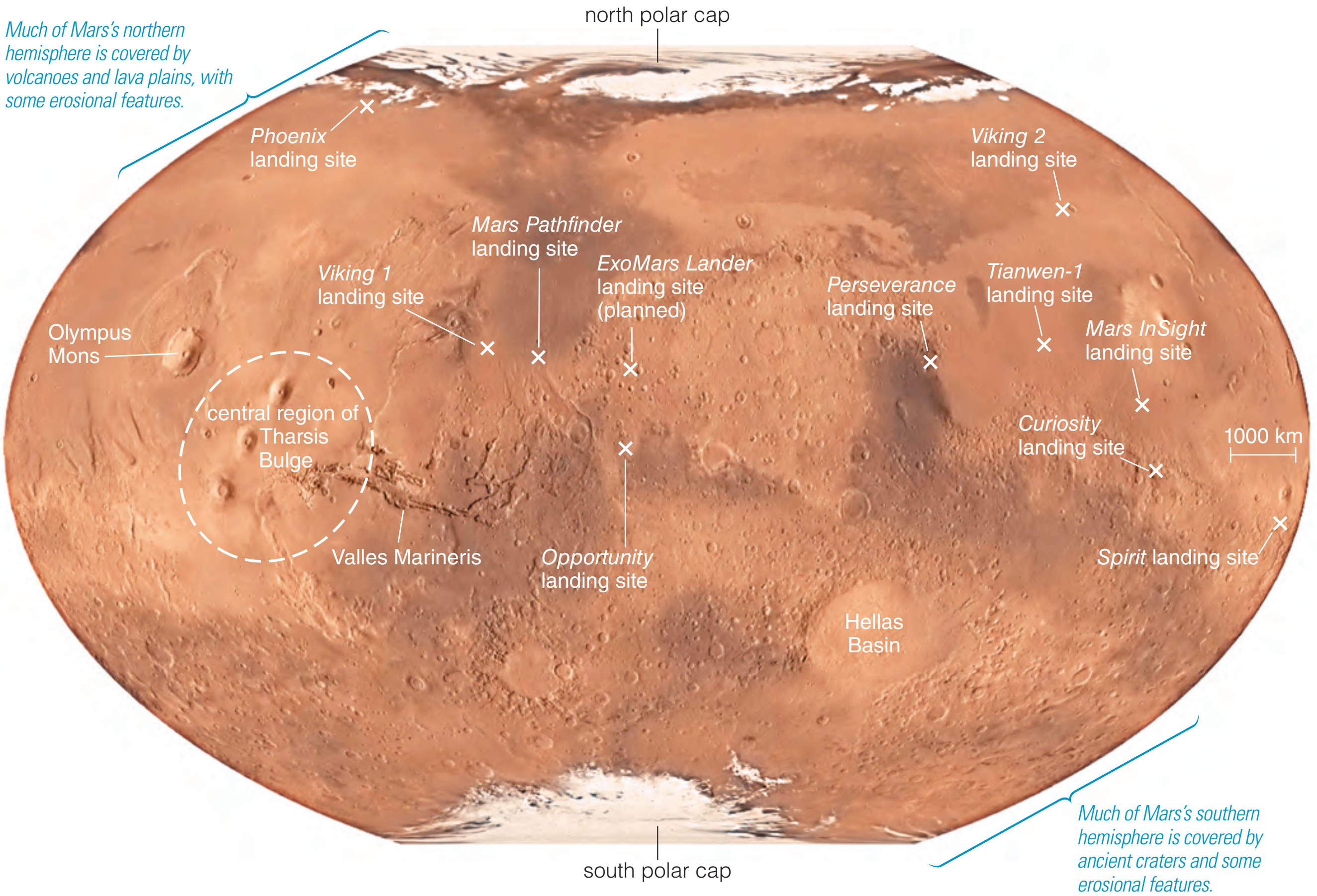


FIGURE 8.14

This image showing the full surface of Mars was made by combining more than 1000 images with more than 200 million altitude measurements from the *Mars Global Surveyor* mission. Several key geological features are labeled, and landing sites of Mars missions are marked. On the same scale, a map of Earth would be about twice as tall and twice as wide.

by impact craters, while craters are few and far between in the northern plains. The visible difference in cratering corresponds to general differences in elevation (Figure 8.15) and crustal thickness. Most of the northern hemisphere is well below the average martian surface level, and measurements indicate a relatively thin crust (about 40 kilometers thick) in these regions. In contrast, most of the southern hemisphere is high-altitude highlands residing on a thicker crust (about 80 kilometers thick). No one knows the reason for this "martian north–south dichotomy," though one hypothesis suggests a giant impact blasting away crust from the northern hemisphere..

Recall that differences in cratering tell us something about surface ages [Section 4.3]: Older surfaces are more heavily cratered than younger ones (because the "repaving" that covered a younger surface would have covered up old craters). We therefore conclude that the heavily cratered southern highlands are generally an older surface than the northern plains. More detailed crater counts have led planetary scientists to divide the surface of Mars into regions of three different ages (Table 8.4). The most

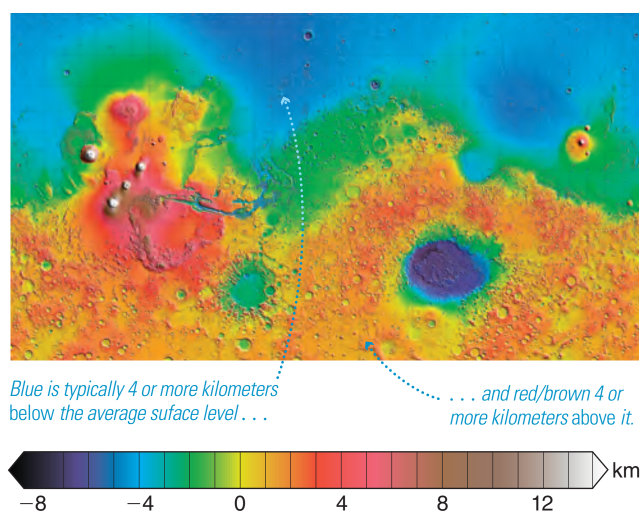


FIGURE 8.15

This map uses the same data as Figure 8.14, but it is color-coded to show differences in elevation (and uses a different projection, called *equirectangular*). Notice the striking difference in average elevation between the northern and southern hemispheres. In general, the crust is also thinner in regions with lower elevations than in regions with higher elevations

TABLE 8.4 Eras of Martian History

Era	*Time Period*	*Representative Surface Region*
Early (Noachian)	Before 3.7 billion years ago	Heavily cratered southern highlands
Middle (Hesperian)	About 3.7 to 3 billion years ago	Moderately cratered terrain south of the Tharsis region
Recent (Amazonian)	Less than 3 billion years ago	Lightly cratered northern plains; volcanic slopes

heavily cratered regions must still look much as they did about 3.7 billion years ago, shortly after the end of the heavy bombardment; these regions therefore represent the "early" era in the history of Mars (more formally called the Noachian ["no-AH-ki-an"] era, from Noah of the biblical flood story). Regions that are more moderately crowded with craters represent the "middle" (or Hesperian) era, which apparently ended about 3 billion years ago. The most lightly cratered regions, which include much of the northern plains and the lava-covered terrain around the Tharsis volcanoes, represent the "recent" (or Amazonian) era on Mars. Keep in mind that there is a great deal of uncertainty in ages based on crater counts, so the given age ranges for the three eras are only approximate. The timing of the end of the middle era (and beginning of the recent era) is especially uncertain and might be anywhere from about 3.5 billion to 2 billion years ago. More precise ages will be known only after we collect rocks from the different eras and measure their ages through radiometric dating [Section 4.2].*

Think About It Much like Mars, Earth's surface also has regions of different ages. Which regions of Earth's surface are generally the youngest? Explain.

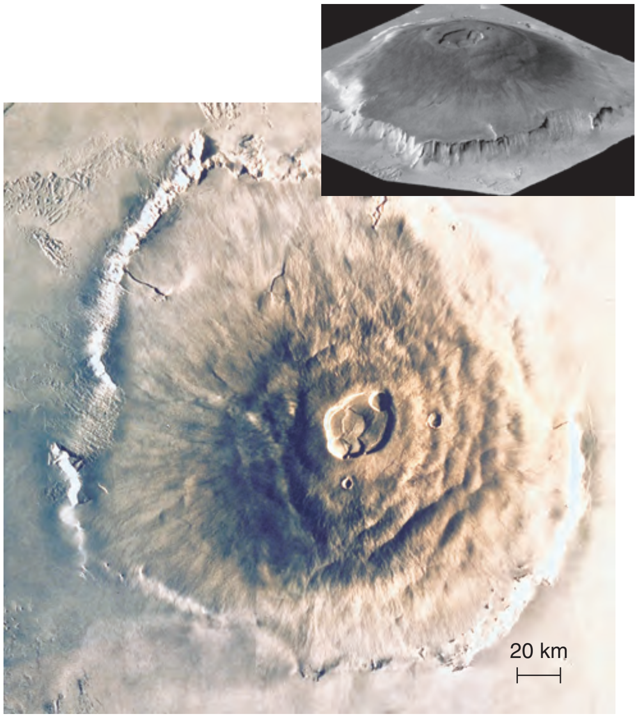
VOLCANISM AND TECTONICS ON MARS Mars shows abundant evidence of volcanism. The northern plains show features that are characteristic of lava flows, suggesting that eruptions of an extremely fluid lava covered up the older impact craters. Interestingly, we can see faint "ghost" craters in some of these regions, suggesting that the lava flows were not thick enough to completely erase the underlying features and confirming that the entire planet was once densely cratered. Plenty of mysteries remain, however. For example, no one knows why volcanism should have affected the northern plains so much more than the southern highlands, though perhaps it is a consequence of a thinner crust in northern regions. It's also possible that in some places the craters were erased by sedimentary rather than volcanic processes. In this case, the craters may have been submerged in sand and other martian material that was transported by wind and water, eventually building up layers of sediment that cover the landscape.

Regardless of their role in reshaping the northern plains, Mars boasts impressive volcanoes, many of which are concentrated on or near the continent-size Tharsis Bulge (some 4000 kilometers across). Most of Tharsis lies at least several kilometers above the average martian surface level, suggesting that it was created by a long-lived plume of rising mantle material that bulged the surface upward and provided the molten rock for the eruptions that built the giant volcanoes.

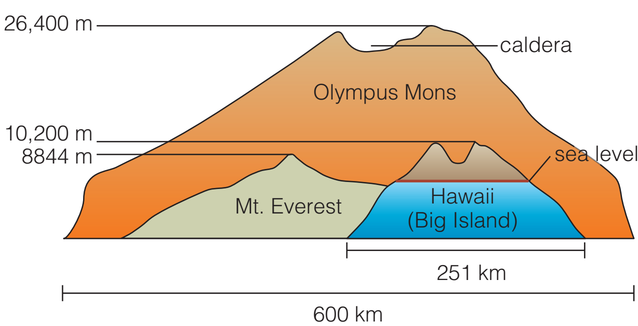
The Tharsis volcanoes dwarf any found on Earth. The largest of them, Olympus Mons (Figure 8.16), is the tallest known mountain in the solar system. Its peak rises about 26 kilometers above the average martian surface level, or about three times as high as Mt. Everest stands above sea level on Earth. Its base is some 600 kilometers across, large enough to cover an area the size of Arizona, and is rimmed by a cliff that in places is 6 kilometers high. Two factors probably explain why the martian volcanoes are so much larger than volcanoes on Earth. First, Mars's weaker gravity makes it easier for tall structures to be built up. Second, the lack of plate tectonics on Mars means that mantle plumes remain stationary relative to the surface, building up huge, single mountains. In contrast, the gradual motion of Earth's crust due to plate tectonics means that a single mantle plume tends to build a chain of volcanic islands (see Figure 4.22).

East of Tharsis and just south of the equator is the long, deep system of valleys called Valles Marineris (Figure 8.17). Named for the *Mariner 9* spacecraft that first imaged it, Valles Marineris is as long as the United States is wide and almost four times as deep as the Grand Canyon. No one knows exactly how Valles Marineris formed, but its location (see Figure 8.14) suggests a link to the Tharsis Bulge. Perhaps it formed through tectonic stresses accompanying the uplift of material that created Tharsis, cracking the surface and leaving the tall cliff walls of the valleys. A few

*Scientists have successfully used *Curiosity*'s on-board instrument called Sample Analysis on Mars (SAM)—which was designed for other purposes—to date a rock by looking at potassium–argon decay. The measured age (3.86 to 4.56 billion years old) had a fairly large uncertainty, but agreed with what had been expected from orbital data based on cratering rates. More important, it demonstrated that future rovers could be designed to do more such analysis.



a Olympus Mons, photographed from orbit. The inset shows a 3-D perspective view of this immense volcano.



b This diagram compares the size of Olympus Mons to those of Mt. Everest and the Big Island of Hawaii. The latter is shown as it appears starting from the bottom of the ocean, with the blue region indicating the part that lies below sea level.

FIGURE 8.16
Olympus Mons is the tallest known mountain in the solar system.

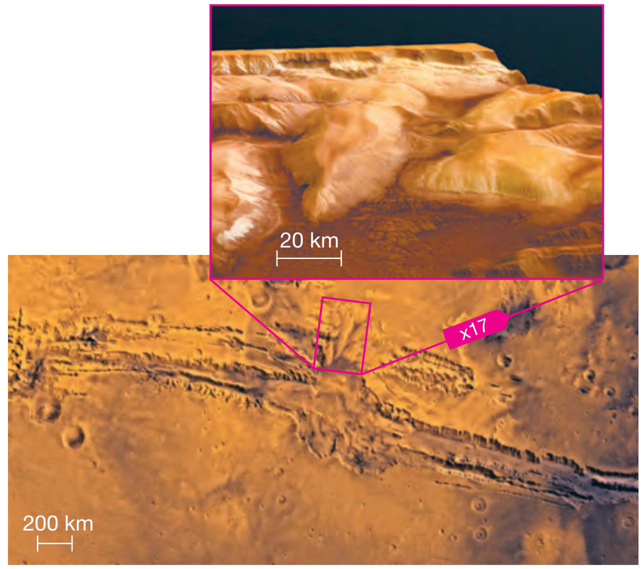


FIGURE 8.17
Valles Marineris is a huge system of valleys on Mars created in part by tectonic stresses. It extends nearly a fifth of the way around the planet (see Figure 8.14), and in some places is 10 kilometers deep. The inset shows a perspective view looking north across the center of the canyon.

features of the valley network appear to have been shaped by flowing water, and spectra from orbit show the presence of minerals likely to have formed in water. Some of the canyon walls also show evidence of layering that may have been caused by deposits of sediments, though the layering could also be due to repeated lava flows. In any event, the canyon is so deep that, if we are correct in assuming it was created by uplift, some of its walls must once have been several kilometers underground, where they may have been exposed to liquid water. For all these reasons, Valles Marineris may be one of the best places to look for fossil evidence of past martian life.

By examining the types of geological features that appear on surfaces of different ages on Mars, we can get an idea both of what processes helped shape the surface and of when they operated. For example, we can look at features that indicate volcanic eruptions, such as lava flows or volcanoes, and deduce the history of volcanism. Such studies suggest that the frequency of volcanic eruptions on Mars has decreased over time, just as we would expect for a planet small enough to have lost much of its internal heat by now.

