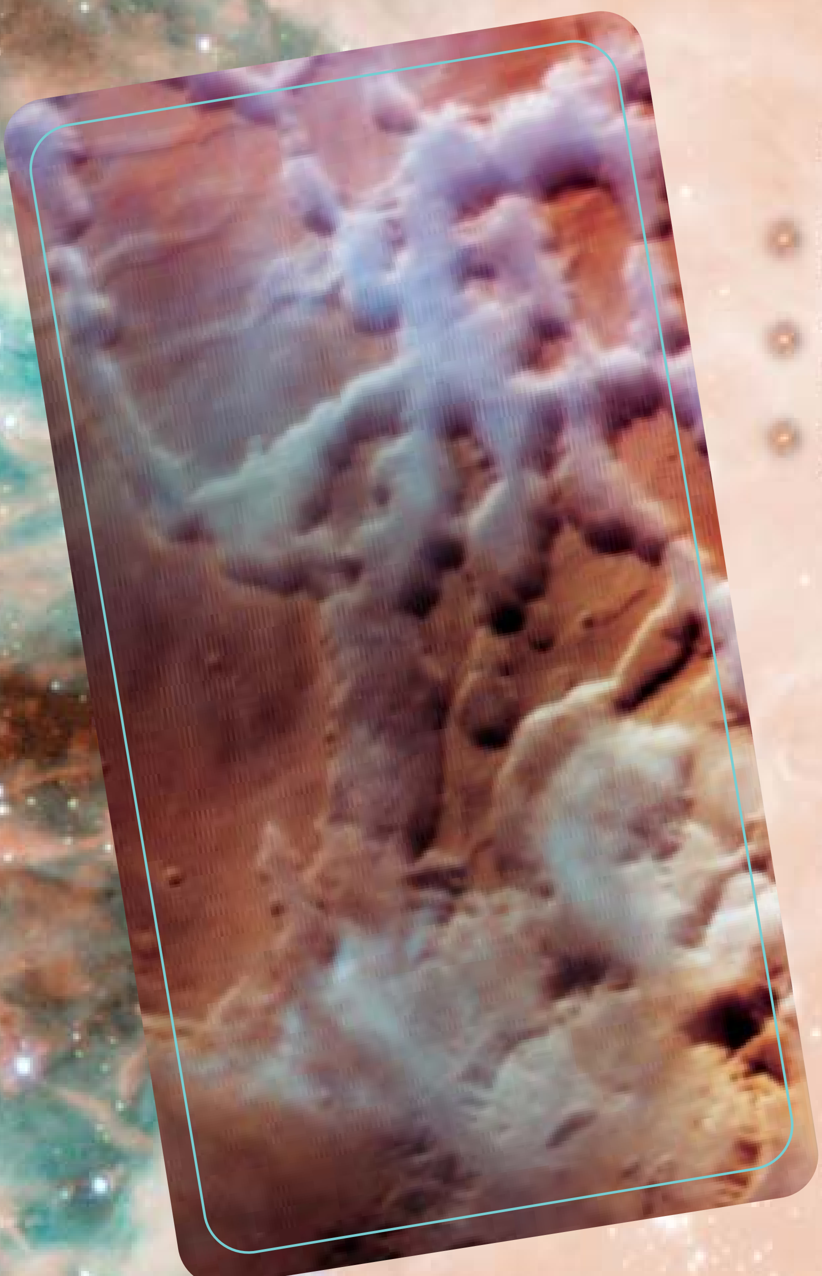
6 THE OTHER TERRESTRIAL PLANETS



IN THIS CHAPTER YOU WILL DISCOVER

- Mercury, a Sun-scorched planet with a heavily cratered surface and an iron core
- Venus, perpetually shrouded in thick, poisonous clouds and mostly covered by gently rolling hills
- Mars, the inspiration for scientific and popular speculation about extraterrestrial life

Canyon Fog
Delicate fog created by the scant water vapor in Mars's atmosphere fills canyons of Labyrinthus Noctis at sunrise and sunset. (NASA/JPL)

R I V U X G

WHAT DO YOU THINK?

1. Is the temperature on Mercury, the closest planet to the Sun, higher than the temperature on Earth?
2. What planet is most similar to Earth?
3. What is the composition of the clouds surrounding Venus?
4. Does Mars have liquid water on its surface today?
5. Is life known to exist on Mars today?

Far from the Sun are planets so alien that comparisons to Earth are virtually meaningless. Closer to home, however, a space traveler from Earth might feel like an ordinary tourist. The craters on Mercury call to mind the Moon. The clouds of Venus look almost comforting, which belies their true chemical composition. A feature on Mars, the Valles Marineris, distinctly brings to mind the Grand Canyon. How can a riverbed exist on such an arid world?

As we begin our tour of the inner solar system, it will help to keep asking: While they look like things back home, are they really the same? See the table "The Inner Planets: A Comparison."

MERCURY

ANIMATION 6.1

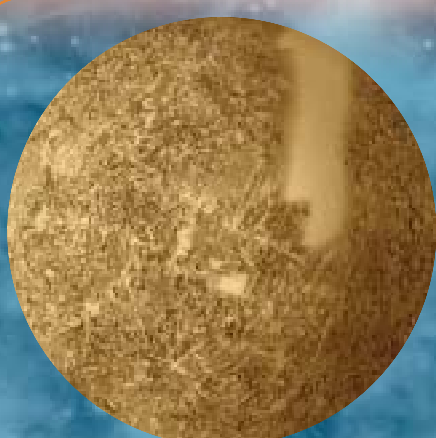
Whenever it rises before the Sun, Mercury heralds the ascending Sun in the brightening eastern sky as a "morning star." When Mercury rises after the Sun, it is seen only for a short time after sunset, hovering low over the western horizon as an "evening star." At its greatest elongation (see Figure 2-3), Mercury is sometimes among the brightest objects in the sky, with an apparent magnitude of about –0.4. Near conjunction, however, Mercury is very hard to see because its apparent magnitude rises to over 5.5 and it is viewed close to the Sun.

6-1 Photographs from *Mariner 10* reveal Mercury's lunarlike surface

WEB LINK 6.1

Telescopic photographs of Mercury taken from Earth reveal almost nothing about the planet's surface. It was only in 1974, when *Mariner 10* coasted past the planet, that astronomers got their first glimpse of Mercury's inhospitable but familiar-looking surface. Figure 6-1 lists Mercury's properties. *Mariner 10* was sent on a remarkable orbit that enabled it to pass Mercury three times. Nevertheless, it photographed only 40% of Mercury's surface, and we still do not know what the other 60% looks like.

Mercury's Vital Statistics



Mass	3.30×10^{23} kg (0.055 $M_\oplus$)
Radius	2439 km (0.382 $R_\oplus$)
Average density	5430 kg/m^3 (0.984 Earth density)
Orbital eccentricity	0.206
Inclination of equator to plane of orbit	0.0°
Sidereal period of revolution (year)	88 Earth days (0.24 Earth year)
Average distance from the Sun	5.79×10^7 km (0.387 AU)
Sidereal rotation period	58.7 Earth days
Solar rotation period (day)	176 Earth days
Albedo (average)	0.12

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WEB LINK 6.2

FIGURE 6-1 *Mariner 10* Mosaic of Mercury This image of Mercury is a composite of dozens of photos taken by the *Mariner 10* spacecraft. The blank region was not imaged by the spacecraft, nor was the opposite side of the planet. Although most of these images were recorded at distances of about 200,000 km (125,000 mi) from Mercury, their resolution is still vastly superior to that of the best Earth-based images. (Astrogeology Team, U.S. Geological Survey)

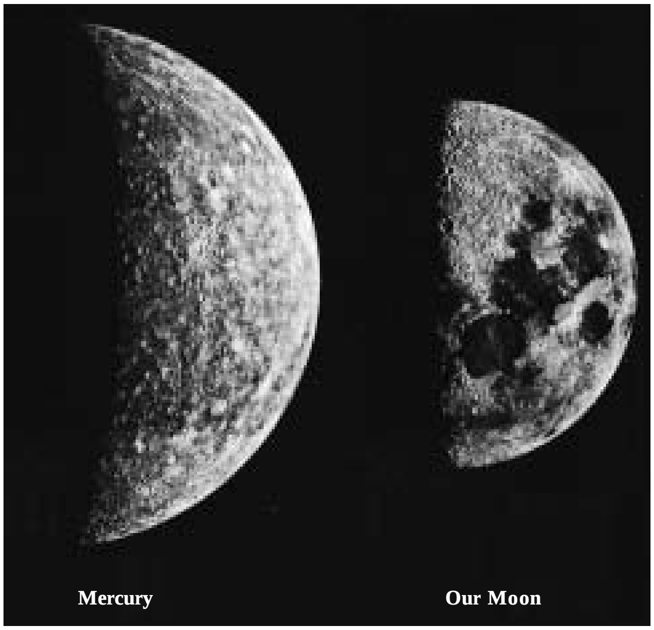
The Inner Planets: A Comparison

	Interior	Surface	Temperature	Atmosphere	Magnetic Field
Mercury	Not known whether liquid or solid	Heavy cratering, scarps	700 K by day, 100 K by night	H, He, K, P, O; transient and tenuous	0.1 times Earth's field
Venus	At least partially molten	Light cratering, mostly volcanic plains, gently rolling hills, some volcanos	750 K	Mostly CO_2, N; 98 times denser than Earth's	None detected
Earth	Solid inner core, molten outer core, mantle	Very little cratering, continents and land at ocean floors, weathering, volcanos, global tectonic plates	200–315 K	Mostly N_2, O_2	Strong global field
Mars	Probably solid core	Moderate cratering, weathering, dormant volcanos, huge canyons	160–280 K	Mostly CO_2, N_2; 0.006 times as dense as Earth's	Weak, local fields

For detailed numerical comparisons between planets, see Tables A-1 and A-2.