We have not witnessed any ongoing volcanic or tectonic activity on Mars, and we expect Mars to be much less volcanically active than Earth, because its smaller size has allowed its interior to cool much more. However, the era of martian volcanism may not be completely over. Crater counts on the slopes of martian volcanoes suggest that some lava flows may have occurred as recently as tens of millions of years ago (and perhaps more recently than that), which is not so long ago in geological terms. In addition, radiometric dating of meteorites that appear to have come from Mars (so-called *martian meteorites* [Section 6.2]) shows some of them to be made of volcanic rock that solidified from molten lava as little as 180 million years ago, which is also fairly recent in the $4\frac{1}{2}$-billion-year history of the solar system. This suggests that Mars still retains some internal heat. No one knows if it is enough to cause the volcanoes to erupt again in the future, but it is almost certainly enough to melt some underground ice into liquid water.

LEARNING OBJECTIVE
Evidence for Past Water

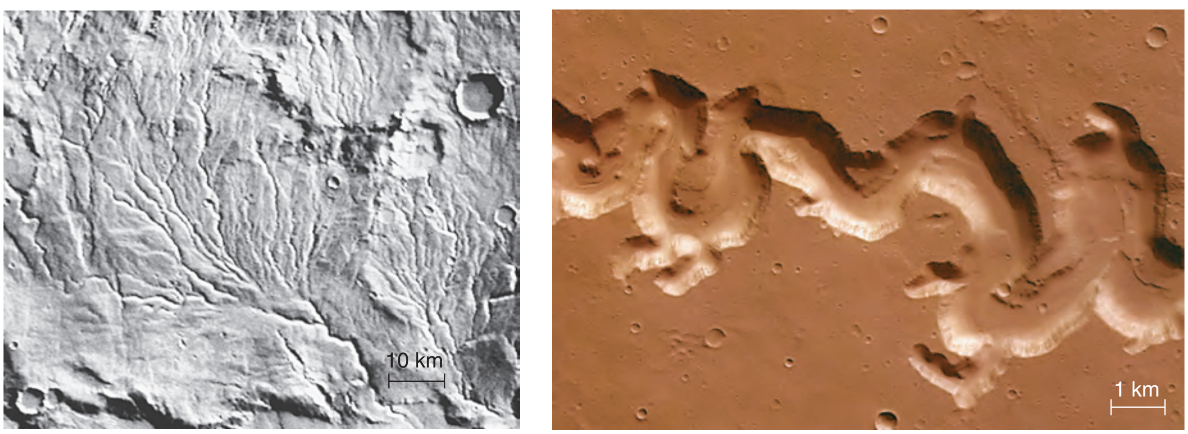
8.2.3 What evidence tells us that water once flowed on Mars?

We now turn our attention to the evidence that makes scientists confident that Mars once had substantial amounts of flowing water. It is this evidence that makes Mars a prime candidate in the search for past or present life beyond Earth.

ORBITAL EVIDENCE The first evidence of past water came from photos taken by *Mariner 9* and the *Viking* orbiters, some of which showed features that look much like dry riverbeds on Earth seen from above (Figure 8.18a). More recent orbiters have photographed these channels with much higher resolution (Figure 8.18b). Careful study indicates that the channels were almost certainly carved by running water, though no one knows whether the water came from runoff after rainfall, from erosion by water-rich debris flows, or from an underground source. Crater counts in and near the channels, along with study of the local terrain, indicate that the channels are in general at least about 3 billion years old, meaning that water has not flowed through most of them since that time. Nevertheless, they tell us an important story about the martian past: Their nature suggests they were carved over a long enough period of time that liquid water must have been stable at or just below the surface. Because the low temperature and atmospheric pressure make liquid water unstable today, we conclude that Mars must have had a warmer and thicker atmosphere during at least some times in its distant past.

Careful examination of impact craters also provides evidence that Mars had surface water long ago. Figure 8.19 shows just three among thousands of orbital images that provide evidence of water erosion. Figure 8.19a shows a broad region of the ancient, heavily cratered southern highlands. Notice the indistinct rims of many large craters and the relative lack of small craters. Both facts argue for ancient rainfall, which would have eroded crater rims and erased small craters altogether. Figure 8.19b is a computer-generated image of the surface that suggests water once flowed between two ancient crater lakes. The *Spirit* rover explored one of these craters, finding minerals that, as we'll discuss shortly, seem to confirm that the crater once held a lake. Figure 8.19c shows a portion of another ancient crater, called Jezero crater, where the orbital view clearly indicates the presence of a dried-up river delta. The *Perseverance* rover is currently exploring this region of Jezero crater.

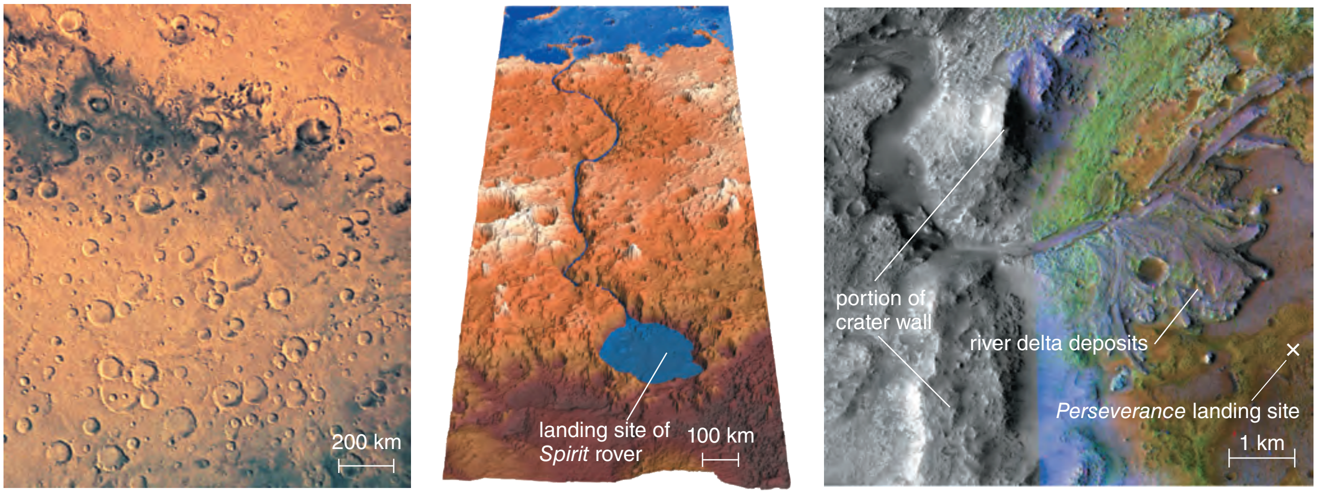
Additional evidence comes from multi-wavelength orbital images and spectra that tell us about the mineral composition of the martian surface. Scientists are particularly interested in what we call **hydrated minerals**, meaning minerals containing water or hydroxide (OH), which are presumed to form only in the presence of liquid water. Three general types of hydrated minerals have been found at numerous locations on Mars: (1) clay minerals, (2) hydrated sulfates, and (3) hydrated silica, more commonly known as opal. For example, the green color coding in Figure 8.19c indicates the presence of clay minerals that may have been deposited by sediments flowing down the river. The opaline minerals are particularly significant, for two reasons. First, they are thought to form in hot springs or hydrothermal



a This photo from a *Viking* orbiter shows what appears to be a network of tributaries flowing from the upper left into the larger "river" near the lower right.

b This photo, taken by the *Mars Express* spacecraft, shows what appears to be a meandering riverbed, now filled with dunes of windblown dust.

FIGURE 8.18
Mars has numerous channels that appear to be dry riverbeds. Notice the many small craters in the photos, which tell us that the riverbeds had dried up by at least about 3 billion years ago.



a This photo shows a broad region of the southern highlands. The eroded rims of large craters and the lack of many small craters suggest erosion by rainfall.

b This computer-generated image shows how a martian valley forms a natural passage between two possible ancient lakes (shaded blue). Vertical relief is exaggerated 14 times to reveal the topography.

c Combined visible/infrared image of the river delta in Jezero Crater, the landing site for NASA's *Perseverance* rover. The delta is located where a river flowed into a lake that may have filled the large crater (portions of the crater wall are identified). Clay minerals are identified in green.

FIGURE 8.19
More evidence of past surface water on Mars.

environments, which on Earth are environments thought likely to have been important to the origin of life [Section 6.1]. Second, some of the regions in which they are found appear to have formed as much as a billion years later than the thick, ancient clay deposits. If this interpretation is correct, the timing suggests that Mars remained wet for an extended period in its ancient history, giving more time for life to arise and evolve. Figure 8.20 shows a region where the *Mars Reconnaissance Orbiter* detected opal near Valles Marineris.

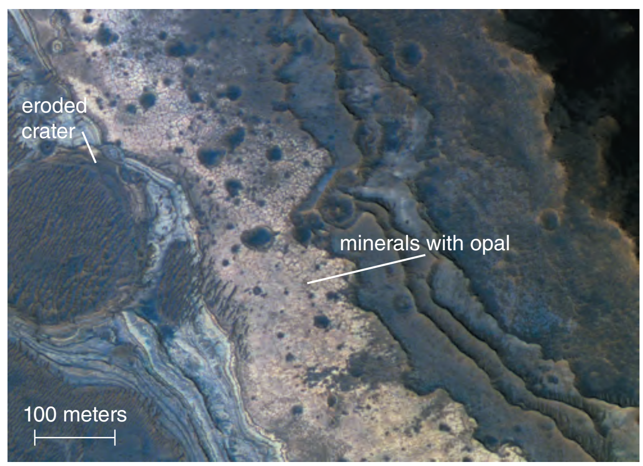
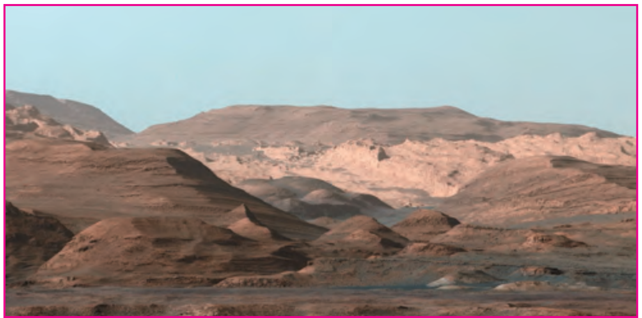


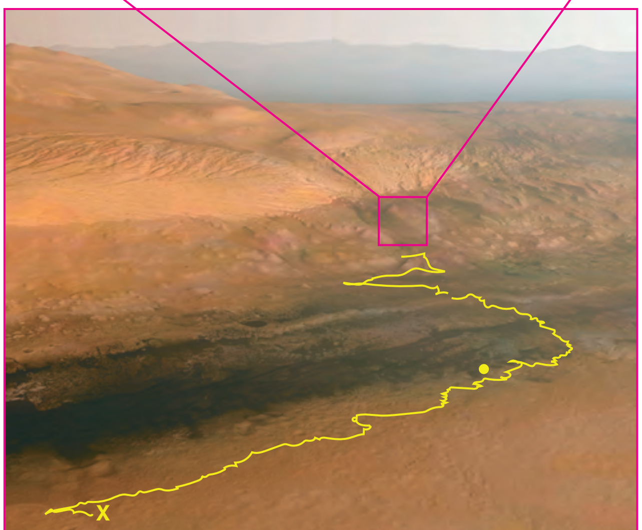
FIGURE 8.20
This color-coded image from the *Mars Reconnaissance Orbiter* shows one of many places where spectral data indicate the presence of opal, possibly formed in hot springs or similar environments.

SURFACE EVIDENCE Surface studies further strengthen the case for past water. In 2004, the robotic rovers *Spirit* and *Opportunity* landed on opposite sides of Mars (see Figure 8.14). The twin rovers long outlasted their design lifetime of 3 months, with *Spirit* lasting more than 6 years and *Opportunity* lasting for 14 years (until its solar power failed during the 2018 global dust storm pictured in Figure 8.12). Extending the streak of rovers that functioned far longer than scientists and engineers expected, the *Curiosity* rover was still going strong when this book went to press in early 2022, more than 9 years after its arrival on Mars. *Curiosity* has been exploring a site called Gale crater (Figure 8.21) with a set of scientific instruments that includes cameras, drills, microscopes, rock and soil analyzers, a laser to vaporize rock, and a spectrograph to analyze the vaporized material.

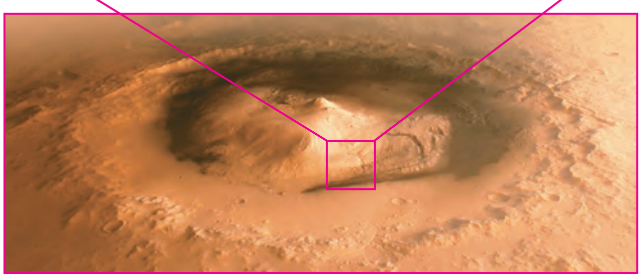
The most recent rover, *Perseverance*, landed on Mars on February 18, 2021, carrying an even more sophisticated set of instruments. These include a chemical analysis camera capable of detecting "biosignatures" (meaning molecules that might indicate past or present life) that organisms might have left behind in the rock layers; a spectral analysis tool to study carbon-bearing molecules and evaluate their possible biological roles; and an instrument package for testing a system to generate oxygen from local materials, which would be important for future human exploration of Mars. The rover also has a set of tubes for collecting soil samples that are intended to be retrieved by future missions for return to Earth; NASA



This image, taken in 2015, captures Curiosity's view looking up the river valley from the location indicated by the dot in the middle panel. (The blue sky color is an artifact of the image processing.)



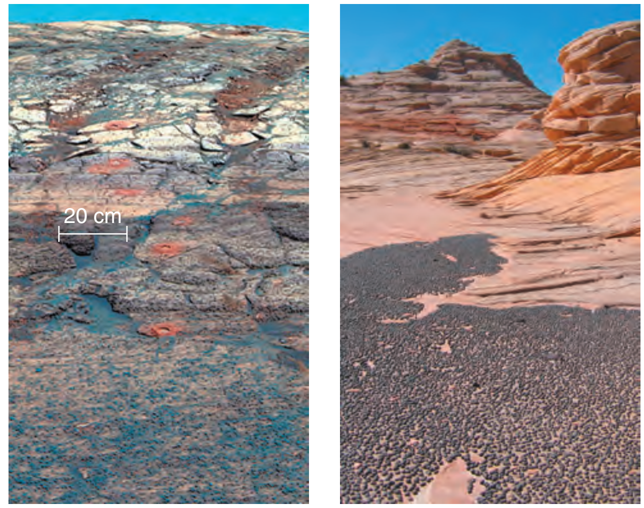
This expanded view shows the first 18 kilometers of the rover's path (yellow) as it traveled up an ancient river valley.



This image from the Mars Reconnaissance Orbiter shows Gale Crater and its central mountain, Mt. Sharp.

FIGURE 8.21

The *Curiosity* rover landed in Gale Crater in 2012 at the location marked by the X in the middle panel. *Curiosity*'s findings support the idea that more than 3 billion years ago, a lake filled the crater, allowing layered sedimentary rocks to build up from the crater floor. Later wind erosion exposed much of the crater while leaving the mountain at the center.



Mars (Endurance Crater) **Earth (Utah)**

FIGURE 8.22

Small hematite-containing spheres called "blueberries" (foreground) are found on both Earth and Mars. Those on Earth formed from sedimentary rock (like that in the background) in water, then later eroded out and rolled downhill. The martian "blueberries" probably formed similarly. The background rocks are about twice as far away from the camera in the Earth photo as in the Mars photo (taken by the *Opportunity* rover using a combination of infrared and visible light).

and the European Space Agency are collaborating in planning this return of the *Perseverance* samples.