(NASA/USGS)

R I V U X G



R I V U X G

FIGURE 6-2 **Mercury and Our Moon** Mercury (left) and our Moon are shown here to the same scale. Mercury's diameter is 4878 km and the Moon's is 3476 km. For comparison, the distance from New York to Los Angeles is 3944 km (2451 mi). Mercury's surface is more uniformly cratered than that of the Moon. Daytime temperatures at the equator on Mercury reach 700 K (800°F), hot enough to melt lead or tin. (NASA, UCO/Lick Observatory)

Mariner 10 and the Exploration of Mercury

Astronomers conclude that most of the craters on both Mercury and the Moon were produced by impacts in the 800 million years after these bodies condensed from the solar nebula. As we saw in Chapter 5, the strongest evidence for this belief comes from analyzing and dating Moon rocks. Debris remaining after the planets were formed pounded these young worlds, gouging out most of the craters we see today. Like the Moon, Mercury has an exceptionally low albedo of 0.12 (12% reflection). It is very bright as seen from Earth only because the sunlight scattering from Mercury is so intense.

Although first impressions of Mercury evoke a lunar landscape, closer scrutiny reveals distinctly nonlunar characteristics. Lunar craters in the highlands (Figure 6-2) are densely packed, with one crater overlapping the next. Furthermore, there are very few craters on the maria. Mercury has neither maria nor other craterless regions. There are broad plains sparsely filled with relatively small craters. Elsewhere, the surface is covered with more numerous, overlapping craters. Figure 6-3 shows a typical close-up view of Mercury.

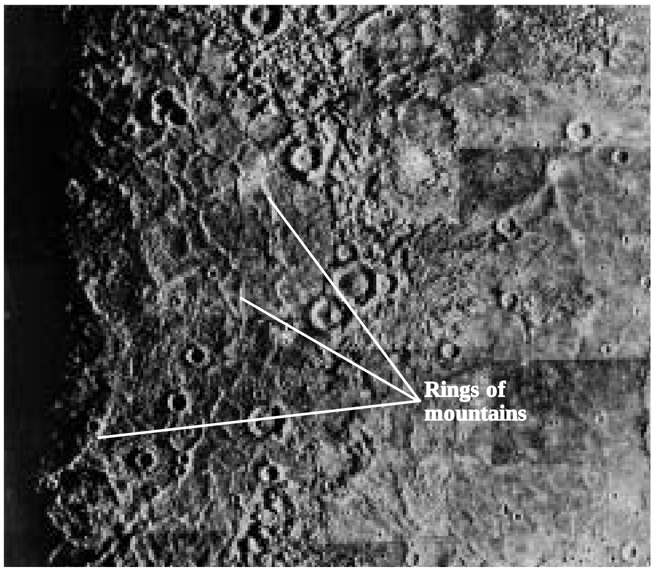
As we learned in Chapter 5, the lunar maria were produced by extensive lava flows that occurred between 3.1 and 3.8 billion years ago. Ancient lava flows also probably formed the Mercurian plains. As large meteorites punctured the planet's thin, newly formed crust, lava welled up from the molten interior to flood low-lying areas. The existence of craters pitting Mercury's plains suggests that these plains formed just over 3.8 billion years ago. Recall from Figure 5-24 that this was near the end of the era of heavy bombardment. Mercury's plains are therefore older than most of the lunar maria, leaving more time for cratering to eradicate marialike features.

The most impressive feature discovered by *Mariner 10* was a huge circular region called the Caloris Basin (Figure 6-4), which measures 1300 km (810 mi) in diameter and lies along the *terminator* (the border between day and night) in the figure. It is surrounded by a 2-km-high ring of mountains, beyond which are relatively smooth plains. Like the lunar maria, the Caloris Basin was probably gouged out by the impact of a large meteorite that penetrated the planet's crust. Because relatively few craters pockmark the lava flows that filled the basin, the Caloris impact must have occurred toward the end of the major crater-making period.

The Caloris impact was a tumultuous event that shook the entire planet. Indeed, the collision seems to have affected the side of Mercury directly opposite the Caloris Basin. That area (Figure 6-5) has a jumbled, hilly region covering nearly

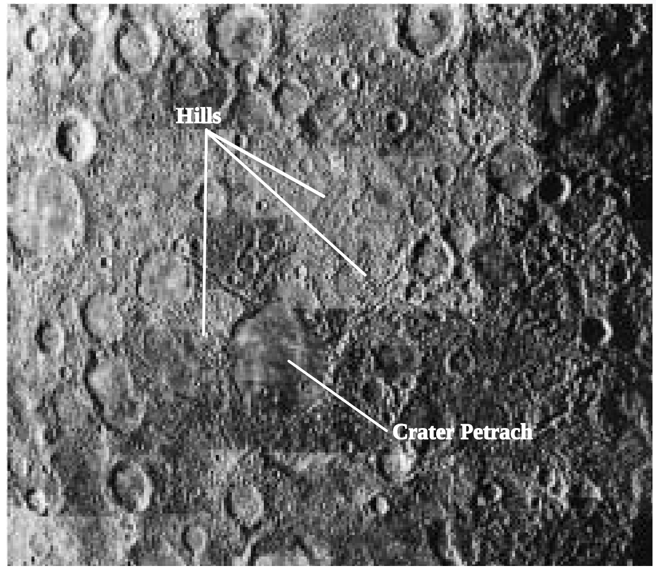
R I V U X G

FIGURE 6-3 **Mercury's Craters and Plains** This view of Mercury's northern hemisphere was taken by *Mariner 10* as it sped past the planet in 1974. Numerous craters on the bottom half of the image and broad intercrater plains on the top half cover an area 480 km (300 mi) wide. (NASA)



R I V U X G

FIGURE 6-4 The Caloris Basin *Mariner 10* sent back this view of a huge impact basin on Mercury's equator. Only about half of the Caloris Basin appears because it happened to lie on the terminator when the spacecraft sped past the planet. Although the center of the impact basin is hidden in the shadows (just beyond the left side of the picture), several semicircular rings of mountains reveal its extent. (NASA)

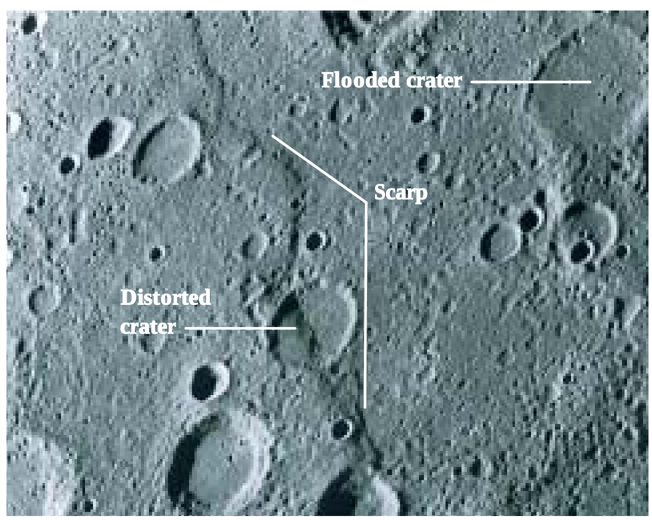


R I V U X G

FIGURE 6-5 Unusual, Hilly Terrain What look like tiny, fine-grained wrinkles on this picture are actually closely spaced hills, part of a jumbled terrain that covers nearly 500,000 km^2 on the opposite side from the Caloris Basin. The large, smooth-floored crater, Petrarch, near the center of this photograph has a diameter of 170 km (106 mi). This impact crater was produced more recently than the Caloris Basin. (NASA)

half a million square kilometers, about twice the size of Wyoming. The hills, which appear as tiny wrinkles that cover most of the photograph, are about 5 to 10 km wide and between 100 and 1800 m high. Geologists believe that energy from the Caloris impact traveled through the planet and became focused, like light through a lens, as it passed through Mercury. As this concentrated energy reached the far surface of the planet, jumbled hills were pushed up. A similar pair of phenomena to Caloris and the jumbled terrain on the other side of Mercury can be seen in our Moon's Mare Orientale and chaotic hills on the opposite side. Finding such a similar pair supports the theory that the impact and the jumbled surface are connected.

Mariner 10 also revealed gently rolling plains and numerous, long cliffs, called **scarps,** meandering across Mercury's surface (Figure 6-6). The scarps are believed to have developed as the planet cooled. Almost everything that cools contracts. Therefore, as Mercury's mantle and molten iron core cooled and contracted, its surface moved inward. Because it was solid, Mercury's crust could not collapse uniformly. Instead, it wrinkled as it contracted, forming the scarps. These features and the lack of recent volcanic activity suggest that the planet's interior is solid to a significant depth. Otherwise, lava would have leaked out as the scarps formed.



R I V U X G

ANIMATION 6.2

FIGURE 6-6 Scarps on Mercury A long, meandering cliff called Santa Maria Rupes runs from north to south across this *Mariner 10* image of a region near Mercury's equator. This cliff, called a scarp by geologists, is more than 1 km high and runs for several hundred kilometers. Note how the crater in the center of the image was distorted vertically when the scarp formed. (NASA)

6-2 Mercury's temperature range is the most extreme in the solar system

By sending radio waves to Mercury and examining the reflected signal, astronomers in 1992 made an extraordinary discovery—water ice near Mercury's poles in craters that are permanently in shadow, as also found on our Moon. Dozens of circular regions, presumably craters, send back signals with characteristics distinct to ice. The origin of this ice, whether from comet impacts, from gases rising from inside the planet and then freezing, or both sources, remains to be determined.

Mercury's mass is quite low, only 5.5% that of the Earth. Like our Moon, the force of gravity is too weak on Mercury to hold a permanent atmosphere, but trace amounts of five different gases have been detected around Mercury. Scientists believe the Sun is the source of the hydrogen and helium gas near Mercury, while sodium and potassium gas escape from rocks inside the planet (a process called *outgassing*, which also occurs on the Earth). Oxygen observed in Mercury's atmosphere may come from polar ice that is slowly evaporating. All these gases drift into space and are continually being replenished in the atmosphere from their respective resources.

Because of Mercury's slow rotation and minimal atmos-
1 phere, the differences in temperature between day and night are far more noticeable there than on the Earth. At noon on Mercury, the surface temperature is 700 K (800°F). At the terminator, where day meets night, the temperature is about 425 K (305°F), and on the night side, the temperature falls as low as 100 K (–280°F)! This range of temperature, 600 K (1080°F), on Mercury contrasts tremendously with the typical change in temperature of 11 K (20°F) between day and night on Earth.

Insight into Science **Model-Building** In modeling real situations, scientists consider several different effects simultaneously. Omit any crucial property and you get inaccurate results. For example, think of how scientists might calculate how long ice can remain at Mercury's poles. They must take into account the planet's distance from the Sun, the tilt of its axis of rotation, its rotation rate, surface features, whether the ice is exposed or mixed with other material, and the chemical composition of Mercury.

6-3 Mercury has an iron core and a magnetic field like Earth

Mercury's average density of 5430 kg/m^3 is quite similar to Earth's (5520 kg/m^3). As we saw in Chapter 5, typical rocks on Earth's surface have a density of only about 3000 kg/m^3 because they are composed primarily of lightweight elements. The high average densities of both Mercury and our planet are caused by their iron cores.

Because Mercury is less dense than the Earth, you might conclude that Mercury has a lower percentage of iron, a heavy element, than our planet. In fact, it is the Earth's greater mass pressing inward that makes it denser. This inward force compresses the iron core, making our planet denser than it would otherwise be.

Mercury is actually the most iron-rich planet in the solar system. Figure 6-7 shows a scale drawing of its interior, where an iron core fills 42% of the planet's volume. Surrounding the core is a 600-km-thick rocky mantle. For comparison, the Earth's iron core occupies only 17% of the planet's volume. How much of Mercury's core is molten is still unknown.

Events early in Mercury's history must somehow account for its high iron content. We know that the inner regions of the primordial solar nebula were incredibly hot. Perhaps only iron-rich minerals were able to withstand the solar heat there, and these subsequently formed iron-rich Mercury. According to another theory, an especially intense outflow of particles from the young Sun stripped Mercury of its low-density mantle shortly after the Sun formed. A third possibility is that, during the final stages of planet formation, Mercury was struck by a large planetesimal. Computer simulations show that this cataclysmic collision would have ejected much of the lighter mantle (Figure 6-8).

6-4 Mercury's rotation and revolution are coupled

ANIMATION 6.3

When the Earth was young, its gravitational force created tides on the Moon, thereby forcing the Moon into synchronous rotation. The Sun created

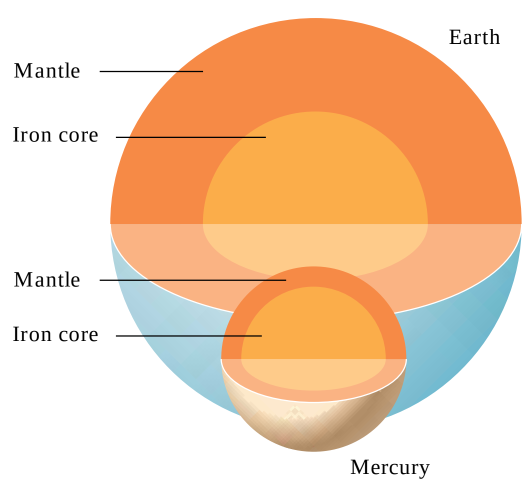


FIGURE 6-7 The Interiors of Mercury and Earth Mercury has the highest percentage of iron of any planet in the solar system. Its iron core occupies an exceptionally large fraction of its interior.

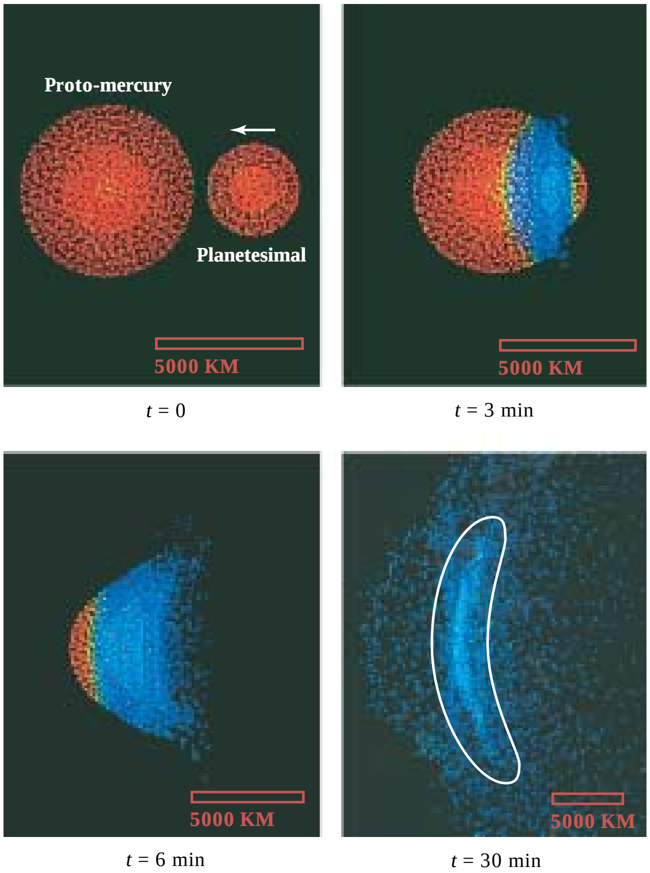


FIGURE 6-8 The Stripping of Mercury's Mantle To account for Mercury's high iron content, one theory proposes that a collision with a massive asteroid stripped Mercury of most of its rocky mantle. These four images show a computer simulation of a head-on collision between proto-Mercury and a body one-sixth its mass. Both worlds are shattered by the impact, which vaporizes much of their rocky mantles. Mercury eventually reforms from the iron-rich debris left behind (material inside banana-shaped region). The rest of the material (outside the banana) left the vicinity of the planet. (W. Benz, A. G. W. Cameron, and W. Slattery)

a significant tidal bulge on Mercury that locked into place when the planet solidified. This is analogous to what the Earth would look like if the oceans suddenly froze solid. Furthermore, Mercury is so close to the Sun (average separation: 0.387 AU) that the Sun's gravitational force also influenced Mercury's rotation rate. However, Mercury's highly eccentric orbit ($e = 0.21$) prevented the planet from being locked into synchronous orbit. Instead, Mercury has what is called a **3-to-2 spin-orbit coupling.** This means that Mercury undergoes three sidereal rotations (rotations measured with respect to the distant stars, not the Sun), while undergoing two revolutions around the Sun (Figure 6-9).