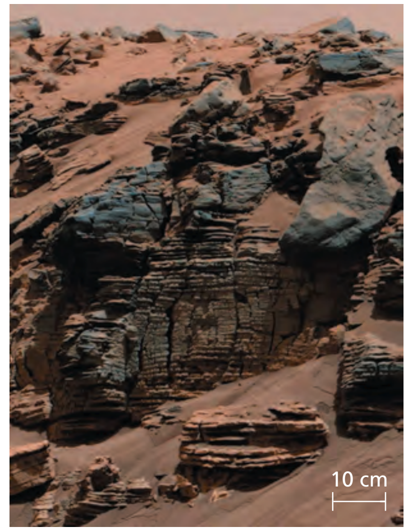
All of the rovers have found abundant mineral evidence of past liquid water. However, the character of the water appears to have differed at different sites. For example, *Opportunity* discovered tiny spheres—nicknamed "blueberries"—that have apparently eroded out of the underlying rock layers in much the same way as similar spheres found on Earth (Figure 8.22). The "blueberries" are composed largely of an iron-bearing mineral called *hematite*, while the rock layers in which they were embedded are rich in the sulfur-bearing mineral *jarosite*. Both of these mineral types form in salty, acidic water, suggesting that water like this once percolated through the rocks at *Opportunity*'s landing site.

In contrast, *Curiosity* found evidence that Gale Crater once contained much purer ("drinkable") water (Figure 8.23), at least at the lower elevations the rover explored during the first few years of its journey. The dry clay and sedimentary rocks clearly indicate that a lake once existed here, and the clumps of pebbles are so similar in structure and chemical composition to pebbles on Earth that they must have formed in an ancient streambed. *Curiosity's* chemical analysis of these sedimentary layers indicated that they contain minerals known to form only in water as pure as that found in most lakes on Earth.

Why would two different landing sites (those of *Opportunity* and *Curiosity*) have such a difference in the purity of the water they once held? Scientists suspect that the difference actually indicates a change in martian water with time. The region explored by *Curiosity* is thought to contain sediments laid down earlier in martian history, when the water was relatively pure, while *Opportunity* explored sediments laid

a *Curiosity* drilled into this rock formation of dry clay, finding minerals that should form only in water that was not very acidic or salty.

b These clumps of rounded pebbles show a structure nearly identical to that found in streambeds on earth, providing strong evidence that the pebbles were rounded by flowing water before being cemented together into rock.



c The even layers of the foreground rocks in this image from *Curiosity* are characteristic of sediments deposited over time in the delta of a river that emptied into a lake.

FIGURE 8.23
Evidence of past water in Gale Crater, from the *Curiosity* rover.

down later, after the water became saltier and more acidic. This hypothesis gained additional support as *Curiosity* continued its journey along the flanks of the 5-kilometer-tall Mount Sharp, where evidence indicates that the higher-elevation sediments formed in saltier and more acidic water. Orbital studies had already indicated that Mount Sharp was surrounded by sedimentary rock layers dating to many different times over the past several billion years; indeed, this was the major reason why this location was chosen as *Curiosity*'s landing site. *Curiosity*'s on-the-ground studies have now enabled scientists to piece together the following history at this site: A vast lake once filled Gale Crater, though it dried out more than 3 billion years ago. Sediments were deposited on the lake bottom in layers, ultimately filling much of the crater. More rock was then deposited on top by later volcanic eruptions, compressing the sediments. Over the three billion years since Mars dried out, winds eroded away much of the overlying rock, exposing the rock layers visible to *Curiosity*. The oldest layers, which are at the lowest elevations, formed when the water was relatively pure, and the younger and higher layers formed as the water became more acidic and less plentiful.

The *Perseverance* rover is already adding to the evidence for past water, even though it has been on Mars for less than a year as this book goes to press. *Perseverance* spent that time exploring its landing site and confirming the prior assumption that Jezero Crater was once filled by a lake and fed by a river. Images such as the one in Figure 8.24 make this clear, showing river sediments deposited in alternating horizontal and tilted layers that match what we see in river deltas on Earth. The lake must have been nearly 100 meters deep to leave these deposits. Most of the fine-grained material would have been deposited when slow, steady currents came to a stop on entering the lake. However, the rover also encountered refrigerator-size boulders deposited among finer sediments, which provide evidence for occasional flash floods; the floods sent the boulders tumbling from the crater rims some 50 kilometers away. This evidence of flooding suggests that martian weather once went through tumultuous cycles, something that still occurs on Earth.

Think About It Find the current status of the *Curiosity* and *Perseverance* rovers and look at images they have taken recently. Have they made any significant discoveries since this book went to press in early 2022?

THE EXTENT AND TIMING OF ANCIENT WATER The evidence for past liquid water on Mars seems quite strong. But was the water shallow and localized, or widespread and deep? Did it exist in liquid form only

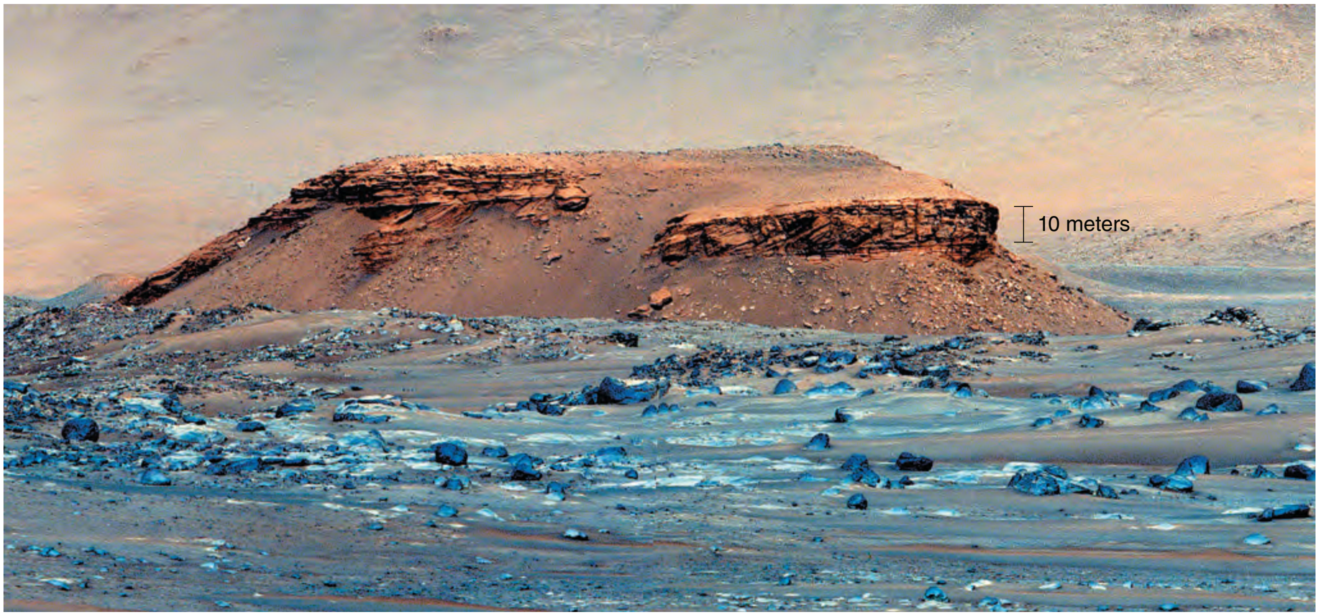


FIGURE 8.24
This mesa imaged by the *Perseverance* rover was once connected to the river delta in Figure 8.19c before billions of years of erosion had their way. Tilted layers in the orange rocks indicate that a river dumped its sediments here when a lake filled the crater. The blue color of foreground rocks is an artifact of the image processing. Distant crater walls are visible in the background.

intermittently, or were there lakes (or even oceans) that lasted for millions of years? Vigorous debate still surrounds these questions, and the martian surface seems to yield conflicting clues.

In many places, Mars shows evidence of having suffered large and catastrophic floods. For example, Figure 8.25 shows a region near the top of a long valley (called Ares Vallis) marked by outflow channels that look like channels carved by floodwaters on Earth. Tracing the channels upstream to their source reveals a landscape lacking anything that looks like a past lake or reservoir, suggesting that the floodwaters emerged from underground. The *Pathfinder* mission, which landed downstream of this region in 1997, provided support for this hypothesis by showing a surface that appears to be a vast floodplain, with rocks scattered and stacked against each other in the same way that we see them after floods on Earth (see Figure 8.5).

The timing and source of past floods are uncertain, but orbital images suggest a link between temporary heating events and some of the floods. Some channels may have been created after ice was melted by impacts. Others may be tied to ice melted by volcanic heating. Figure 8.26 shows a volcano with numerous downhill channels flowing outward in all directions from its central caldera. Toward the lower right, we see a much wider channel that was probably carved by floodwaters released during one or more eruptions. Such events might produce liquid water that flowed

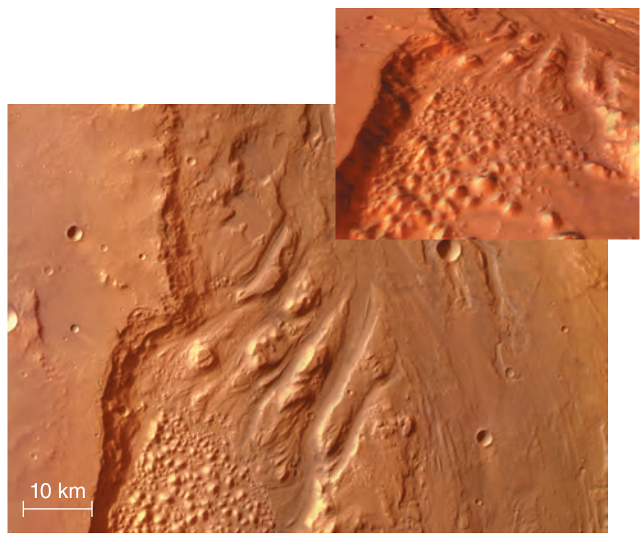


FIGURE 8.25
This image from Europe's *Mars Express* orbiter shows outflow channels likely carved by floodwaters. The inset is a perspective view of the region.

only for relatively short times, but with so much water released at once that it resulted in a large flood. Moreover, the evidence of flooding near volcanoes suggests that volcanic heat can create subsurface pockets of liquid water, offering potential habitats for life.

One way to estimate how much water might once have flowed on Mars is to look at water ice that still exists today. The polar caps are made mostly of water ice, overlaid with a thin layer (at most a few meters

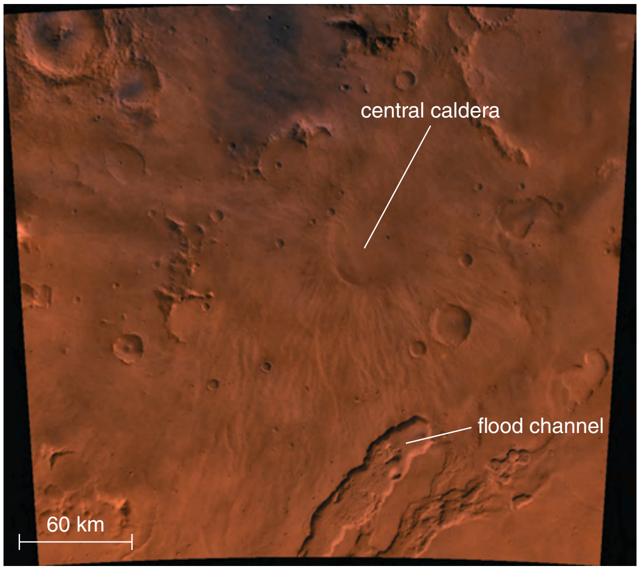
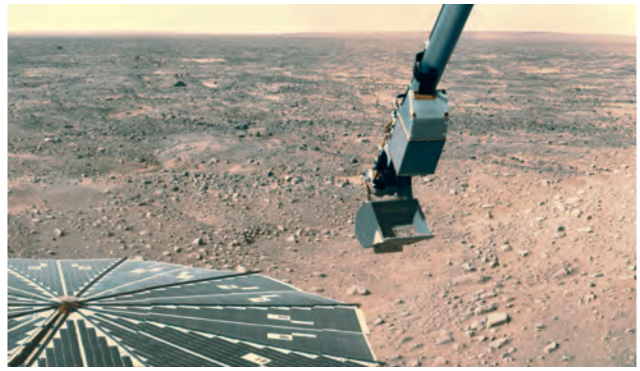


FIGURE 8.26
This photo from a *Viking* orbiter shows the volcano Hadriaca Patera; its central caldera is marked. Note the many channels flowing downhill from the caldera and the wide flood channel (called Dao Vallis) toward the lower right.



a The view from the *Phoenix* lander, showing part of its robotic arm.

b The robotic arm camera found a bright patch of water ice right under the lander; the lander's rockets (visible at top) had blasted away an overlying layer of dust.

FIGURE 8.27
The *Phoenix* lander reached Mars in 2008. Its landing site was in the martian "arctic" (latitude 69° N), but still several hundred kilometers south of the polar ice cap.

thick) of carbon dioxide ice (see Figure 8.11). Radar instruments on Mars orbiters have found substantial quantities of water frozen in vast layers of dusty ice surrounding both poles. The *Phoenix* lander, which landed several hundred kilometers from the north polar cap in 2008, even found a patch of surface ice directly underneath it (Figure 8.27). The *Phoenix* finding suggests that water ice is widespread in the arctic region, but not usually visible because it is mixed in with the surface soil or hidden just beneath a layer of dust.

Radar also indicates the presence of abundant icy glaciers at lower latitudes, where they are kept frozen by a protective layer of rocks and dust above the ice. Images support this idea. For example, Figure 8.28 shows a thick layer of exposed ice on the face of a mid-latitude (57° S) cliff. Note that it wouldn't take much digging to reach such ice, since the ice appears to extend to within a meter or two of the surface at the cliff top. Several similar icy cliffs have been observed elsewhere in the martian mid-latitudes, providing further evidence that water ice is abundant under the martian surface.

All in all, the total amount of ice now known to be on Mars represents (if melted) enough water to make an ocean averaging about 20 to 30 meters deep over the entire planet. But scientists have reason to suspect that far more water was present on Mars in the distant past.

Scientists can estimate how much water Mars has lost over time in several ways. One method uses measurements of the ratio of deuterium (hydrogen with a neutron) to ordinary hydrogen. As we'll discuss in more detail shortly, Mars may have lost water because ultraviolet light from the Sun split atmospheric water vapor molecules apart, allowing some of the lightweight hydrogen atoms to escape to space. Deuterium does not escape as easily as ordinary hydrogen because of its greater weight, so an elevated ratio of deuterium to hydrogen suggests that a lot of ordinary hydrogen has been lost to space. Studies of the current ratio of deuterium to hydrogen suggest that Mars once had significantly more water, perhaps enough to cover the entire surface to a depth of more than 50 meters. Additional water may have been absorbed into Mars's crust, where it may still reside today, chemically locked away in rocks. Indeed, some scientists studying geological evidence suggest that Mars once had enough water to cover the surface to a depth of 500 meters. The bottom line is clear: While much more research will be needed to pin down an accurate value for the total water once present on Mars's surface, it was almost certainly enough to fill an ocean.