MORE TO KNOW 6.2 Radar Doppler Measurements

Why not synchronous rotation? Basically Mercury's orbit is too eccentric to allow it. Planets rotate at constant rates, and so for the Sun to always be up in a planet's sky, the planet would have to have a nearly circular orbit around it. Our Moon, for example, has synchronous rotation around the Earth with an orbital eccentricity of 0.055. As seen from the Moon, therefore, the Earth remains essentially fixed in the sky. However, Kepler's second law (see section 2-3) dictates

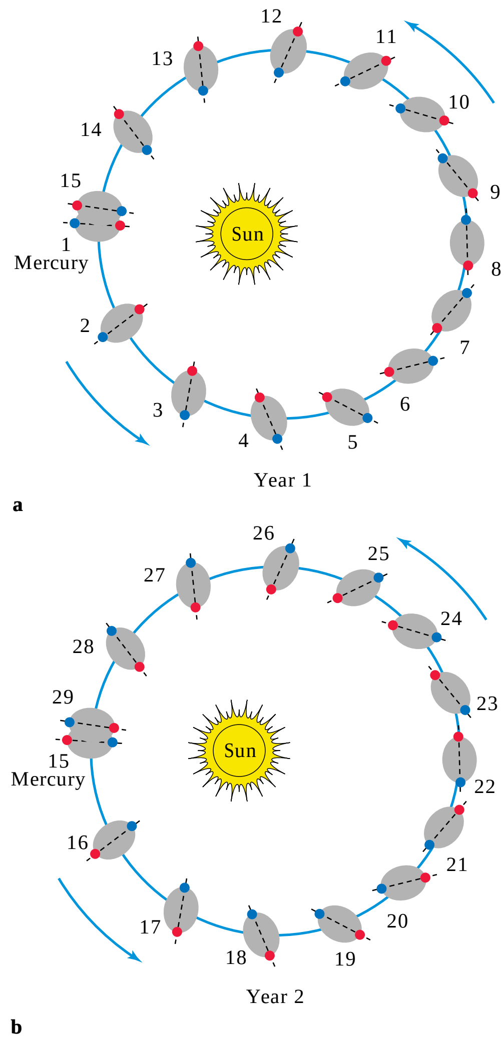


FIGURE 6-9 3-to-2 Spin-Orbit Coupling Mercury undergoes three sidereal rotations every two years. You can see this by following the red (or blue) dot from time 1 to time 29 and observe that the dot points to the right 3 times during this interval, which corresponds to two Mercurian years. Therefore, a sidereal day on Mercury is 58.7 Earth days long. During the same interval, however, the Sun is at noon as seen from the red dot's location only twice: at time 1 and time 29. Therefore, a solar day is 176 Earth days long.

that the Sun moves faster across Mercury's sky at perihelion than at aphelion. Therefore, from Mercury's surface, the Sun is seen to rise and set.

Although the strength of the Sun's tidal force on Mercury was unable to put it into synchronous rotation as the Earth did to the Moon, the Sun's tidal force did change Mercury's original rotation rate. Today, one of only two regions on Mercury (with slight variations) always faces the Sun at the planet's perihelion. In other words, at perihelion, only the regions of Mercury with the high tidal bulges are pointing toward the Sun (see Figure 6-9). This is a result of the 3-to-2 spin-orbit coupling mentioned above.

The motion of the Sun across Mercury's sky is unique in the solar system. First, a solar day there (noon to noon) is 176 Earth days long, twice the length of a year! Furthermore, standing at the location of high tide on Mercury near perihelion, you would see the Sun start to rise in the east, stop high in the sky, move back toward the east, stop again, and then continue its westward journey. Similarly, at perihelion, you could watch the Sun set, rise in the same place, and then set again a day or two later.

As we saw in Chapter 5, electric currents flowing in a planet's liquid iron core create a planetwide magnetic field. The Earth creates its electric current by rotating once a day. Mercury rotates 59 times more slowly (see Figure 6-1). This is hardly fast enough to generate a magnetic field, yet *Mariner 10* did find a weak magnetic field on Mercury. The origin of its present magnetic field remains a mystery. Besides Pluto, Mercury is the planet from which we have the least observational data. Therefore, several missions to Mercury are planned for the coming decade.

VENUS

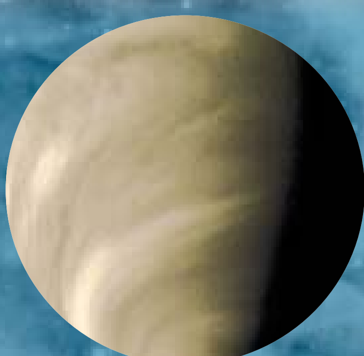
Venus and Earth have almost the same mass, the same diameter, and the same average density. Indeed, if Venus were 2
located at the same distance from the Sun as is the Earth, then it, too, might well have evolved life. However, Venus is 30% closer to the Sun than the Earth is, and this one difference between the two planets leads to a host of others, making Venus inhospitable to life.

6-5 The surface of Venus is completely hidden beneath a permanent cloud cover

At nearly twice the distance from the Sun as Mercury, Venus is often easy to view without interference from the Sun's glare. At its greatest elongation, Venus is seen high above the western horizon after sunset, where, like Mercury, it is often called the "evening star." High in the eastern sky before sunrise, it is called the "morning star."

Venus is so easy to identify because it is often one of the brightest objects in the night sky. Only the Sun and the Moon

Venus's Vital Statistics



Mass	4.87×10^{24} kg (0.815 $M_\oplus$)
Radius	6051 km (0.949 $R_\oplus$)
Average density	5240 kg/m^3 (0.949 Earth density)
Orbital eccentricity	0.007
Sidereal period of revolution (year)	224.7 Earth days (0.615 Earth year)
Average distance from the Sun	1.08×10^8 km (0.723 AU)
Sidereal rotation period	243 days (retrograde)
Solar rotation period (day)	116.8 Earth days
Albedo (average)	0.65

R I V U X G

WEB LINK 6.3

FIGURE 6-10 Venus's Vital Statistics Venus's thick cloud cover efficiently traps heat from the Sun, resulting in a surface temperature even hotter than that on Mercury. Unlike Earth's clouds, which are made of water droplets, Venus's clouds are very dry and contain droplets of concentrated sulfuric acid. This ultraviolet image was taken by the *Pioneer Venus Orbiter* in 1979. (NASA) outshine Venus at its greatest brilliance. Venus is often mistaken for a UFO, because when it appears low on the horizon, its bright light is strongly refracted by the Earth's atmosphere, making it appear to rapidly change color and position.

Unlike Mercury, Venus is intrinsically bright (Figure 6-10), because it is completely surrounded by light-colored, highly reflective clouds. Visible light telescopes cannot penetrate this thick, unbroken layer of clouds. Until 1962, we did not even know how fast Venus rotates. In the 1960s, however, both the United States and the former Soviet Union began sending probes to Venus. The Americans sent fragile, lightweight spacecraft into orbit near Venus. The Soviets, who had more powerful rockets, sent massive vehicles directly into the Venusian atmosphere.

Building spacecraft that could survive the descent proved to be more frustrating than anyone had expected. Finally, in 1970, a Soviet probe managed to transmit data for a few seconds directly from the Venusian surface. Soviet missions, which continued until 1983, measured a surface temperature of 750 K (900°F) and a pressure of 90 atm. This is the same pressure you would feel if you were swimming 0.82 km (2700 ft) underwater on Earth.

In contrast to Earth's present nitrogen and oxygen–rich atmosphere, Venus's thick atmosphere is 96% carbon dioxide, with the remaining 4% being mostly nitrogen. This atmosphere is remarkably similar to the Earth's early carbon dioxide–rich atmosphere. These gases were vented from inside Venus through volcanoes and other openings. Unlike the Earth, however, Venus has no liquid oceans to dissolve the carbon dioxide, so it remains in the atmosphere there today.

Soviet spacecraft also discovered that Venus's clouds are confined to a 20-km-thick layer located 48 to 68 km above the planet's surface. Above and below the clouds are 20-km-thick layers of haze. Beneath the lower level of haze, the Venusian atmosphere is clear all the way down to the surface. Standing on the surface of Venus, you would experience a perpetually cloudy day.

Unlike the clouds on Earth, which appear white from
3 above, the cloudtops of Venus appear yellowish or yellow-orange to the human eye. These colors are typical of sulfur and its compounds. Indeed, spacecraft found substantial amounts of sulfur dust in Venus's upper atmosphere and sulfur dioxide and hydrogen sulfide at lower elevations. The clouds are composed of droplets of concentrated sulfuric acid! Because of the tremendous atmospheric pressure at Venus's surface, the droplets remain suspended as a thick mist, rather than falling as rain.

All of the major chemical compounds spewed into our air by Earth's volcanoes have also been detected in Venus's atmosphere. Among these molecules are large quantities of sulfur compounds. Because many of these substances are very short-lived, they must be constantly replenished by new eruptions. In fact, the abundance of sulfur compounds in Venus's atmosphere does vary. These data suggest the possibility that the sulfurous compounds in Venus's atmosphere come from active volcanoes. This question is very much open, however, because of the question of lightning on Venus. Lightning is a frequent event around active volcanoes here on Earth. Astronomers have searched for lightning on Venus's atmosphere, but whether it has been detected there remains highly controversial.

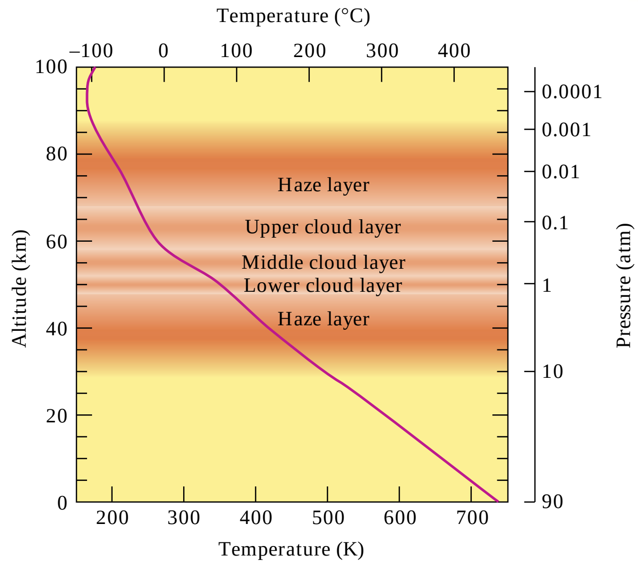


FIGURE 6-11 **Temperature and Pressure in the Venusian Atmosphere** The pressure at the Venusian surface is a crushing 90 atm (1296 lb/in.^{2}). Above the surface, atmospheric pressure decreases smoothly with increasing altitude. The temperature of Venus's atmosphere increases smoothly from a minimum of about 173 K (–150°F) at an altitude of 100 km to a maximum of nearly 750 K (900°F) on the ground.

The results of the early probing of Venus are summarized in Figure 6-11. Both pressure and temperature decrease smoothly with increasing altitude. From the changes in temperature and pressure above a planet's surface, we can understand the structure of its atmosphere.

6-6 The greenhouse effect heats Venus's surface

At first, no one could believe reports that the surface temperature on Venus was higher than the surface temperature on Mercury, which, after all, is closer to the Sun. After some initial skepticism astronomers quickly found a straightforward explanation—the **greenhouse effect** (Figure 6-12).

Perhaps you have had the experience of parking your car in the sunshine on a warm summer day. You roll up the

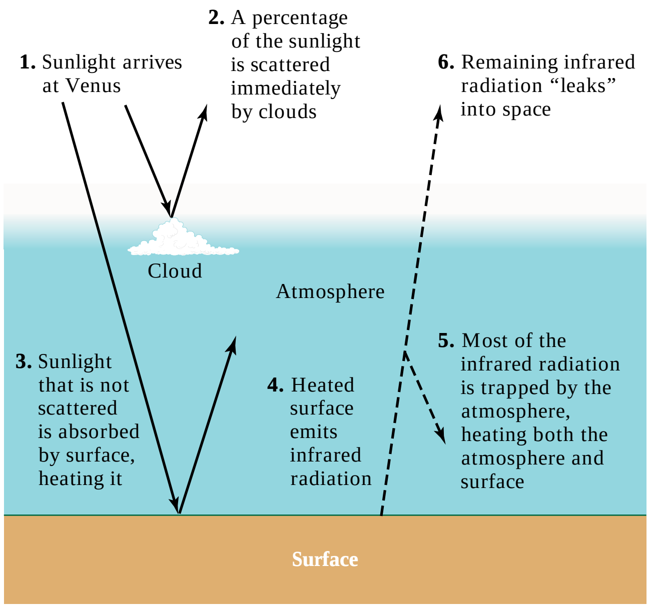


FIGURE 6-12 The Greenhouse Effect A portion of the sunlight reaching a planet penetrates through the atmosphere and heats the planet's surface. The heated surface emits infrared radiation, much of which is absorbed by water vapor and carbon dioxide. The trapped radiation helps raise the average temperatures of the surface and atmosphere. Some infrared radiation does penetrate the atmosphere and leaks into space. In a state of equilibrium, the rate at which the planet loses energy to space in this way is equal to the rate at which it absorbs energy from the Sun.

windows, lock the doors, and go on an errand. After a few hours, you return to discover that the interior of your automobile has become stiflingly hot, typically 20 K (36°F) warmer than the outside air temperature.

What happened to make your car so warm? First, sunlight entered your car through the windows. This radiation was absorbed by the dashboard and the upholstery, raising their temperatures. Because they become warm, your dashboard and upholstery emit infrared radiation, which you detect as heat and to which your car windows are opaque. This energy is therefore trapped inside your car and absorbed by the air and interior surfaces. As more sunlight comes through the windows and is trapped, the temperature continues to rise. The same trapping of sunlight warms an actual greenhouse.

Carbon dioxide is responsible for a similar warming of Venus's atmosphere. Like your car windows, carbon dioxide is transparent to visible light but opaque to infrared radiation. Although most of the visible sunlight striking the Venusian cloudtops is reflected back into space, enough light reaches the Venusian surface to heat it. The warmed surface in turn emits infrared radiation, which cannot escape through Venus's carbon dioxide–rich atmosphere. This trapped radiation produces the high temperatures found on Venus.

Without the greenhouse effect, the surface of Venus would have a noontime temperature of 465 K. Because of it, that temperature is actually a sweltering 750 K, hotter than the hottest spot on Mercury! Furthermore, the thick atmosphere keeps the night side of Venus at nearly the same temperature, unlike the night side of Mercury, where the temperature drops precipitously. This high temperature prevents liquid water from existing on Venus; its surface is dry.

On Earth, atmospheric water and carbon dioxide both contribute to the greenhouse effect in our air. Warmed by sunlight, the Earth emits infrared radiation, some of which is absorbed by water vapor and carbon dioxide gas, causing the air temperature to rise. The small amounts of these gases in the Earth's atmosphere produce a comparatively gentle greenhouse effect. The heating due to the greenhouse effect is, however, increasing on Earth as our atmosphere acquires more carbon dioxide from burning fossil fuels and other sources. The air retains this gas due to large-scale clear-cutting of forests, which decreases the number of plants that can convert this gas into other carbon compounds and oxygen.

6-7 Venus is covered with gently rolling hills, two "continents," and numerous volcanoes

Soviet spacecraft that landed on Venus provided us with intriguing close-up images of the planet's arid surface. Figure 6-13 is a view of Venus's regolith taken in 1981. Russian scientists believe that this region was covered with a thin layer of lava that contracted and fractured upon cooling to create the rounded, interlocking shapes seen in the photograph. Indeed, measurements by several spacecraft indicate that Venusian rock is quite similar to lava rocks called basalt, which are common on Earth and the Moon.

By far the best images of the Venusian surface came from the highly successful *Magellan* spacecraft that arrived at Venus in 1990. In orbit about the planet, *Magellan* sent radar signals through the clouds surrounding Venus. It mapped Venus using a radar altimeter that bounced microwaves off the ground directly below the spacecraft. By measuring the time delay of the radar echo, scientists determined the heights and depths of Venus's hills and valleys. As a result, astronomers have been able to construct a three-dimensional map of the planet. The resolution of this map is about 75 m. You could see a football stadium on Venus if there were any! (None were detected.)

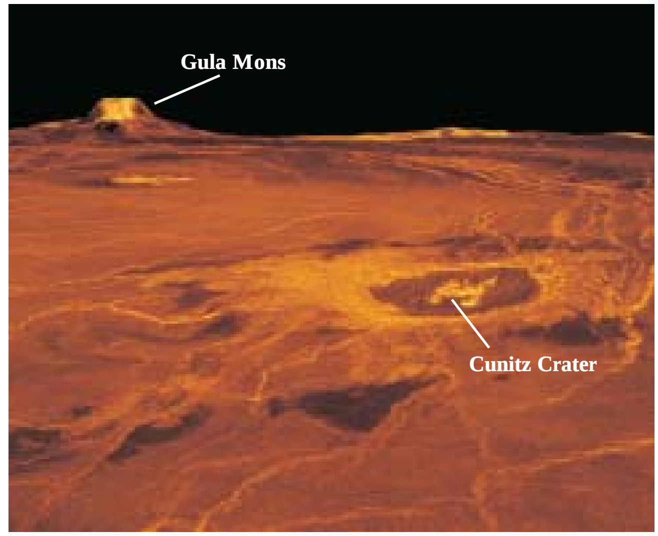
Venus is remarkably flat compared to the Earth. More than 80% of Venus's surface is covered with volcanic plains and gently rolling hills created by numerous lava flows. Figure 6-14 is a computer-generated view showing a typical Venusian landscape.

a

b

R I V U X G

FIGURE 6-13 The Venusian Surface (a) This color photograph, taken by a Soviet spacecraft, shows rocks that appear orange because the light was filtered through the thick, sulfur-rich clouds. (b) By comparing the apparent color of the spacecraft to the color it was known to be, computers can correct for the sulfurous light. The actual color of the rocks is gray. In this view, the rocky plates covering the ground may be fractured segments of a thin layer of lava. The toothed wheel in each image is part of the landing mechanism that keeps the spherical spacecraft from rolling. (a: C. M. Pieters and the USSR Academy of Sciences)



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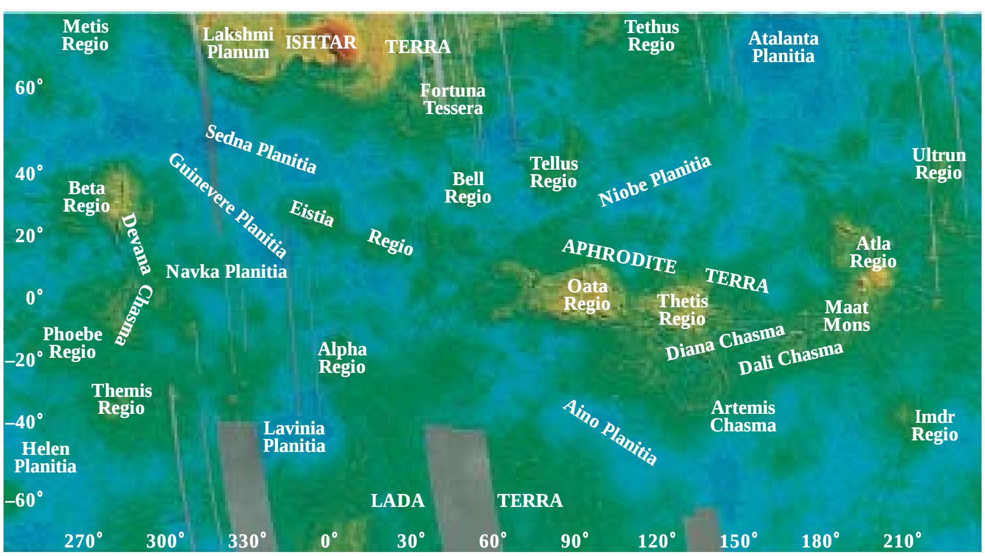
VIDEO 6.2

FIGURE 6-14 A Venusian Landscape Most of Venus is covered with plains and gently rolling hills produced by numerous lava flows. The crater in the foreground is 48 km (30 mi) in diameter. The volcano near the horizon is 3 km (1.9 mi) high. Note the cracks in the Venusian surface toward the right side of the image. (NASA/JPL)

Radar images revealed two large highlands, or "continents," rising well above the generally level surface of the planet (Figure 6-15). The continent in the northern hemisphere is Ishtar Terra, named after the Babylonian goddess of love and approximately the same size as Australia. Ishtar Terra is dominated by a high plateau ringed by towering mountains. The highest mountain is Maxwell Montes, whose summit rises to an altitude of 11 km above the average surface. For comparison, Mount Everest on Earth rises 9 km above sea level.