Of course, the depth of any past ocean would not be expected to have been uniform over the whole planet, because it would have depended on the martian topography. This has led some scientists to hypothesize that Mars once had a vast, deep ocean where its low-elevation northern plains are now (Figure 8.29). Evidence for such an ocean includes data suggesting that many of the largest flood channels drained into the northern plains and geographic features that look like they could mark an ancient shoreline. In addition, radar data suggest that the rock along the possible shoreline is sedimentary rather than volcanic, just as we would expect if it had once been at the edge of an ocean.

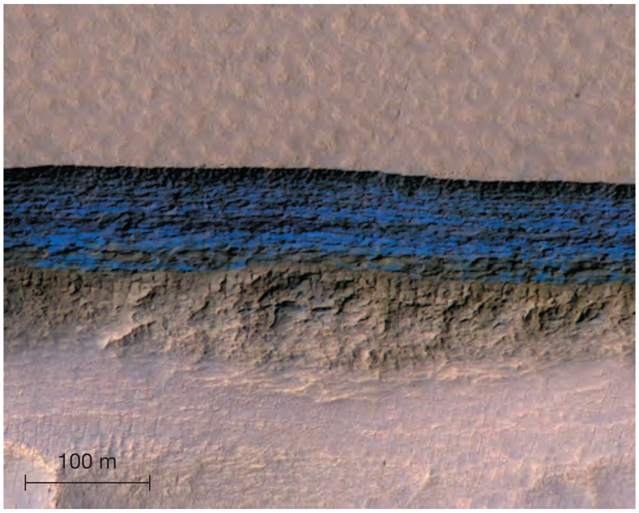


FIGURE 8.28
This enhanced color image from the *Mars Reconnaissance Orbiter* shows an approximately 80-meter-thick layer of water ice (blue) exposed on the face of a steep, mid-latitude (57° S) martian cliff.

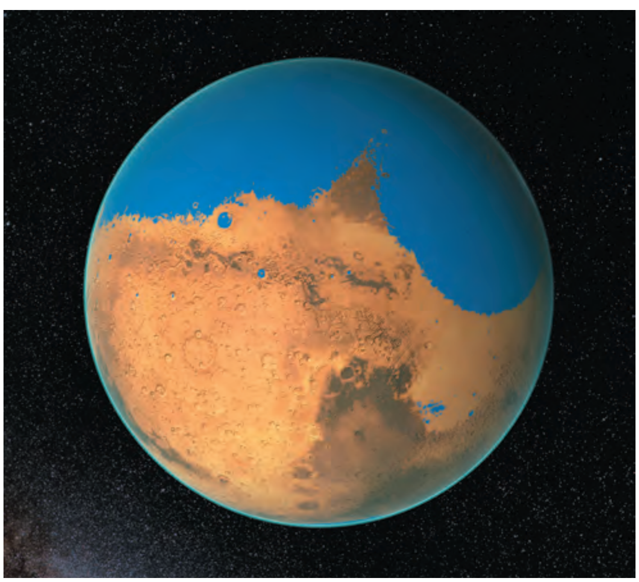


FIGURE 8.29
Mars's northern hemisphere may once have held a vast ocean; this artist's conception shows what it might have looked like some 4 billion years ago.

Think About It Do a Web search for "ocean on Mars" and look for the latest news about the hypothesis. Overall, do you think an ancient ocean seems likely? Why or why not?

The overall question of the persistence of liquid water on Mars remains unsettled, though the recent discoveries by *Curiosity* and *Perseverance* are beginning to tilt scientific opinion toward the idea that surface liquid water persisted for millions of years. Learning whether this is the case will have important implications for the possibility of past or present life on Mars. If lakes and rivers were present only intermittently, then these periods of surface habitability may have been too short for life to arise. But if habitable lakes or oceans were present for millions of years, life might have had a chance to take hold and perhaps to evolve sufficiently so that it could survive to this day in any available pockets of subsurface liquid water. Either way, it is important to remember that the period of widespread surface liquid water ended at least about 3 billion years ago.

MARTIAN WATER TODAY Although Mars clearly had plenty of liquid water in the distant past and still has plenty of water ice today, it is an open question as to whether there is any liquid water on Mars today. A few years ago, some scientists thought they had found evidence of liquid water flows in orbital images showing gullies and dark streaks on many crater walls (Figure 8.30); these features look much like similar features found on Earth in places where water flows

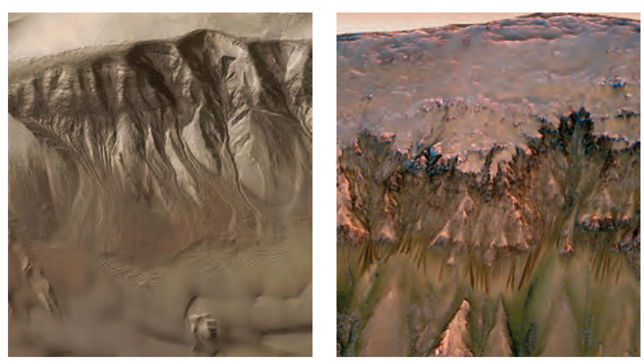


FIGURE 8.30
Many crater walls on Mars have gullies or dark streaks that look like features formed on Earth by flowing water. However, recent evidence suggests that the martian features are more likely formed by dry sand or dust, rather than water. Both images are from the *Mars Reconnaissance Orbiter.*

downhill. Such flows are possible in principle, as long as they are short-lived: Remember that liquid water is unstable on Mars today, but can last for a short time before it freezes or evaporates. The images seemed to suggest that near-surface ice was melting and flowing downhill for a short time until it refroze or vaporized. However, more recent study of these features suggests that they were formed either by the seasonal vaporization of carbon dioxide frozen onto the surface, or by dry sand or dust slipping down a slope, as happens on sand dunes.

A more promising potential location for liquid water is underground. As we've discussed, Mars should still have enough internal heat to keep water in liquid form in at least some places. In fact, radar images from the European Space Agency's *Mars Express* orbiter contain bright spots (places where the radar is strongly reflected) that some scientists have interpreted as representing subsurface lakes of salty water, perhaps somewhat like Lake Vostok, which is buried under the Antarctic ice on Earth. This interpretation is controversial, however, as other scientists have suggested that clays, metal-bearing minerals, or even salty ice could be responsible for the radar reflections.

If any liquid water is still present under the surface of Mars, the total amount must be a tiny fraction of the water that flowed on the surface when riverbeds and lakes were formed long ago. Mars clearly was warmer and wetter at times in the past than it is today. Ironically, Percival Lowell's supposition that Mars was drying up has turned out to be basically correct, although in a very different way than he imagined.

LEARNING OBJECTIVE
Climate History of Mars

8.3 The Climate History of Mars

While we have much left to learn about water in Mars's past, the evidence we've discussed makes it seem clear that liquid water was stable or nearly stable on the martian surface during at least some time periods prior to about 3 billion years ago. For that to have been possible, both the atmospheric pressure and the temperature must have been significantly higher than they are today. Mars in the past offered a much more hospitable climate than it does now, and perhaps one in which life could have arisen and taken hold.

8.3.1 Why was Mars warmer and wetter in the past?

It's easy to conclude that Mars must have been warmer and wetter in the past, but more challenging to explain why. The basic answer is presumably the greenhouse effect. Recall that the greenhouse effect can make a planet's surface much warmer than it would be otherwise. A moderate greenhouse effect keeps our own planet Earth from freezing over [Section 4.5], while an extremely strong greenhouse effect is responsible for the blistering temperatures on Venus [Section 7.2].

Today, Mars has such a thin atmosphere that it has only a weak greenhouse effect, despite the fact that 95% of its atmosphere is composed of the greenhouse gas carbon dioxide (see Table 8.3). However, Mars almost certainly had a much stronger greenhouse effect in the past. Calculations suggest that martian volcanoes should have outgassed enough carbon dioxide to make the atmosphere about 400 times as dense as it is today (and enough water to fill oceans tens to hundreds of meters deep).

If Mars had this much carbon dioxide today, it would have a surface pressure about three times that of Earth and a temperature above freezing; in other words, Mars would have a climate in which liquid water could flow. However, because we think that the Sun was dimmer in the distant past [Section 4.5], even more greenhouse warming would have been needed to allow for liquid water when Mars was young. Current models are unable to account for the necessary additional warming with carbon dioxide gas alone. Many scientists hypothesize that additional warming was provided by a greenhouse effect due to carbon dioxide ice clouds or methane and/or sulfur gases. Alternatively, perhaps Mars never had an extended period of warmth, but instead had only intermittent wet periods, possibly triggered by the heat of large impacts or volcanic action. But even in this case, the evidence we've found for extensive water flows means that Mars's atmosphere must have been much thicker and warmer in the distant past than it is today.

8.3.2 Why did Mars change?

Given that Mars must once have had a much denser atmosphere with a much stronger greenhouse effect, we can explain the current extremely different conditions only if Mars somehow lost a vast quantity of carbon dioxide gas. This loss would have weakened the greenhouse effect until the surface of the planet essentially froze over. Where did all this gas go? Some of the carbon dioxide condensed to make the polar caps, some may be chemically bound to surface rock, and some still makes up the martian atmosphere today. However, the bulk of the gas was probably lost to space.

LOSS OF CARBON DIOXIDE AND WATER The precise way in which Mars lost its carbon dioxide gas is not clear, although some gas was almost certainly blasted away by large impacts. However, the leading hypothesis suggests that an even more important gas loss mechanism was linked to a change in Mars's magnetic field (Figure 8.31). Early in its history, Mars probably had molten, convecting metals in its core, much like Earth today [Section 4.4]. The combination of this convection with Mars's rotation should have produced a magnetic field and a protective magnetosphere. The magnetic field would have weakened as the small planet cooled and core convection ceased, leaving the atmosphere vulnerable to solar wind particles. More specifically, the hypothesis suggests that carbon dioxide molecules were dissociated into carbon and oxygen atoms by sunlight or chemical processes, and the resulting atoms were then stripped away by the solar wind.

This hypothesis has been put to the test by the *MAVEN* mission, which has been orbiting Mars since 2014 and measuring the rate at which gases escape from Mars's atmosphere today. The first two panels of Figure 8.32 show results demonstrating that Mars is indeed losing the carbon and oxygen atoms that once made up carbon dioxide molecules, supporting the idea that Mars has lost substantial amounts of carbon dioxide gas through this process over the past few billion years.

Much of the water once present on Mars is also probably gone for good. Like the carbon dioxide, some water vapor may have been lost through stripping by the solar wind. In addition, Mars lost water in another way. Because Mars lacks an ultraviolet-absorbing stratosphere, atmospheric water molecules would have been easily broken apart by ultraviolet light from the Sun. The lightweight hydrogen atoms that broke away from the water molecules would have been lost rapidly to space through *thermal escape*, which is the process in which low-mass gas atoms can reach escape velocity and escape into space [Section 4.4]. The third panel of Figure 8.32 confirms the loss of hydrogen atoms in this way, and as we discussed earlier, the deuterium-to-hydrogen ratio lends further support to the idea that a lot of hydrogen was lost to space. Once the hydrogen atoms were lost, the water molecules could not be made whole again. Initially, oxygen from the water molecules would have remained in the atmosphere, but over time this oxygen was lost, too. Some was probably stripped away by the solar wind, and the rest was drawn out of the atmosphere through chemical reactions with surface rock. This process literally rusted the martian rocks, giving the "red planet" its distinctive tint.

In summary, the hypothesis we have described suggests that Mars changed primarily because of its relatively small size (see Do the Math 8.1, p. 265). It was big enough for volcanism and outgassing to release plenty of water and atmospheric gas early in its history, but too small to maintain the internal heat needed to create a strong magnetic field and a magnetosphere that could prevent this loss of water and gas. As its interior cooled, its volcanoes quieted and released far less gas into the atmosphere, while its relatively weak gravity and the loss of its magnetic field allowed existing gas to be stripped away to space. If Mars had been as large as Earth, so that it could still

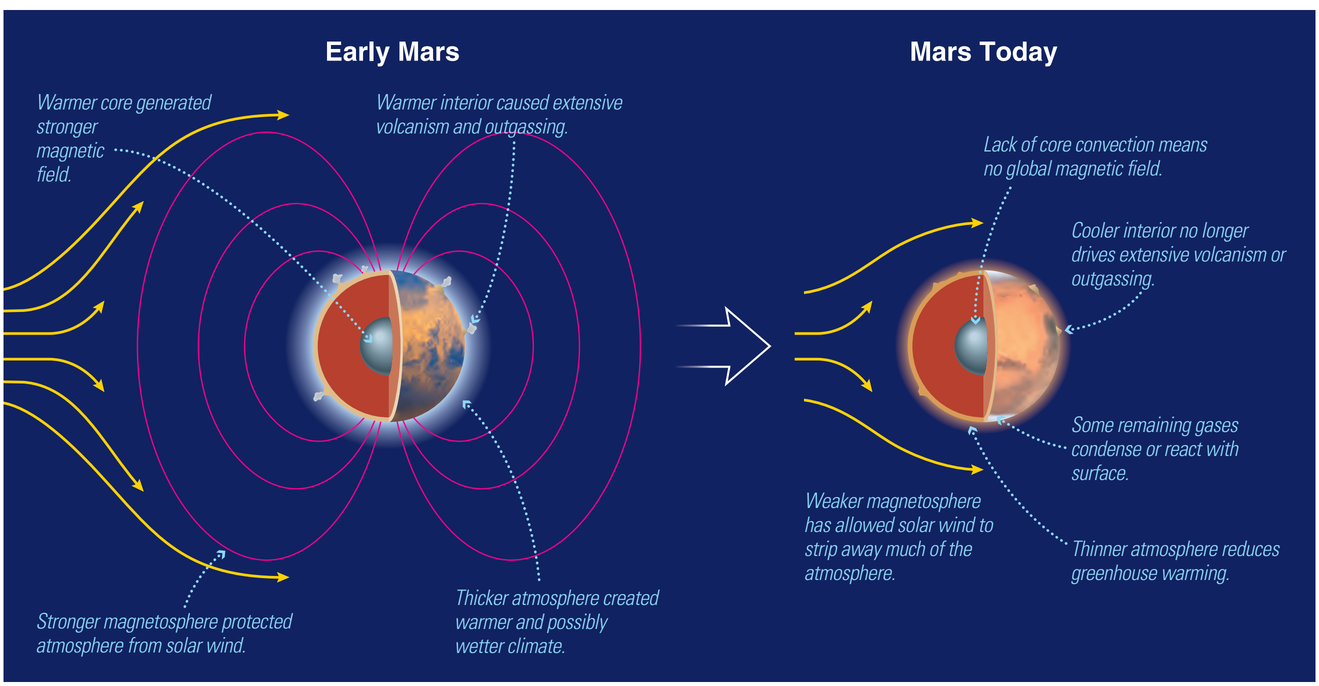


FIGURE 8.31
About 3 billion years ago, Mars underwent dramatic climate change, probably because it lost its global magnetic field, leaving its atmosphere vulnerable to the solar wind.

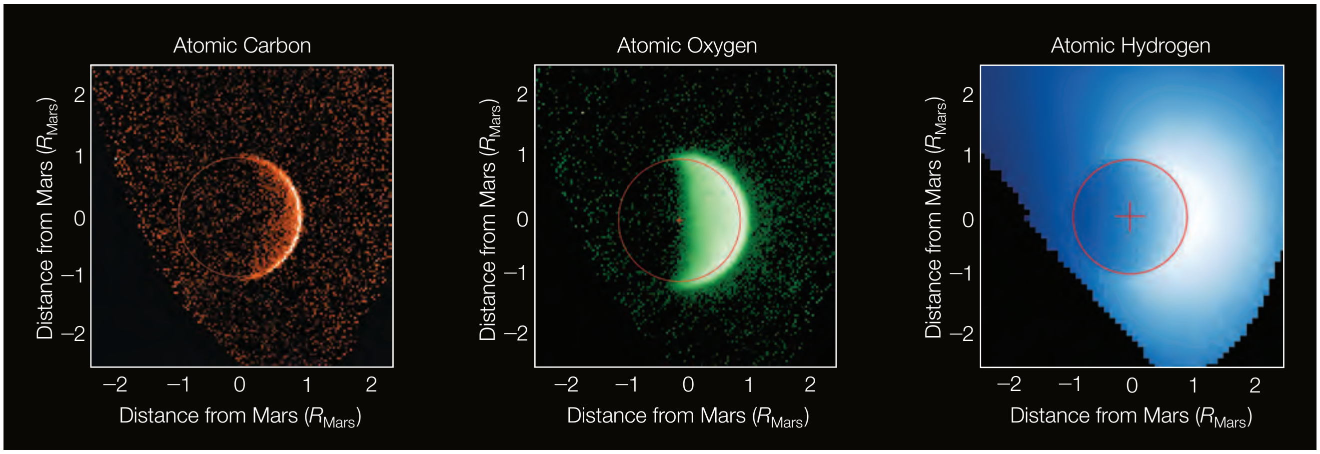
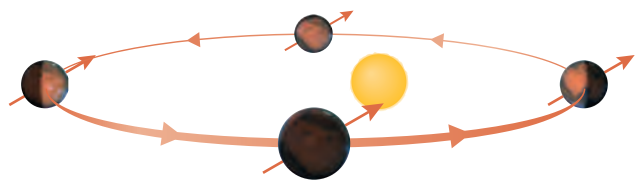


FIGURE 8.32
These ultraviolet images from NASA's *MAVEN* spacecraft show carbon, oxygen, and hydrogen atoms (which came from the dissociation of carbon dioxide and water molecules) in the martian atmosphere; the red circle shows the size of Mars, and black areas lack data. Notice that the atomic gases extend high above the surface, where some of the carbon and oxygen is escaping through solar wind stripping and hydrogen is being lost to thermal escape. Hydrogen extends the highest because light gases move fastest.

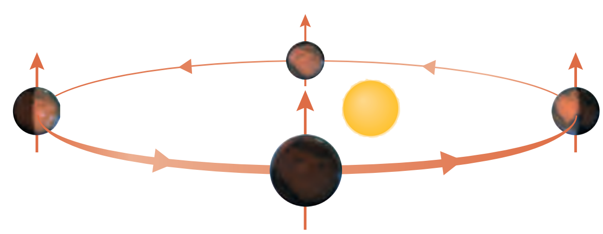
have outgassing and a global magnetic field, it might still have a pleasant climate today. Mars's distance from the Sun also helped seal its fate: Even with its small size, Mars might still have surface liquid water if it were significantly closer to the Sun, where the extra warmth could melt the water that remains frozen underground and at the polar caps.

MARS CLIMATE AND AXIS TILT With the gas that once warmed the planet now gone, there is little hope that Mars will ever again have a warm, wet climate (not counting the possibility of terraforming, which we'll discuss shortly), and aside from its occasional planet-wide dust storms, the planet's weather varies little from year to year. However, both theoretical and observational studies suggest that Mars undergoes longer-term cycles of climate change on time scales of hundreds of thousands to millions of years. This climate change arises from changes in axis tilt, and it may have significant implications for the potential habitability of Mars.

Recall that Earth experiences long-term climate cycles, such as ice ages, due to small changes in its rotation and orbit, including small changes in axis tilt. Earth's axis tilt doesn't change much—varying only between about 22° and 25°—because our large Moon exerts a gravitational pull that helps stabilize it. Mars lacks a large moon, and its two tiny moons (Phobos and Deimos) are far too small to offer any stabilizing influence on its rotation axis. In addition, because Mars is closer to Jupiter (compared to Earth), Jupiter's gravity more strongly perturbs Mars as it orbits the Sun. This effect may be further magnified by the fact that Mars is less perfectly spherical than any other planet (as evidenced by measurements of small differences in gravity over different regions).



a When the axis is highly tilted, the summer pole receives fairly direct sunlight and becomes quite warm.



b When the axis tilt is small, the poles receive little sunlight at any time of year.

FIGURE 8.33
Mars's axis tilt probably varies dramatically, causing climate change because of the effect on the seasons.

Calculations suggest that the lack of a stabilizing moon and the effects of Jupiter together may cause the martian axis tilt to vary over time from 0° to as much as 60°, which means that the current 25° is near the middle of the range. These changes in tilt would have dramatic effects on the climate (Figure 8.33). When the tilt is small, the martian poles may stay in a perpetual deep freeze for tens of thousands of years, which means much of the carbon dioxide now in the atmosphere is instead frozen at the poles.

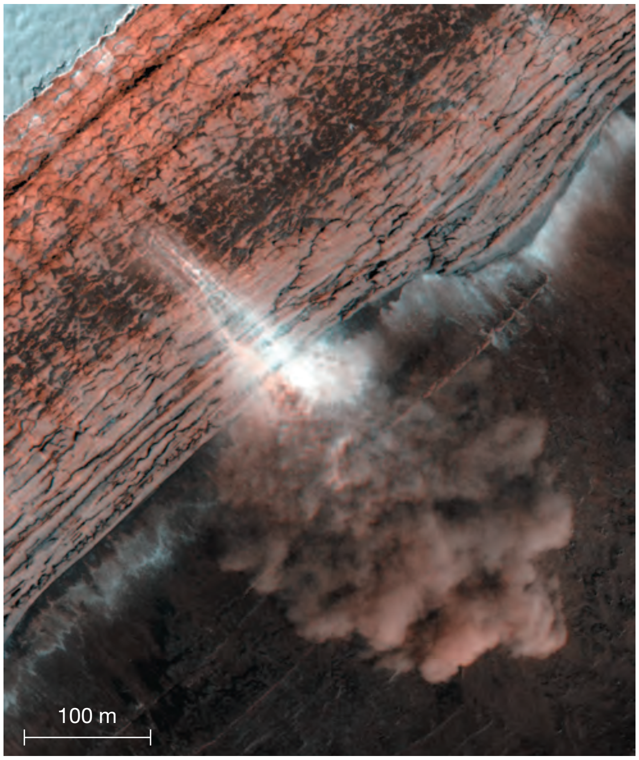


FIGURE 8.34
The *Mars Reconnaissance Orbiter* captured this image of a landslide in layered terrain in the north polar region. Despite the dark appearance, water makes up the bulk of the material. Layers of dusty ice more than 700 meters thick built up over many cycles of climate change. During the northern spring (of 2010), warming conditions apparently weakened the cliff walls and triggered this and other landslides.

The atmosphere therefore becomes thinner, which lowers the pressure and weakens the greenhouse effect. When the tilt is large, the summer pole becomes warm enough to allow frozen carbon dioxide and substantial amounts of water ice to vaporize into gas, thereby raising the atmospheric pressure and warming the planet through the stronger greenhouse effect. The martian polar regions show layering of dust and ice that probably reflects changes in climate due to the changing axis tilt (Figure 8.34).

Even at the greatest tilts, the atmospheric pressure probably does not become high enough to allow liquid water to pool in surface lakes or ponds. Nevertheless, models suggest that liquid water might form just beneath the surface or at rock/ice boundaries on the surface whenever the tilt is greater than about 40°, implying that Mars could have zones of liquid water during those time periods.

Do the Math 8.1

THE SURFACE AREA–TO–VOLUME RATIO

The total amount of heat contained in Mars or any other planet depends on the planet's *volume*, but this heat can escape to space only from the planet's *surface*. As heat escapes, more heat flows upward from the interior to replace it, until the interior is no hotter than the surface. Therefore, the time it takes for a planet to lose its internal heat is related to the ratio of the *surface area* through which it loses heat to the *volume* that contains heat:

$$\text{surface area–to–volume ratio} = \frac{\text{surface area}}{\text{volume}}$$

A spherical planet (radius r) has surface area $4\pi r^2$ and volume $\frac{4}{3}\pi r^3$ so the ratio becomes

$$\underset{\text{(for a sphere)}}{\text{surface area–to–volume ratio}} = \frac{4\pi r^2}{\frac{4}{3}\pi r^3} = \frac{3}{r}$$

Because r appears in the denominator, we conclude that *larger objects have smaller surface area–to–volume ratios*. (Although we've considered a sphere, this idea holds for objects of any shape.)

Example: Compare the surface area–to–volume ratios of the Moon and Earth.

Solution: Dividing the surface area–to–volume ratios for the Moon and Earth, we find

$$\frac{\text{surface area–to–volume ratio (Moon)}}{\text{surface area–to–volume ratio (Earth)}} = \frac{3/r_{\text{Moon}}}{3/r_{\text{Earth}}} = \frac{r_{\text{Earth}}}{r_{\text{Moon}}}$$

The radii of the Moon and Earth are $r_{\text{Moon}} = 1738$ km and $r_{\text{Earth}} = 6378$ km:

$$\frac{\text{surface area–to–volume ratio (Moon)}}{\text{surface area–to–volume ratio (Earth)}} = \frac{6378\ \cancel{\text{km}}}{1738\ \cancel{\text{km}}} = 3.7$$

The Moon's surface area–to–volume ratio is nearly four times as large as Earth's, which means the Moon would cool four times faster if all else were equal. In fact, Earth has retained heat much longer, because its larger size gave it more heat to begin with and because Earth has a higher proportion of radioactive elements. (See Problem 48 at the end of this chapter for a similar analysis of Mars.)

8.3.3 Is Mars habitable?

Mars clearly has the elements needed for life, and energy is available for life in the form of sunlight (on the surface) and chemical energy (underground). The question of whether Mars is habitable therefore hinges on the availability of liquid water.

The geological evidence strongly suggests that Mars once had abundant liquid water at its surface, meaning that the surface *was* habitable some time before about 3 billion years ago. In particular, findings from the *Curiosity* rover clearly indicate a habitable environment in Gale Crater around 3.5 billion years ago. The only question is whether it was habitable for a long period of time—making an indigenous origin of life seem plausible—or only for shorter, intermittent periods. As we have discussed, there is still debate on this question, though recent findings make it seem increasingly likely that liquid water was present for millions or tens of millions of years. In that case, the young Mars may have been quite similar to the young Earth, with a habitable environment during the same time period in which life arose on Earth [Section 6.1].

The *surface* of Mars is no longer habitable, because of the lack of liquid water (as well as the lack of ozone or other gases to absorb solar ultraviolet light). However, we've noted that pockets or even lakes of liquid water could still exist underground, as a result of remaining internal heat, so it is possible that Mars still has underground zones of habitability. Moreover, the climate changes tied to the changing martian axis tilt imply that these zones may reach to rock/ice boundaries at the surface during some time periods. On Earth, we find microbes that live in thin films of liquid water at such boundaries, which opens the intriguing possibility that similar life might be found on Mars.

Unless we are drastically misinterpreting the evidence, the conclusion seems clear. The surface of Mars was habitable during some periods of its early history, and it might still sometimes be habitable when the axis tilt is greater. Moreover, the subsurface probably has been habitable throughout the planet's history and may still contain habitable zones today. Given the apparent habitability of Mars, it is time for us to turn our attention to the search for actual life.

8.4 Searching for Life on Mars

While we have some confidence in the past and present habitability of Mars, we do not yet know whether Mars has ever actually had life. The only way to learn whether life existed in the past is to search for fossil evidence in martian rocks, and the only way to learn whether life exists today is to find it. To date, only very limited searches for life have been carried out on Mars, but many more are planned for the future.

LEARNING OBJECTIVE

Claims for Evidence for Martian Life

8.4.1 Is there any evidence of life on Mars?

The discovery of life on Mars would forever alter our view of life in the universe, so it should be no surprise that many scientists are working hard in hopes of being the first to discover evidence for life on Mars. As we'll discuss, a few scientists have already claimed to have found such evidence. But have they interpreted data correctly, or are they engaged in the same type of wishful thinking that led Percival Lowell astray?

The answer is the subject of heated scientific debate, but the vast majority of scientists are skeptical of any claimed evidence for martian life. Nevertheless, it is worth examining the claims, both to illustrate why there is scientific controversy and because they may point us toward ways of resolving the question in the future.

The claims of evidence of life fall into three main categories: claims based on results from the *Viking* landers, claims based on evidence of methane in the martian atmosphere, and claims based on studies of martian meteorites found on Earth. We'll examine the first two categories here; we'll save discussion of the martian meteorites for Section 8.5.

THE *VIKING* EXPERIMENTS One obvious way to search for life on Mars is to study the soil to see whether it contains living microbes. This type of search was first carried out by the two *Viking* landers in 1976. Each of the landers was equipped with materials for four onboard, robotically controlled experiments, along with a robotic arm for scooping up soil samples (Figure 8.35) to test in the experiments. The arm could push aside rocks to get at shaded soil that was less likely to have been sterilized by ultraviolet light from the Sun.

The first experiment (the *carbon assimilation experiment*) mixed a sample of martian soil with carbon

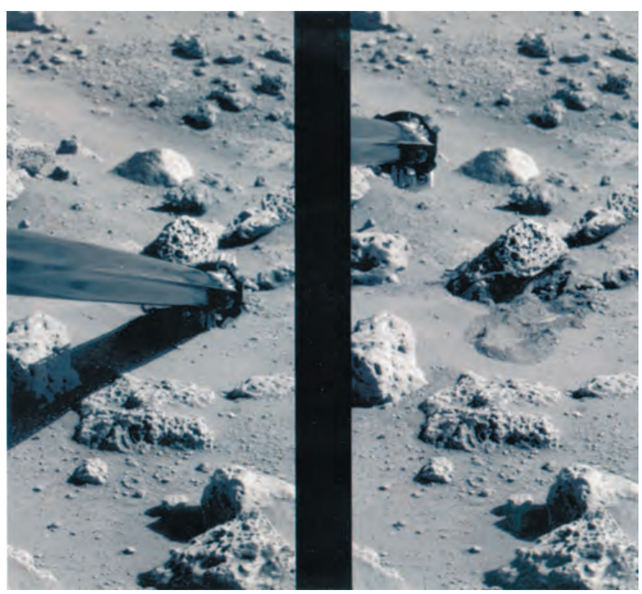


FIGURE 8.35
This pair of before (left) and after (right) photos from the *Viking 2* lander shows how the robotic arm pushed away a small rock on the martian surface. (You can see the entire robotic arm in the inset of Figure 8.4.)

dioxide (CO_2) and carbon monoxide (CO) gas brought from Earth. (In some runs of the experiment, the soil was also mixed with water.) The carbon dioxide and carbon monoxide from Earth could be distinguished from the same gases in the martian atmosphere because they had been "tagged" with radioactive carbon-14. Results showed that the carbon-14 became incorporated into the soil, which at first seemed to suggest that life was present and was using the carbon for metabolism. However, when the experiment was repeated with soil heated to 175°C (347°F), the tagged carbon still became incorporated into the soil. Because 175°C is hot enough to break chemical bonds between carbon and other atoms—and presumably to kill any carbon-based organisms—most scientists concluded that a chemical rather than a biological process was responsible for all the experiment's results.