The larger Venusian continent, Aphrodite Terra (named after the Greek goddess called Venus by the Romans) is a vast belt of highlands just south of the equator. Aphrodite is 16,000 km (10,000 mi) in length and 2000 km (1200 mi)



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WEB LINK 6.4

FIGURE 6-15 A Map of Venus This false-color radar map of Venus, analogous to a topographical map of Earth, shows the large-scale surface features of the planet. The equator extends across the middle of the map. Color indicates elevation—red for highest, followed by orange, yellow, green and blue for lowest. The planet's highest mountain is Maxwell Montes on Ishtar Terra. Scorpion-shaped Aphrodite Terra, a continentlike highland, contains several spectacular volcanoes. Do not confuse the blue and green for oceans and land. (Peter Ford/MIT, NASA/JPL)

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FIGURE 6-16 A "Global" View of Venus A computer was used to map numerous *Magellan* images onto a simulated globe. Color is used to enhance small-scale structures. Extensive lava flows and lava plains cover about 80% of Venus's relatively flat surface. (NASA)

wide, giving it an area about one-half that of Africa. The global view of the surface of Venus in Figure 6-16 shows that most of Aphrodite Terra is covered by vast networks of faults and fractures.

While more than 1600 major volcanoes and volcanic features were discovered on Venus, fewer than a thousand impact craters have been observed there (Figure 6-17). This compares to the hundreds of thousands seen on the Moon and Mercury. Today, of course, Venus's thick atmosphere heats, and thereby vaporizes, much of the infalling debris that would otherwise create craters. Because its atmosphere is thicker than Earth's, Venus vaporizes such space junk falling toward it more efficiently than Earth does. However, there should have been a period shortly after Venus formed and before its atmosphere developed (from gases escaping from the planet's interior) when impacts were common.

The low number and random distribution of craters on Venus lead to the belief that the planet's surface is periodically erased and replaced. Because geologists have found no large-scale tectonic plate motion on Venus to refresh the surface, the current theory explaining the lack of extensive cratering is that the entire surface of the planet melts! This would occur if the crust is very thick compared to the Earth's crust. A crust 300 km thick (Earth's crust is everywhere less than 65 km thick) would insulate the interior so much that, heated by radioactive elements in it, the mantle could become hot enough to melt the crust on occasion.

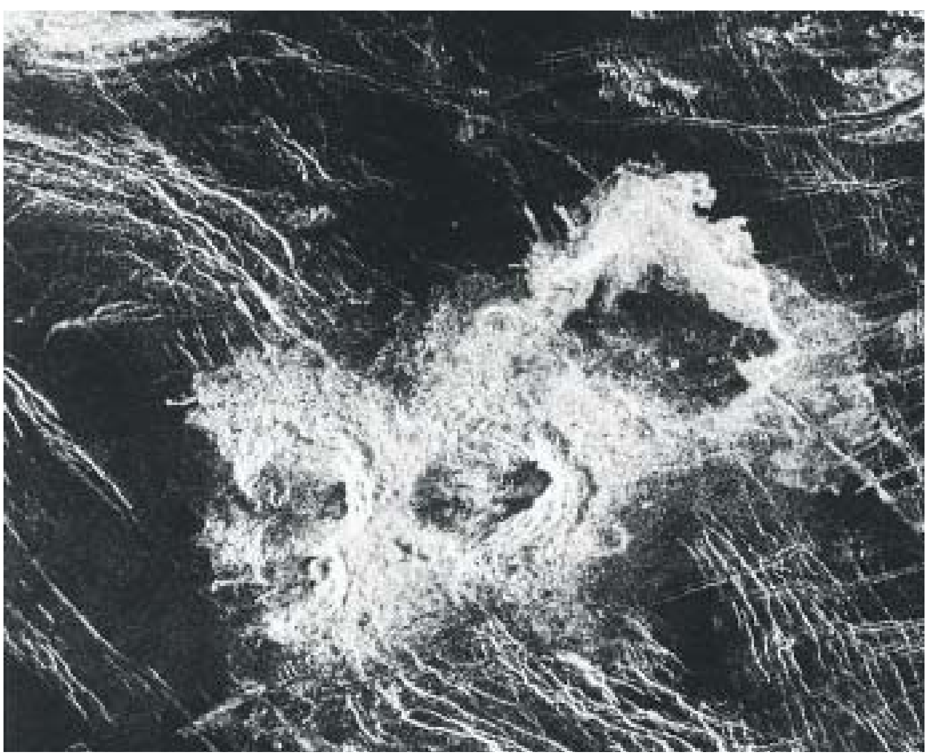

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FIGURE 6-17 Craters on Venus Impact craters on Venus tend to occur in clusters, which suggests that they are formed from large, single pieces of infalling debris that are broken up in the atmosphere. Shown here is the triple-impact Crater Stein. (NASA/JPL)

It has been proposed that every 700 million years or so, the entire surface of Venus liquefies until the pent-up heat escapes, a new solid crust forms, and the process begins anew.

The sulfur content of the air and the traces of active volcanoes on the surface are compelling indicators that, like the Earth, Venus has a molten interior. Because the average density of Venus is similar to that of Earth, its core is predominantly iron. Currents in the molten iron should generate a magnetic field. However, none of the spacecraft sent there has detected one. This is plausible only if Venus rotates exceptionally slowly, which it does (see Figure 6-10). In fact, the planet takes 116.8 Earth days to get from one sunrise to the next (if you could see the Sun from Venus's surface).

ANIMATION 6.5

Unlike the Earth, Venus has **retrograde rotation.** This means that the direction of Venus's orbit around the Sun (counterclockwise as seen from space far above the Earth's north pole) is *opposite* the direction of its rotation (clockwise as seen from the same vantage point). In other words, sunrise on Venus occurs in the west. Venus's rotation axis is tilted more than 177°, compared to the Earth's 23½° tilt. Because Venus's axis is within 3° of being perpendicular to the plane of its orbit around the Sun, the planet has no seasons. Although we do not know the cause of Venus's retrograde rotation, one likely explanation is that a monumental impact altered the rotation early in the planet's existence.

6-8 *Magellan*'s last gasp revealed irregularities in Venus's upper atmosphere

WEB LINK 6.5

Magellan finished mapping the surface of Venus in 1994. Instead of keeping it in orbit, NASA astronomers decided to give it one last mission. They fired braking rockets on the spacecraft, sending it spiraling down toward the planet's surface. By doing so, it was hoped that *Magellan* would transmit useful data about Venus's dense atmosphere before the spacecraft vaporized. On October 12, 1994, *Magellan* stopped transmitting, but before it did so, it sent back tantalizing information.

Magellan indicated that the density of Venus's atmosphere is lower at some altitudes and higher at other altitudes than was expected. This information will be useful in helping astronomers plan future missions to the cloud-shrouded planet.

MARS

Mars is the only planet whose surface features can be seen through Earth-based telescopes. Its distinctive rust-colored hue makes it stand out in the night sky (Figure 6-18). When Mars is near opposition, even telescopes for home use reveal its seasonal changes. Dark markings on the Martian

Mars' Vital Statistics

Mass	6.42×10^{23} kg (0.107 $M_\oplus$)
Radius	3393 km (0.532 $R_\oplus$)
Average density	3950 kg/m^3 (0.716 Earth density)
Orbital eccentricity	0.093
Sidereal period of revolution (year)	687 Earth days (1.88 Earth years)
Average distance from the Sun	2.28×10^8 km (1.52 AU)
Sidereal rotation period	24 h 37 min 22 s
Solar rotation period (day)	24 h 39 min
Albedo (average)	0.16

WEB LINK 6.6

FIGURE 6-18 **Mars Viewed from the Earth** This photograph of Mars was taken by the Hubble Space Telescope in 2001, when the Earth-Mars distance was 68 million km (43 million miles). (NASA)

R I V U X G

surface can be seen to vary, and prominent polar caps shrink noticeably during the spring and summer months (Figure 6-19).

6-9 Earth-based observations originally suggested that Mars might harbor life

The Dutch physicist Christiaan Huygens made the first reliable observations of Mars in 1659. Using a telescope of his own design, Huygens identified a prominent, dark surface feature that reemerged about every 24 hours, suggesting a rate of rotation similar to that of Earth. Huygens's observations soon led to speculation about life on Mars because the planet seemed so similar to Earth.

In 1877, Giovanni Virginio Schiaparelli, an Italian astronomer, reported seeing 40 lines crisscrossing the Martian surface. He called these dark features *canali*, an Italian term meaning "channels." It was soon mistranslated into English as *canals,* implying the existence on Mars of intelligent creatures capable of engineering feats. This speculation led Percival Lowell, who came from a wealthy Boston family, to finance a major new observatory near Flagstaff, Arizona. By the end of the nineteenth century, Lowell had allegedly observed 160 Martian "canals."

It soon became fashionable to speculate that the Martian canals formed an enormous, planetwide irrigation network to transport water from melting polar caps to vegetation near the equator. (The seasonal changes on Mars's dark surface markings can be mistaken for vegetation.) In view of the planet's reddish, desertlike appearance, Mars was thought to be a dying planet whose inhabitants must go to great lengths to irrigate their farmlands. No doubt the Martians would readily abandon their arid ancestral homeland and invade the Earth for its abundant resources. Hundreds of science fiction stories and dozens of monster movies owe their existence to the *canali* of Schiaparelli.

> **Insight into Science** **Perception and Reality** Our perceptual tendency to see patterns, even where they do not exist, makes it easy for us to leap to conclusions. Scientific images and photographs, however, require objective analysis.

On October 30, 1938, Orson Welles presented a radio program announcing the invasion of Earth by Martians. His broadcast, live from New York City, was inspired by the 1898 book *War of the Worlds* by H. G. Wells. (You might ask your grandparents if they heard the show.) So realistic was the performance that it caused panic throughout the New York–New Jersey area. Let's see how close to the mark H. G. Wells was when it comes to life on Mars.

6-10 Early space probes to Mars found no canals but did find some controversial features

WEB LINK 6.7

Spacecraft journeying to Mars since the 1970s have sent back pictures that clearly show numerous flat-bottomed craters, volcanoes, and canyons, but not one canal of a size consistent with those allegedly seen from Earth (Figure 6-20). Schiaparelli's *canali* were optical illusions, and H. G. Wells was completely off the mark. We have observed no cities or roads or other signs of civilization on the red planet. There is no evidence that intelligent Martian life has ever existed.

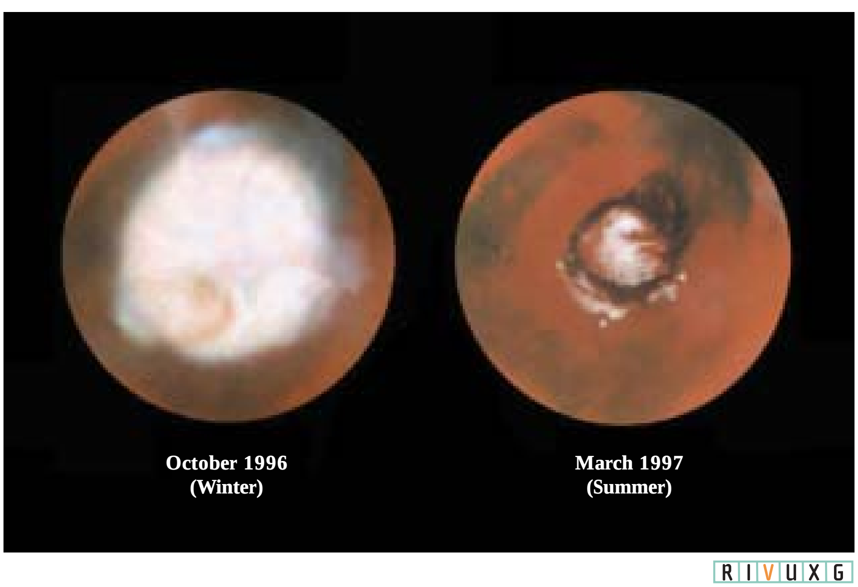


FIGURE 6-19 Changing Seasons on Mars During the Martian winter, the temperature drops so low that carbon dioxide freezes out of the Martian atmosphere. A thin coating of carbon dioxide frost covers a broad region around Mars's north pole. During summer in the northern hemisphere, the range of this north polar carbon dioxide cap decreases dramatically. In the summer a ring of dark sand dunes is exposed around Mars's north pole. (S. Lee/J. Bell/M. Wolff/Space Science Institute/NASA)

R I V U X G

FIGURE 6-20 **Martian Terrain** This high-altitude photograph shows a variety of the features on Mars, including broad, towering volcanoes (left) on the highland called Tharsis Bulge, impact craters (upper right), and vast, windswept plains. An enormous canyon system called Valles Marineris crosses horizontally just below the center of the image. (A. S. McEwen, USGS)

Insight into Science **Fact and Fiction** Science fiction may foreshadow real scientific discoveries. (Can you think of some examples?) But science also reins in the fantasies of the science fiction writer. A century ago, millions of people, including top scientists, believed that technologically advanced life existed on Mars.

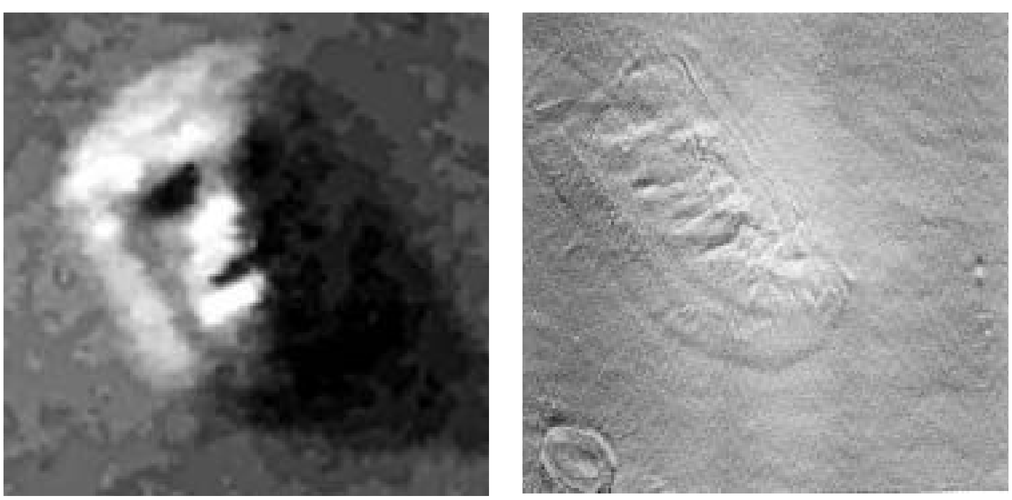
Astronomers have photographed several surface features that at first glance could have been crafted by intelligent lifeforms. In 1976, a hundred years after Schiaparelli's alleged discovery of canali, the *Viking Orbiter 1* spacecraft photographed a feature that appeared to be a humanlike face (Figure 6-21a). However, when the *Mars Orbiter* photographed the surface in greater detail and from a different angle in 1998 (Figure 6-21b), it found no facial features. If anything, the same spot looked more like a giant shoeprint.

Scientists universally believe that the face and other alleged patterns were created by shadows on wind-blown hills. Other features, in the shape of pyramids, are consistent with the winds eroding softer rock around harder rock pushed upward from inside Mars billions of years ago. The same thing happens on Earth.

Insight into Science **Keep It Simple** Was the Martian "face" made by intelligent life or by wind-sculpted hills? When two alternative interpretations present themselves, scientists apply the principle of Occam's razor and always choose the one requiring the fewer unproven assumptions.

6-11 Probes to Mars found craters, volcanoes, and canyons

The partially eroded, flat bottoms of the Martian craters probably result from dust storms that frequently rage across the planet's surface. Over the past two centuries, astronomers have seen faint surface markings disappear under a reddish-orange haze as thin Martian winds have stirred up finely powdered dust from the Martian regolith. Some storms obscure the entire planet as happened in 2001. Over the ages, deposits



a

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WEB LINK 6.8

FIGURE 6-21 **In the Eye of the Beholder** These two images of the same site on Mars, taken 22 years apart, show how the apparent face in (a) changed to a more "natural-looking" feature in (b). This transformation was due to weathering of the site, improved camera technology, and the change in angle at which the photograph was taken. (a: NSSDC/NASA; b: NSSDC/NASA and Dr. Michael H. Carr)

GUIDED DISCOVERY The Inner Solar System

In this section, we will learn more about the appearances of the inner planets as seen from Earth using your *Starry Night Backyard™* program.

Mercury Find Mercury (Edit/Find/Mercury). The first step is to see that Mercury is always close to the horizon when it is visible in the night sky.

1. *If Mercury is below the horizon:* Choose the "Reset Time" option when the "Obscured by Horizon" warning comes up. You will then see Mercury in the eastern sky.

Now, if the Sun is not yet up, Mercury is the "morning star." Step forward in time by 3 minute intervals and watch the Sun rise and Mercury disappear near the horizon. Go to section 3.

On the other hand, if the Sun is already up, it will be to the west (to the right) of Mercury. Set the time to 6 P.M., relocate Mercury, and run the time forward or backward until the Sun has set in the west but Mercury is still up. Mercury is now the "evening star," located near the western horizon. Step forward in time by 3 minute intervals and watch Mercury set. Go to section 3.