The second experiment (the *gas exchange experiment*) mixed martian soil with a "broth" containing organic nutrients from Earth. As soon as the soil was exposed to the nutrients, oxygen was released from the mixture, a result that seemed to suggest a process of photosynthesis. However, the process occurred in the dark rather than in sunlight, making photosynthesis seem implausible. Moreover, oxygen was released even when the soil was exposed only to water vapor (rather than to the nutrients), and as in the first experiment, the reactions continued even when the soil was heated to temperatures that should have killed any organisms present. Again, most scientists concluded that the results were due to chemical and not biological processes.

The third experiment (the *labeled release experiment*) provided the most intriguing results. This experiment also mixed martian soil with organic nutrients from Earth, which were tagged with radioactive carbon-14 and sulfur-35. It then looked for changes in the level of radioactivity in the gas in the experimental chamber that might occur if living organisms consumed the nutrients and released the tagged, radioactive gases. Just as would be expected if life were present, the radioactivity rose at first and then leveled off as the nutrients were used up. Moreover, in contrast to the cases of the first two experiments, heating of the soil in this experiment produced results consistent with life: Heating to 50°C (122°F) substantially reduced the amount of radioactivity, and heating to 160°C (320°F) eliminated any sign of the tagged isotopes in the chamber gas.

The seemingly contradictory results of the first three experiments were further exacerbated by the fourth (the *gas chromatograph/mass spectrometer experiment*), which sought to measure the abundance of organic molecules in the martian soil. This experiment found no sign of organic molecules in the martian soil, seemingly ruling out the possibility of carbon-based life in the samples studied.

Movie Madness THE MARTIAN

There was a time, not long ago, when the term *Martian* was synonymous with "space alien." Red Planet natives were frequently found at the local cinema, busily destroying Earth and ruining everyone's whole day.

But today we know that real Martians, if there are any, would be smaller than a flake of dandruff and condemned to spend their lives floating around in dark, underground water. Such a dull existence is inconsistent with the demands of A-list actors. So in the space opera *The Martian*, the title character, Mark Watney (played by Matt Damon), is, despite the film's title, actually an Earthling.

Watney's dilemma is that he has been abandoned by his astronaut buddies. A fierce wind storm has blown through their campsite, and Watney, clobbered by some airborne debris, is presumed dead. His fellow astronauts, ignoring the military injunction to leave no one behind, scramble into their rocket, crank the motor, and bid adieu to the Red Planet.

That would be the end of the movie, except that Watney is not yet toes up. He has survived, and has perforce become the sole multicellular life form on the entire planet. Rather than pounding his chest as the top dog on Mars, Watney starts figuring a way to survive long enough to get back to Earth.

Now as an aside, it's worth noting that while winds can blow at something like 300 kilometers per hour on Mars, the atmosphere is only 1 percent as dense as on Earth. The pressure of even a fierce wind would be piddling, not even enough to flutter a flag.

But Watney doesn't spend time pondering this factual incongruity because he's busy trying to grow some potatoes to eat. An all-spud diet may be repetitious, but eight out of ten astronauts agree it beats starving. (Incidentally, there's another factual *faux pas* here. The perchlorates in the martian soil would probably kill potato plants. But audiences just don't care.)

The rest of the film revolves around the working out of Watney's ingenious plan to return to Earth. This entails first getting himself to Schiaparelli Crater, 3000 kilometers away. Audiences are treated to an imaginative visualization of what it would be like to go for the mother of all treks on Mars. It's kind of like the yellow brick road, except it's red. And fortunately for the film's audience, who might otherwise wonder what Watney is thinking, he frequently talks to himself. Perhaps he was an only child.

Does Watney make it? Well, you could always see the movie or read the book to find out. Suffice it to say that Watney's body will not be found by the *Perseverance* rover.

More recent results from the *Phoenix* lander and *Curiosity* rover may have finally solved the mystery of the *Viking* results. The martian soil contains a salt known as *perchlorate,* which, when heated, releases oxygen and chlorine that can destroy organic molecules. *Curiosity* has found strong evidence that the martian soil *does* contain at least some organic molecules—though, rather than having a biological source, these might have been brought by meteorites—suggesting that the reason *Viking* failed to find organics was because they were destroyed by heating the perchlorate. The chemistry of perchlorate also appears to explain the conflicting results of the other *Viking* experiments.

The bottom line is that scientists now generally regard the *Viking* results as inconclusive and recognize that different experiment designs will be needed for more definitive searches for life on Mars.

METHANE ON MARS Atmospheric studies can also provide clues about potential life, and scientists have been particularly intrigued by a mystery surrounding the apparent detection of methane (CH_4) in the martian atmosphere. Methane gas could not last more than a few centuries in the martian atmosphere before chemical reactions would transform it into other gases.* Therefore, if methane is present, Mars must have an active source of methane gas. On Earth, the predominant source of atmospheric methane is life. Could methane on Mars also be a sign of life?

Claims of methane gas detection were first announced in 2003 and 2004, based on telescopic observations from Earth and measurements from the *Mars Express* orbiter. Subsequent telescopic observations suggested that the methane level varies with time. However, the signals were weak enough that many scientists doubted the claims. Scientists hoped that the *Curiosity* rover could put the controversy to rest with measurements on the ground, and the results appeared to do just that: *Curiosity* has indeed detected methane gas at the surface of Mars as it has traveled through Gale Crater. The detected level is quite low: Typically, the methane concentration that *Curiosity* has measured is less than 0.5 part *per billion*, meaning that you'd have to collect about 2 billion molecules of martian air to find just 1 molecule of methane, though the methane concentration occasionally spikes to as high as 20 parts per billion.

If the occasional spikes detected by *Curiosity* weren't baffling enough, an added mystery came after the 2018 arrival of the European Space Agency's *ExoMars Trace Gas Orbiter*, or *TGO* for short. Making better measurements of the methane concentration in Mars's atmosphere was one of the primary goals of *TGO*'s mission, but it found essentially none at all at the altitudes where it can make measurements, which are about 5 kilometers above the surface. How could *Curiosity* be detecting methane at the surface while *TGO* found none—at least within its detection threshold of about 0.05 part per billion—higher in the atmosphere?

A possible answer to this question was proposed in mid-2021. The instrument on *Curiosity* that measures methane requires a lot of power, and as a result it generally makes measurements only during the martian nights, when other instruments are not being used. In contrast, the remote sensing instrument used by *TGO* to measure methane works only in sunlight, which means *TGO* is measuring methane during the martian day. The explanation for the conflicting data could then be as follows: If the methane seeps out of the ground, it could build up near the surface during the martian nights, when the atmosphere is generally calmer, explaining the measurable concentrations detected by *Curiosity*. As this methane rises upward, it becomes so diluted in the larger volume of the martian atmosphere that it is undetectable to *TGO*.

This explanation seems to make sense, but it leads to one more mystery: Although methane can't last more than a few centuries in the martian atmosphere, the amount detected by *Curiosity* should still build up enough in that time to make a measurable concentration throughout the atmosphere. So the lack of detection by *TGO* seems to further imply that methane is destroyed in the martian atmosphere faster than scientists would expect.

To summarize, current data (as of 2022) suggest that there is indeed a subsurface source from which methane seeps out of the ground—and this source is variable with time—but there is also some process that destroys the methane fairly quickly. From the standpoint of astrobiology, it is the source that is the most interesting. Only two sources are known that could account for the variable ground seepage: geological activity or life. Life might emit methane in seasonal or other cyclical patterns, while geological sources might release differing amounts of gas depending either on seasonal changes or on winds that plugged or unplugged holes from which gases could escape from underground.

Either way, the presence of methane has important implications for the possibility of life. Even if the source is geological rather than biological, the amount of volcanic heat necessary for methane release would probably also be sufficient to maintain pockets of liquid water underground. That would make the

*The methane would be oxidized to form water and carbon dioxide; this oxidation would occur because the martian atmosphere always contains some amount of free oxygen made by the breakup of atmospheric carbon dioxide molecules.

possibility of a habitable environment more likely. And, of course, if the source is biological, it should be only a matter of time until we are able to identify the organisms responsible.

LEARNING OBJECTIVE
Searching for Life on Mars

8.4.2 How do we plan to search for life on Mars?

The world scientific community has ambitious plans for continued exploration of Mars. The orbits of Earth and Mars bring the two planets to closest approach about every 26 months (Figure 8.36), and scientists hope to take advantage of upcoming alignments to send new and ever more sophisticated spacecraft to Mars. The ultimate goal of these missions is to answer the question of whether life on Mars has ever existed.

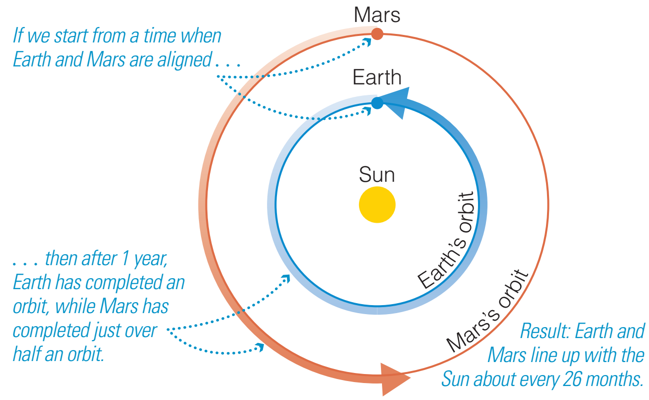


FIGURE 8.36
Mars takes almost 2 years to orbit the Sun, compared to Earth's 1 year. So if you start from an alignment as shown here, after 1 year Earth will be back in the same place, but Mars will be only halfway around. It takes a second year before the two planets line up again. Using Mars's more precise orbital period of 1.88 years, we find the alignments occur every 780 days, or about 26 months, which is why there is a "launch window" for missions to Mars approximately every 2 years.

UPCOMING MISSION PLANS Several new missions in various stages of development are designed to build upon the successes of recent and ongoing missions.

The next launch window, in late 2024 with arrival at Mars in 2025, is currently scheduled to include Japan's *Martian Moons eXploration* mission (*MMX*), which is designed to scoop up a sample from Mars's moon Phobos and return it to Earth, and NASA's *Escape and Plasma Acceleration and Dynamics Explorers* (*EscaPADE*) mission. The latter consists of two orbiters that will build on results from the *MAVEN* mission to help scientists understand the climate history of Mars. Also tentatively scheduled for this launch window is India's second Mars orbiter, called *Mangalyaan 2*. This window will hopefully also include the European Space Agency's *Rosalind Franklin** rover and Russia's *Kazachok* lander, which were delayed from a joint 2022 launch by the outbreak of war as this book went to press. The rover will be equipped with a drill that should be able to collect samples from depths up to 2 meters beneath the surface, and will be able to perform on-board experiments that will search for potential biosignatures in the samples.

SEARCHING FOR LIFE There is always a possibility that an ongoing mission will find evidence of life. For example, the *Perseverance* rover is equipped to search for at least some potential biosignatures. By the time you are reading this, the rover should have ascended through many layers of the main river delta in Jezero crater, which in essence represents a trek upward through geological time. Perhaps it will identify some biosignature in the outcrops and soil samples it examines. But identifying life with robotic instruments poses at least two major challenges: First, it is very difficult to design complex experiments that can be performed by a robotic spacecraft. Second, since we don't know what martian life would be like if it exists, it's difficult to know what robotic experiments would be most likely to find it. For example, it is now clear that the *Viking* experiments had a key limitation (which was not known at the time): They in essence attempted to "culture" life (that is, to get it to metabolize or grow in an experimental chamber), but even on Earth most forms of life are very difficult to culture. Therefore, a better approach to searching for life is to look for biochemical markers. But what markers should we look for? On Earth we can now search for life in almost any sample by looking for DNA. But martian life may not use DNA, and even if it does, its DNA might be sufficiently different from that of Earth life that detectors that work on Earth may not work on Mars. The same is true for experiments that might search for various proteins.

For this reason, our best hope of finding evidence of life on Mars is to collect martian rock samples and bring them back to Earth, where they could be analyzed in many more ways than would be possible with predesigned robotic experiments sent to Mars. Recall that the *Perseverance* rover is collecting such samples, though their return must await a future "Mars Sample

*Rosalind Franklin (1920–1958) was a chemist whose work is credited with having been crucial to the discovery of the molecular structure of DNA. She is widely considered to have been deserving of the Nobel Prize; however, she had already died (at age 37) by the time a Nobel was awarded for this discovery, and Nobels are generally not awarded posthumously, though there was no rule against it at the time.

Return" mission that would retrieve them and return them to Earth. No details or launch date for this return have yet been set (as of 2022), but scientists hope the sample return might occur late in this decade or early in the next.

Think About It Find the current status of plans for returning the samples collected by *Perseverance* to Earth. When can we expect the samples to reach Earth-based labs?

PREVENTING CONTAMINATION—IN BOTH DIRECTIONS
Given the likelihood that some Earth organisms could survive in at least a few locations on Mars, it's important to make sure that our robotic missions don't accidentally contaminate Mars with life from Earth. Otherwise, microbes that hitched a ride from Earth aboard a spacecraft might fool us into thinking we'd found evidence of martian life. The possibility of contamination also poses an ethical issue: It's at least conceivable that terrestrial life could outcompete any indigenous martian life, driving the martian life to extinction. Do we have a right to do something that could endanger native life on another planet? Clearly, the best way to avoid these problems is to prevent contamination in the first place. An international treaty, signed in 1967, requires that any spacecraft sent to Mars must have a less than 1 in 1000 chance of causing contamination. Today, scientists strive for even lower contamination probabilities by sterilizing spacecraft before they are launched.

Similarly, but in the other direction, the prospect of a sample return mission has caused some people to fear we might unleash dangerous martian microbes on Earth. Could such microbes cause disease for which we are unprepared or outcompete terrestrial organisms on our own turf? We cannot completely rule out any danger, but it is quite unlikely, because disease-causing microbes are highly adapted to the species they infect. For example, diseases that infect plants generally do not infect animals. Indeed, "species jumping" by diseases is quite rare and generally occurs only between species that are evolutionarily close. HIV (the virus that causes AIDS), for example, is thought to have jumped from chimpanzees to humans, while COVID-19 likely originated in bats; in both cases, these are fairly small jumps between different species of mammals. Therefore, even if martian microbes were accidentally released and subsequently survived on Earth, it's unlikely that they would cause disease. In addition, because martian meteorites must frequently land on Earth, any life that hides in martian rocks would almost certainly have reached Earth already. The fact that we do not see any harmful effects from this "natural contamination" makes it unlikely that any martian life can harm Earth life.

Nevertheless, it pays to be cautious, given the high stakes involved, and samples brought back from Mars will surely be transported in sealed containers that would not break open even if they were to crash on Earth. Once here, they will be quarantined and subjected to biological tests such as being exposed to terrestrial microbes. Biologists already know how to deal with dangerous terrestrial microbes, such as the Ebola virus, and scientists are developing protocols to ensure safe handling of any harmful martian organisms, if they actually exist and are actually harmful to terrestrial life.

Think About It Should we allow samples from Mars to be brought to Earth, or should they be studied only in space, such as on the International Space Station or at a Moon colony? Defend your opinion.

LEARNING OBJECTIVE
Human Exploration of Mars

8.4.3 Should we send humans to Mars?

Many people hope that we will soon be able to send humans to Mars. Sending people is far more difficult than sending robots. Even with the most advanced rockets that we can envision building over the next couple of decades, the trip to Mars would take at least 3 to 4 months in each direction. A human mission would have to carry not only the weight of the astronauts and their living quarters, but also that of enough food, air, and water to last the trip. Shielding against dangerous radiation would also be necessary, which means having an on-board "storm cellar" in case a violent flare erupted on the Sun. Moreover, because the rockets could travel between Earth and Mars only when the two planets were nearly aligned every 26 months, the astronauts would likely have to spend almost 2 years on Mars before they could return home. Although they might conceivably get water from the subsurface ice and chemically extract oxygen from martian water or rock, they would still need food, which would have to be either taken along with them or sent separately aboard other spacecraft. They'd also need fuel for the return journey, which would add far more weight to the mission, unless they could manufacture the fuel for the return mission on Mars (an idea that is being actively explored). No matter how you look at it, the enormous amount of stuff required for a human mission ensures it would cost at least as much as dozens of robotic missions, and it would pose many dangers to the crew.

Think About It Some people have proposed reducing the cost of human missions to Mars by getting volunteers who would make only a one-way trip, living out the rest of their lives on Mars. A few hundred people have already volunteered for such a mission, and many say they would do it if they were terminally ill. Do you support or oppose such ideas? Defend your opinion.

SCIENTIFIC PROS AND CONS While the cost and inherent danger of sending humans to Mars would be very high, the scientific payoff could potentially be even higher. We humans are far more capable than any robot, and a team of scientists with vehicles for traveling around the planet and equipment for drilling into the crust might well answer our questions about martian life long before they would be answered by robotic explorers. However, sending humans to Mars also has at least one significant scientific drawback: It vastly complicates the issue of avoiding contamination by terrestrial organisms. People are veritable warehouses of microbes: The number of bacteria in the average person's mouth, for example, is far greater than the number of people who have ever lived. We harbor microbes on our skin, in our breath, in our food, and in our excrement. Preventing all these microbes from escaping into the martian environment during an extended stay on the planet would be nearly impossible.

The scientific pros and cons of sending humans to Mars are fairly clear, but the history of the space program shows that human exploration has rarely been driven by science. The human space program began for political reasons, largely as part of a "race" between the United States and the Soviet Union. For example, while the *Apollo* program provided valuable scientific data about the Moon, its primary purpose was to prove to the world that the Americans could get there before the Soviets. If we decide to send humans to Mars, the decision will also probably be based more on social and political considerations than on scientific ones.

TERRAFORMING MARS Some people dream of establishing permanent colonies on Mars. For the near future, any such colonies would have to be self-contained environments, and no one would dare venture outside without a space suit. For the more distant future, a few scientists have suggested the possibility of altering the martian environment to make it more hospitable to us. This process goes by the name *terraforming*, because the changes would tend to make the planet more Earth-like.

Proposals to terraform Mars envision raising the atmospheric pressure and temperature. The temperature might be raised by adding a greenhouse gas to the atmosphere, while increasing the pressure simply requires more gas of any type. One suggestion involves manufacturing chlorofluorocarbons (CFCs), which are strong greenhouse gases, and releasing them into the martian atmosphere. If we could strengthen the greenhouse effect enough, the warmer temperatures might begin to release frozen carbon dioxide from the polar caps and elsewhere beneath the surface, which would further increase the atmospheric pressure and strengthen the greenhouse effect. There still wouldn't be oxygen to breathe, but if the pressure rose enough, we might be able to walk around on Mars carrying only an oxygen tank (and some protection from ultraviolet radiation) rather than having to wear a full, pressurized space suit. Such conditions might also allow liquid water to be stable and plants to survive outdoors, making it much easier to grow food and eventually increasing the concentration of atmospheric oxygen.

The idea might just work, but putting it into practice wouldn't be easy. Because CFCs tend to be broken apart by sunlight, we would have to manufacture them continually and in great abundance in order to start the greenhouse warming. Calculations suggest that we would need a manufacturing capability about a million times greater than our recent CFC-manufacturing capability on Earth and would need to keep it up for *thousands of years* before we might safely go for a space suit–free walk outside. Moreover, there may be significant ethical issues to consider, especially if Mars turns out to have life. For example, do we have a right to alter a planet in a way that could harm its native life?

Think About It A similar ethical issue surrounds endangered species on Earth. Some people say that we have no right to drive any species to extinction—an idea that was embodied in the U.S. Endangered Species Act. Others say that potential extinctions must be weighed against the human and economic costs of preventing them. Where do you stand on this issue? Does your answer affect your opinion of whether it would be ethical to terraform Mars? Explain.

Interestingly, some of the ethical issues involved in Mars colonization were explored by science fiction writers well before the idea of terraforming ever arose. In particular, back in the days when people believed in canals and a dead or dying martian civilization, many stories dealt with the conditions under which humans might colonize Mars. So for our last word on the topic of human colonization, we turn to a science fiction story called "The Million-Year Picnic," written in 1946 by Ray Bradbury and included in his book *The Martian Chronicles*. It tells the story of a human family who escape to Mars just as people on Earth are finishing off our civilization through hatred and war. On Mars, the family finds plenty of water and the vacant cities left by extinct Martians. The story ends with the family on the bank of a canal, where one of the children asks his father about a promise made earlier:

> *"I've always wanted to see a Martian," said Michael. "Where are they, Dad? You promised."*
>
> *"There they are," said Dad, and he shifted Michael on his shoulder and pointed straight down.*
>
> *The Martians were there. Timothy began to shiver.*
>
> *The Martians were there—in the canal—reflected in the water. Timothy and Michael and Robert and Mom and Dad.*
>
> *The Martians stared back up at them for a long, long silent time from the rippling water. ...*

THE PROCESS OF SCIENCE IN ACTION

8.5 Martian Meteorites

As we briefly noted earlier, one claim of evidence for life on Mars comes from the study of rocks from Mars that have fallen to Earth—the so-called *martian meteorites* [Section 6.2]. The story begins in 1984, when a team of American scientists scooped up a 1.9-kilogram meteorite from the Allan Hills region of Antarctica. It was cataloged as ALH84001: "ALH" for Allan Hills, "84" for the year in which it was found, and "001" to indicate that it was the first meteorite found on the expedition (Figure 8.37). It did not immediately draw special attention, but an analysis a decade later showed that it was one of those rare meteorites to have come from Mars. It then proved itself special even among this small group of rocks, and was subject to intense study. In 1996, a team of researchers (led by David McKay at NASA) made an astonishing claim: They said that ALH84001 might contain fossil evidence of past life on Mars. Because this claim would be so important if true, and because it has proved so controversial, we use it as this chapter's case study of the process of science in action.

FIGURE 8.37
Chemical analysis of this meteorite, known as ALH84001, indicates that it came from Mars. The small block shown for scale to the lower right is 1 cubic centimeter, about the size of a typical sugar cube.

LEARNING OBJECTIVE
Claims of Evidence for Martian Life

8.5.1 Is there evidence of life in martian meteorites?

To evaluate the claims about ALH84001, we must begin by understanding the rock. Scientists are fairly confident that ALH84001 really is a meteorite from Mars. It is definitely not an Earth rock, because its relative abundances of the isotopes oxygen-16, oxygen-17, and oxygen-18 are significantly different from those found in terrestrial rocks. But neither does it match what we'd expect from a piece of an asteroid or a rock from the Moon. Most important, gas trapped within ALH84001 appears very similar in its chemical and isotopic composition to that of the martian atmosphere—and distinctly different from any other known source of gas in our solar system—leading to the conclusion that it most likely came from Mars.

ALH84001 was singled out to be studied more intensely than other martian meteorites for a simple reason: While other known martian meteorites are geologically young, radiometric dating showed ALH84001 to be a piece of igneous rock that solidified about 4.1 billion years ago. That is, it formed about 400 million years after Mars was born, but was only blasted into space much more recently, which means that it resided on Mars at times when liquid water flowed on the surface. Scientists therefore wondered if it might tell us something about the past habitability of Mars.

HISTORY OF THE METEORITE Careful study tells us quite a lot about the history of ALH84001. Radiometric dating tells us its age, while study of its structure reveals evidence of later shocks, probably due to the effects of impacts that occurred long before the one that ultimately launched it into space. The meteorite also contains carbonate grains (about 0.1 to 0.2 millimeter in diameter) that date to about 3.9 billion years ago and tell us that the rock must have been infiltrated by liquid water from which the carbonate minerals precipitated out—evidence that is consistent with the idea that Mars once had flowing water.

We can determine the timing of the impact that blasted ALH84001 into space by looking for effects of exposure to *cosmic rays*, high-energy particles that leave telltale chemical signatures on anything unprotected by an atmosphere. The results tell us that ALH84001 spent about 16 million years in space, which means the impact that started its journey occurred on Mars about 16 million years ago. By studying decay products from radioactive isotopes produced by the cosmic rays, we can learn when cosmic rays stopped disturbing the meteorite, which must be when it fell to Earth and gained the protection of Earth's atmosphere. Such analysis shows that ALH84001 landed in Antarctica about 13,000 years ago. Table 8.5 summarizes the history of ALH84001.

EVIDENCE OF LIFE The claimed evidence of life in ALH84001 came from detailed studies of its carbonate grains and the surrounding rock. In brief, four types of evidence were cited as pointing to the existence of biology on Mars:

- The carbonate grains have a layered structure, with alternating layers of magnesium-rich, iron-rich, and calcium-rich carbonates. On Earth, this type of layering generally occurs only as a result of biological activity.
- The carbonate grains contain complex organic molecules known as *polycyclic aromatic hydrocarbons,* or *PAH*s. These molecules can be produced by both biological and nonbiological processes, and they have indeed been found in many meteorites that are not from Mars. However, they are much more abundant in ALH84001 than in other meteorites, and on Earth these molecules are most commonly produced by the decay of dead organisms or by reactions between such decay products and the environment (for example, in the burning of fossil fuels).

TABLE 8.5 The History of Meteorite ALH84001

Time	*Event*
4.1 billion years ago	Solidifies from molten rock in the southern highlands of Mars
4.0–4.1 billion years ago	Is affected by nearby impacts, but not launched into space
3.9 billion years ago	Is infiltrated by water, leading to the formation of carbonate grains within the rock
16 million years ago	Is blasted into space by an impact on Mars
13,000 years ago	Falls to Earth in Antarctica
December 27, 1984	Is found by scientists
October 1993	Is recognized as a martian meteorite
August 1996	Is cited as containing possible evidence of martian life

- Electronic microscopy techniques reveal crystals of the mineral magnetite within the iron-rich layers of the carbonate grains. The sizes, shapes, and arrangements of these crystals were claimed to match those of magnetite grains that on Earth occur only when made by bacteria.
- Highly magnified images of the carbonate grains revealed rod-shaped structures that look much like fossilized bacteria, except they are much smaller in size (Figure 8.38).

While none of these lines of evidence alone would prove biological activity, the original investigators argued that, on the whole, biology seemed a much more likely explanation than nonbiological processes. They argued that it would be a simpler and better scientific explanation (in effect invoking Occam's razor [Section 2.3]) if only a single process—biology—was hypothesized to account for each observation than if a different process was required to explain each result.

ALTERNATIVE EXPLANATIONS The four lines of evidence for fossil life in ALH84001 might seem to make a strong case for past life on Mars. However, other scientists proposed alternative, nonbiological mechanisms that could have produced each observed phenomenon. Let's look at these alternatives in the same order that we presented the evidence:

- There are nonbiological ways to get layered carbonate. For example, several pulses of hot water with different dissolved elements might have passed through the rock and laid down the different mineral layers.
- Other meteorites prove that PAHs can be produced by chemical rather than biological processes, and their high abundance might also be

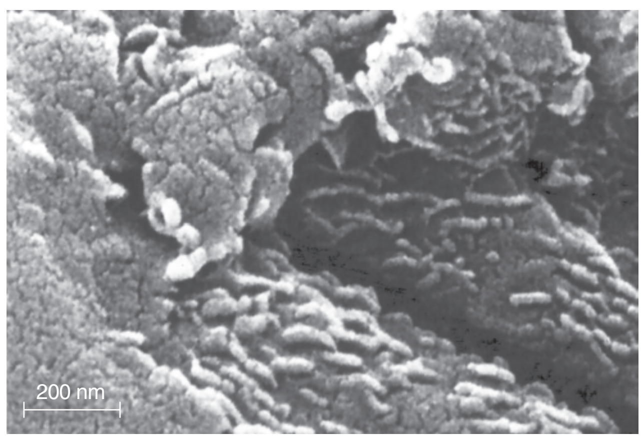


FIGURE 8.38
The tiny rod-shaped structures in this microscopic photo (of a slice of ALH84001) look much like fossilized bacteria, except they are smaller.

explained by terrestrial contamination during the time the rock resided in Antarctica.

- The resemblance between the magnetite crystals in the meteorite and those made by bacteria on Earth may be coincidental, and some scientists have proposed nonbiological ways in which the crystals might have been formed.
- The rod-shaped structures may look like bacteria, but some are about 100 times smaller than typical terrestrial bacteria. Indeed, they are so small (only 10 to 20 nanometers in width) that it is difficult to see how the complex molecules presumably needed for life (such as RNA- or DNA-like molecules) could fit inside them. Furthermore, similar-looking structures have been found in meteorites that haven't come from Mars, suggesting that these are not reliable evidence of life.

Perhaps most significantly, subsequent study of the meteorite found modern, terrestrial bacteria living inside it, which means the meteorite has been contaminated by Earth life. While this is not too surprising in retrospect—after all, the meteorite spent 13,000 years sitting in Antarctica before scientists found it—it clearly complicates the issue of distinguishing organic materials from Mars from those that could have been made on Earth.

Think About It Considering the fact that ALH84001 has apparently been contaminated by terrestrial bacteria, do you think we could ever be sure that any martian meteorite holds evidence of life on Mars? Defend your opinion.

OTHER MARTIAN METEORITES In 1996, when ALH-84001 became a big news story, there were only six known meteorites from Mars. That tally has since grown significantly, and several of these meteorites are also old enough to date from a time when liquid water, and possibly life, may have existed on the martian surface. One of these, known as the *Tissint meteor*, fell to Earth 40 miles from the Moroccan town of the same name in 2011. It too has been said to contain evidence of martian life, on the basis of organic carbon lining fissures in its interior. These carbon deposits are postulated to have come from organic-rich fluids that seeped into the rock a half-billion years ago, lining the rock with evidence of past life. However, many experts remain skeptical of these claims, and point out that such organic-rich liquids can also be the result of volcanic action.

SUMMARY OF THE CONTROVERSY The debate over possible evidence of life in ALH84001 and other martian meteorites continues, though most scientists now lean toward nonbiological explanations of the evidence. Nevertheless, the debate has taught us at least two crucial facts relevant to the search for life on Mars. First, it now seems unlikely that a meteorite found on Earth could make a conclusive case about life on Mars; instead, we'll need to study rocks on Mars itself (or bring rocks back from Mars to Earth for study). Second, while meteorites are unlikely to tell us about life, they can tell us a great deal about past conditions on Mars. The geological history revealed by martian meteorites strongly supports the idea that Mars once had water, heat sources, and perhaps organic molecules, all of which strengthen the case for the planet's past habitability.

The Big Picture

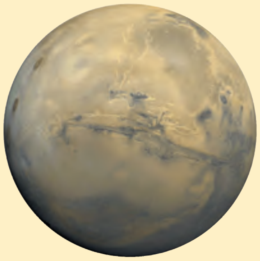
In this chapter, we have discussed past fantasies about martian civilization, our current understanding of the habitability of Mars, and the search for life on the red planet. As you continue your studies, keep in mind the following "big picture" ideas:

- Mars holds a special allure not only because of legitimate scientific questions, but also because past fantasies led many people to imagine a martian civilization. Mars and Martians became deeply embedded in modern popular culture, helping generate great public interest in Mars exploration both by robotic spacecraft and by future human explorers.
- Different regions of the martian surface appear to be almost frozen in time, representing different eras in the planet's history. As a result, we can piece together at least a partial story of Mars from its earliest times to the present. We find a planet that has gone through dramatic change. Its surface, once warm and wet, is now dry and frozen.
- According to present understanding, Mars almost certainly was a habitable planet in the past and may still have habitable zones underground. This makes Mars a prime target in the search for life beyond Earth.

Summary of Key Concepts

8.1 Fantasies of Martian Civilization

8.1.1 How did Mars invade popular culture?



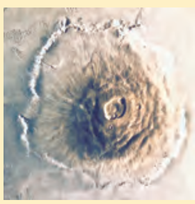
Superficial similarities between Mars and Earth led to speculation about martian civilization. Astronomer Percival Lowell thought he saw canals built by an advanced society, but the canals do not really exist.

8.2 A Modern Portrait of Mars

8.2.1 What is Mars like today?

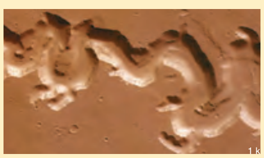
Mars is cold and dry, with an atmospheric pressure so low that water is unstable. Martian weather is driven largely by seasonal changes that cause carbon dioxide alternately to condense and to sublime at the poles, creating winds that sometimes generate huge dust storms.

8.2.2 What are the major geological features of Mars?



Mars has regions that are densely cratered and must be very old, and other regions that have fewer craters and must be much younger. The different regions also vary greatly in elevation, with younger terrain generally found in low-lying northern plains and older terrain in southern highlands. Giant volcanoes dot certain regions of Mars, and we also see evidence of past tectonics, which probably created Valles Marineris.

8.2.3 What evidence tells us that water once flowed on Mars?



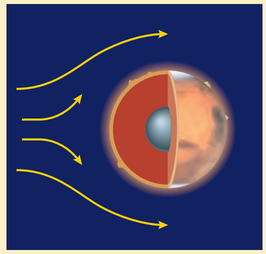
Orbital images of eroded craters, dry river channels, and floodplains all point to past water flows, and supporting evidence is found in chemical analysis of martian rocks studied by landers and rovers. The era of lakes (or possibly oceans) seems to have ended at least 3 billion years ago, but some flooding may have occurred later. Mars today still has water ice underground and in its polar caps, and could possibly have pockets or lakes of liquid water underground.

8.3 The Climate History of Mars

8.3.1 Why was Mars warmer and wetter in the past?

Mars's atmosphere must once have been much thicker with a much stronger greenhouse effect, though we do not yet know for certain whether this made Mars warm and wet for an extended period of time or only intermittently.

8.3.2 Why did Mars change?



Change must have occurred due to loss of atmospheric gas, which weakened the greenhouse effect. Some gas was probably blasted away by impacts, but more was likely stripped away by the solar wind as Mars cooled and lost its magnetic field and protective magnetosphere. Water was probably also lost because ultraviolet light could break apart water molecules in the atmosphere, and the lightweight hydrogen atoms could then escape to space.

8.3.3 Is Mars habitable?

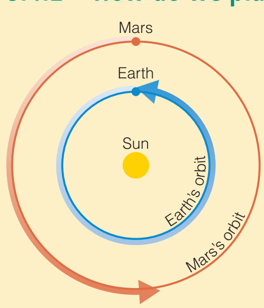
Mars almost certainly had a habitable surface during its wet period(s) more than 3 billion years ago. Its surface or near-surface might still sometimes be habitable when its axis tilt is greater than it is now, and the subsurface may still have habitable regions today.

8.4 Searching for Life on Mars

8.4.1 Is there any evidence of life on Mars?

The *Viking* experiments produced results that were in some ways suggestive of life but are now deemed to have been inconclusive. The detection of methane gas suggests a source that is either biological or due to geological activity, and the latter would still indicate enough internal heat to raise hopes for the existence of life on Mars.

8.4.2 How do we plan to search for life on Mars?



Space scientists plan an ongoing series of Mars missions, timed for the close approaches of Mars to Earth that occur about every 26 months.

8.4.3 Should we send humans to Mars?

Human missions to Mars could probably answer scientific questions about life much more quickly than robotic missions, but humans also pose a risk of contamination. Ultimately, the question will probably be decided by considerations beyond science alone.

THE PROCESS OF SCIENCE IN ACTION

8.5 Martian Meteorites

8.5.1 Is there evidence of life in martian meteorites?

Several lines of evidence have been put forth as suggesting the presence of past life in martian meteorites, but each also has a potential nonbiological explanation. Overall, most scientists doubt current claims for evidence of life in these meteorites, but research continues.

Exercises and Problems

You will find many of these questions and more, including guidance and study aids, in the Life in the Universe *courseware.*

QUICK QUIZ

Start with these questions as a quick test of your general understanding. Choose the best answer in each case, and explain your reasoning. Answers are provided in the back of the book.

1. When we say that liquid water is *unstable* on Mars, we mean that (a) a cup of water would shake uncontrollably; (b) it is impossible for liquid water to exist on the surface; (c) any liquid water on the surface would quickly either freeze or evaporate.
2. Mars's seasonal winds are driven primarily by (a) dust; (b) vaporization of carbon dioxide ice; (c) vaporization of water ice.
3. Olympus Mons is (a) a giant volcano; (b) a huge canyon network; (c) a continent-size plateau.
4. We can recognize the oldest surface regions of Mars by the fact that they have (a) the most impact craters; (b) the most volcanoes; (c) the most evidence of past water flows.
5. Minerals in surface rocks studied by the martian rovers seem to tell us that the rocks (a) formed in water; (b) were formed by impacts; (c) hold fossil evidence of life.
6. Rivers on Mars (a) have never existed; (b) existed in the past but are dry today; (c) continue to have flowing water today.
7. Which must be true if Mars was warmer and wetter in the past? (a) Mars was once closer to the Sun. (b) Mars once had a much thicker atmosphere. (c) Mars must somehow have avoided the effects of the heavy bombardment.
8. Which of the following fundamental properties of Mars could explain why it once had a global magnetic field but later lost it? (a) its small size; (b) its larger distance than Earth from the Sun; (c) a rotation rate that is slightly slower than Earth's
9. According to the leading hypothesis, if Mars once had much more carbon dioxide in its atmosphere, most of this carbon dioxide is now (a) gone, because it was lost to space; (b) frozen at the polar caps; (c) locked up in the form of carbonate rocks, just like on Earth.
10. The *Viking* experiments found (a) no evidence of life on Mars; (b) clear evidence of life on Mars; (c) results that were inconclusive about the possibility of life on Mars.

READING REVIEW QUESTIONS

You should be able to answer these questions by re-reading portions of the chapter as needed.

11. Briefly summarize the evidence, both real and imagined, that had led to widespread belief in a Martian civilization at the end of the nineteenth century.
12. What would it be like to walk on Mars today? Briefly discuss the conditions you would experience.
13. Why isn't liquid water stable at the martian surface today? What would happen if you were to heat water ice on Mars (outdoors)?
14. How do martian seasons differ from Earth seasons? Describe major seasonal changes that occur on Mars.
15. Give a brief overview of the geography and major features of Mars.
16. What evidence tells us that different regions of the martian surface date to different eras in the past? What have we learned about changes in martian volcanism during those past eras?
17. Summarize the evidence suggesting that Mars must have been warm and wet, possibly with rainfall, in its distant past.
18. How do we estimate the amount of water that may have once been present on Mars? What makes scientists think that Mars might still have subsurface liquid water today?
19. Why do we conclude that Mars must once have had a thicker atmosphere with a stronger greenhouse effect, and what gases could have made such an atmosphere possible?
20. What is the leading hypothesis concerning how Mars lost its once thick atmosphere? What role does Mars's size play in this hypothesis?

21. How and why does Mars's axis tilt change with time, and how do these changes affect the climate?
22. Based on all the geographic and geological evidence, summarize the current view about the past and present habitability of Mars.
23. Briefly summarize the *Viking* experiments and their results. Do the results constitute evidence of life? Explain.
24. What is the evidence for atmospheric methane on Mars, and what is the significance of this methane to the possibility for life?
25. Briefly summarize ongoing and planned Mars exploration. Why do we send missions to Mars only about every 26 months?
26. Discuss the issue of biological contamination in either direction between Earth and Mars. How serious is each problem? What steps can we take to prevent contamination in each direction?
27. Summarize the scientific pros and cons of sending humans to Mars. What other considerations are likely to play a role in decisions about such missions?
28. What do we mean by *terraforming* Mars? Is it something we could do within our lifetimes?
29. What evidence indicates that ALH84001 came from Mars? How and what have we learned about the meteorite's history?
30. Briefly summarize the possible evidence of past life discovered in studies of martian meteorites, and explain why this evidence generates controversy.

THINK CRITICALLY

Surprising Discoveries? Suppose we were to make the following discoveries. (These are not *real discoveries.) In light of your understanding of Mars, decide whether each discovery would be considered plausible or surprising. Explain clearly; because not all of these have definitive answers, your explanation is more important than your chosen answer.*

31. The first human explorers on Mars discover that the surface is littered with the ruins of an ancient civilization, including remnants of tall buildings.
32. We discover a string of active volcanoes in the heavily cratered southern highlands on Mars.
33. We find underground pockets of liquid water on the slopes of one of the Tharsis volcanoes.
34. One of our spacecraft observes rain falling on Mars.
35. A future orbiter finds a plume of volcanic gas emerging from Olympus Mons.
36. We find a lake of liquid water filling a small crater close to one of the dry river channels on Mars.
37. The first fossils discovered on Mars come from the canyon walls of Valles Marineris.
38. A sample return mission finds fossil evidence not only of martian microbes, but also of photosynthetic plants that lived on the exposed surfaces of martian rocks.
39. We discover that the martian polar caps have in the past extended more than twice as far toward the equator as they do now.
40. We find rocks on Mars showing clearly that the planet once had a global magnetic field nearly as strong as Earth's magnetic field.

CONCEPTUAL QUESTIONS

Answer each question in short answer or essay form.

41. *Hold Your Breath.* If you held your breath, would it be safe to walk outside on Mars? Why or why not?
42. *Miniature Mars.* Suppose Mars were significantly smaller than its current size—say, the size of our Moon. How would this have affected its potential habitability? Explain.
43. *Larger Mars.* Suppose Mars were significantly larger than its current size—say, the same size as Earth. How would this have affected its potential habitability? Explain.
44. *Civilization on Mars.* Based on what we can see on the surface of Mars, does it seem possible that Mars once had a civilization with cities on the surface but that the evidence has now been erased or buried underground? Explain.
45. *Terraforming Mars.* Make a list of the pros and cons of terraforming Mars, assuming that it is possible. Overall, do you think it would be a good idea? Write a short defense of your opinion.
46. *Mars Movie Review.* Watch one of the many science fiction movies that concern trips to Mars. In light of what you now know about Mars, does the movie give a realistic view of the planet? Are the plot lines that concern Mars plausible? Write a critical review of the movie, focusing on these issues.
47. *Martian Literature.* Read a science fiction book about Mars, such as H. G. Wells's *The War of the Worlds*, Ray Bradbury's *The Martian Chronicles*, or Andy Weir's *The Martian*. Write a critical review of the book, being sure to consider whether it merits interest in light of current scientific understanding of Mars.

QUANTITATIVE PROBLEMS

Be sure to show all calculations clearly and state your final answers in complete sentences.

48. *Interior Heat.* Compare the surface area–to–volume ratios (that is, total surface area divided by total volume) of the Moon, Earth, and Mars. What does your answer tell you about how quickly each world should have cooled with time? What does your answer tell you about the implications of planetary size for habitability?
49. *Mars's Elliptical Orbit.* Mars's distance from the Sun varies from 1.38 AU to 1.66 AU. How much does this change the globally averaged strength of sunlight over the course of the martian year? Give your answer as a percentage by which sunlight at perihelion (the orbital point closest to the Sun) is stronger than that at aphelion (the farthest orbital point). Comment on how this affects the martian seasons. (*Hint:* Remember that light follows an inverse square law; see Figure 7.2.)
50. *Atmospheric Mass of Earth.* What is the total mass of Earth's atmosphere? Use the fact that, under Earth's gravity, the sea level pressure of 1 bar is equivalent

to 10,000 kilograms pushing down on each square meter of the surface. Also remember that the surface area of a sphere of radius r is $4\pi r^2$.

51. *Atmospheric Mass of Mars.* The weaker gravity of Mars means that 1 bar of pressure on Mars would be the pressure exerted by about 25,000 kilograms pushing down on each square meter of the martian surface. Based on this approximation, the atmospheric pressure on Mars (see Table 8.3), and the size of Mars, estimate the total mass of Mars's atmosphere. Compare to Earth's atmospheric mass from Problem 50.
52. *Past Gas on Mars.* Models suggest that Mars today could have liquid water on its surface if the atmosphere were about 400 times as dense as it actually is. What would the atmospheric mass be in that case? How does this compare to the present mass of Earth's atmosphere? Does it seem plausible that Mars might once have had this much gas? Explain why or why not.

ACTIVITY AND DISCUSSION

These questions are intended to prompt additional research and/or discussion.

53. *The Role of the Martians.* Percival Lowell may have been sadly mistaken in his beliefs about Martians, but he succeeded in generating intense public interest in Mars. If he had never made his wild claims about canals and civilization, do you think we would be exploring Mars with the same fervor today? Defend your opinion.
54. *Learning from Past Mistakes.* The *Viking* missions landed on Mars about 40 years ago, with ambitious experiments designed to search for life. Today, however, we know that the experimental designs were flawed and thus the results were not sufficient to determine whether the missions were finding signs of life. Do you think the scientists should have known better at the time? How can the lessons from *Viking* inform future searches for life on other worlds? Defend your opinions clearly.
55. *Lessons from Mars.* Discuss the nature of the climate change that occurred on Mars some 3 billion years ago. Do you think this climate change holds any important lessons for us as we consider the climate change that humans are causing on Earth? Explain.
56. *Robotic Landing Site.* Suppose you were in charge of a mission designed to land on Mars. Assume the mission carries a rover that can venture up to about 50 kilometers from the landing site. What landing site would you choose, and why? Briefly summarize the kinds of instruments you would want on this robotic mission.
57. *Human Exploration of Mars.* Should we send humans to Mars? If so, when? How much would you be willing to see spent on such a mission? Would you volunteer to go yourself ? Discuss these questions with your classmates, and try to form a class consensus regarding the desirability and nature of a human mission to Mars.
58. *Martian Photo Journal.* By now, we have many thousands of photos of Mars taken both on the surface and from orbit, and virtually all of them can be found on the Web. Make your own photo journal of "Mars's Greatest Photo Hits" by choosing ten of your favorite photos. For each one, write a short descriptive caption and explain why you chose it.
59. *Current Mars Missions.* Pick one of the Mars missions that is currently operating and visit its website. Write a short report about the mission's history, goals, and accomplishments to date.
60. *Group Activity: Human Mission to Mars.* Your group is the planning team for a mission that will carry humans to Mars. The journey will take a few months in each direction, and the explorers will spend about 2 years on the martian surface. Make a list of key provisions needed for the mission, explaining the purpose of each item. In addition, briefly discuss whether any of these provisions could be found or manufactured on Mars rather than having to be brought from Earth. *Note*: You may wish to do this activity using the four roles described in Exercise 59 in Chapter 2.