2. *If Mercury is already up in the sky:* If Mercury is west (to the right) of the Sun: We want to set up the screen with Mercury as the "morning star." To do this, re-set the time to 5 a.m., relocate Mercury, and run time forward or backward until Mercury is above the eastern horizon and the Sun is below the horizon. This shows Mercury as the "morning star." Now, run time forward at 3 minutes per timestep, and you will see the white dot of Mercury fade. Now go to section 3.

If Mercury is east (to the left) of the Sun in the sky, then set the time to 6 p.m., relocate Mercury, and run the time forward or backward until the Sun has set but Mercury is still up. Mercury is now the "evening star," located near the western horizon. Step forward in time by 3 minute intervals and watch Mercury set.

3. *Now we explore Mercury's orbit.* Go to Atlas mode (Go/Atlas) and again find Mercury. This time you will see it highly magnified. Zoom away using the magnifying glass icon with the minus sign until the angle of sky is about 70°. Make sure you are centered and locked on Mercury (grab Mercury, right click, and then left click on Centre/Lock). Set the timestep to 1 day and press the right pointing triangle. Describe and explain the motion of the Sun relative to Mercury. You can learn more about Mercury as seen from Earth by trying Observing Project 49 at the end of this chapter.

Venus Repeat the same procedures for Venus as we have described for Mercury. What similarities and differences do you see?

Mars Return to Atlas mode, set the date to 6/12/2003, time to midnight, and lock on Mars. What is Mars's phase? Zoom away until you have the Sun on the screen or you have gone the maximum distance (about 100° angle on the screen). Determine how far (in angle) the Sun is away from Mars. If the Sun is not visible, you can make this measurement by "dragging" the celestial sphere around and measuring angles from the grid. Does the Sun ever get this far in angle from Mercury or Venus, as seen from Earth? Explain.

of dust have filled in the crater bottoms, but 3 billion years of sporadic storms have not wiped out the craters; the Martian atmosphere is too thin to carry enough of this extremely fine-grained powder to eradicate them completely.

In 1971 the *Mariner 9* spacecraft went into orbit around Mars and began sending back detailed, close-up pictures. The lack of present tectonic plates there soon became evident. However, in 1998, the *Mars Global Surveyor* discovered patterns in the surface magnetic fields of Mars like those found where Earth's tectonic plates separate and lock the Earth's magnetic field in the rock. Geologists propose that when Mars was young, its internal "dynamo" (see section 5-4) created strong magnetic fields and that tectonic plates helped craft its surface, while locking traces of its changing magnetic field in the molten rock. However, the planet quickly cooled, its global magnetic field vanished, and tectonic-plate apparently ceased nearly 4 billion years ago.

Mariner 9 showed the existence of enormous volcanoes and vast canyons (Figure 6-22). The largest Martian volcano, Olympus Mons (Figure 6-23), covers an area as big as the state of Missouri and rises 26 km (16 mi) above the surrounding plains—nearly 3 times the height of Mount Everest. The highest volcano on Earth, Mauna Loa in the Hawaiian Islands, has a summit only 17 km above the ocean floor.

On Earth, the Hawaiian Islands are only the most recent additions to a long chain of volcanoes. They resulted from **hot-spot volcanism,** a process by which molten rock rises to the surface from a fixed hot region far below. The Pacific tectonic plate is slowly moving northwest at a rate of several centimeters per year. As a result, new volcanoes are created above the hot spot, while older ones move off and become extinct, eventually disappearing beneath the ocean.

Because Mars's surface does not appear to be moving due to the lack of tectonic plate motion, one hot spot can keep pumping lava upward through the same vent for millions of years. One result is Olympus Mons—a single giant volcano rather than a long chain of smaller ones. The vol-

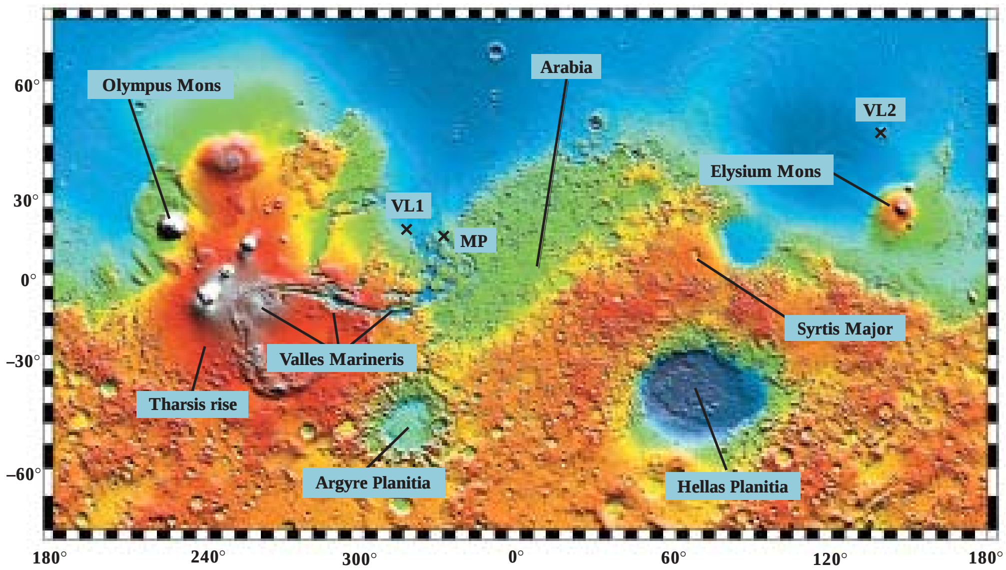

FIGURE 6-22 The Topography of Mars The color coding on this map of Mars shows elevations above (positive numbers) or below (negative numbers) the planet's average radius. To produce this map, an instrument on board *Mars Global Surveyor* fired pulses of laser light at the planet's surface, then measured how long it took each reflected pulse to return to the spacecraft. The *Viking Lander 1* (VL1), *Viking Lander 2* (VL2), and *Mars Pathfinder* (MP) landing sites are each marked with an x. (MOLA Science Team, NASA/GSFC)

cano's summit has collapsed to form a volcanic crater, called a **caldera,** large enough to contain the state of Rhode Island (see Figure 6- 23). Calculations indicate that Mars's interior should be solid, so we do not expect to see any further volcanic activity there.

Since arriving in September, 1997, the *Mars Global Surveyor* has provided more information about Mars than all previous missions to Mars combined. Detailed altitude measurements reveal that Mars has distinctly different northern and southern hemispheres (see Figure 6-22). For reasons we do not yet understand, the average elevation of the northern hemisphere is about 5 km (3 mi) lower than that of the southern hemisphere. Hence, they are referred to as Vastitas Borealis (the **northern vastness** or **northern lowlands**) and the **southern highlands.** Most of the volcanoes on Mars are in the northern hemisphere, but most of the impact craters are in the southern hemisphere. This suggests that the northern vastness has been resurfaced by some process that eradicated ancient lowland craters.

Between the two hemispheres, the earlier *Mariner 9* discovered a vast canyon running roughly parallel to the Martian equator (see Figures 6-20 and 6-24). In honor of the *Mariner* spacecraft that revealed so much of the Martian surface, this enormous chasm has been designated Valles Marineris.

Valles Marineris stretches over 4000 km, about one-fifth the circumference of Mars. The Martian canyons are up to 6 km (4 mi) deep and 190 km (120 mi) wide. Valles Marineris begins with heavily fractured terrain in the west and ends with ancient cratered terrain in the east. If this canyon were located on Earth, it would stretch from New York to Los Angeles. Geologists believe that Valles Marineris is a large crack that formed as the planet cooled. It was enhanced by nearby rising crust to its west and widened further by erosion. Some of the eastern parts of this system appear to have been formed almost entirely by water flow, like Earth's Grand Canyon.

By observing the orbit of *Mars Global Surveyor*, astronomers have concluded that the Martian crust is about 40 km thick under the northern lowlands and about 70 km thick under the southern highlands. However, they find that the boundary between the thin and thick crusts does not line up with the boundary between high and low terrain. Current models of Mars suggest that it has a core about 3400 km in diameter. However, a detailed understanding of Mars's interior waits for the placing of seismic detectors on the planet's surface.

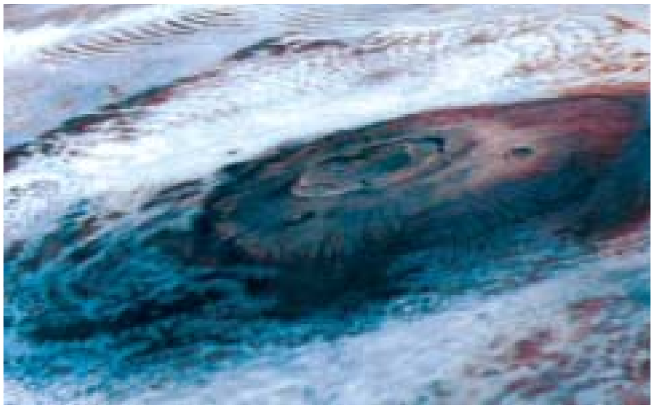

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FIGURE 6-23 The Olympus Caldera This view of the summit of Olympus Mons is based on a mosaic of six pictures taken by one of the *Viking* orbiters. The caldera consists of overlapping, volcanic craters and measures about 70 km across. The volcano is wreathed in mid-morning clouds brought upslope by cool air currents. The cloudtops are about 8 km below the volcano's peak. (NASA)

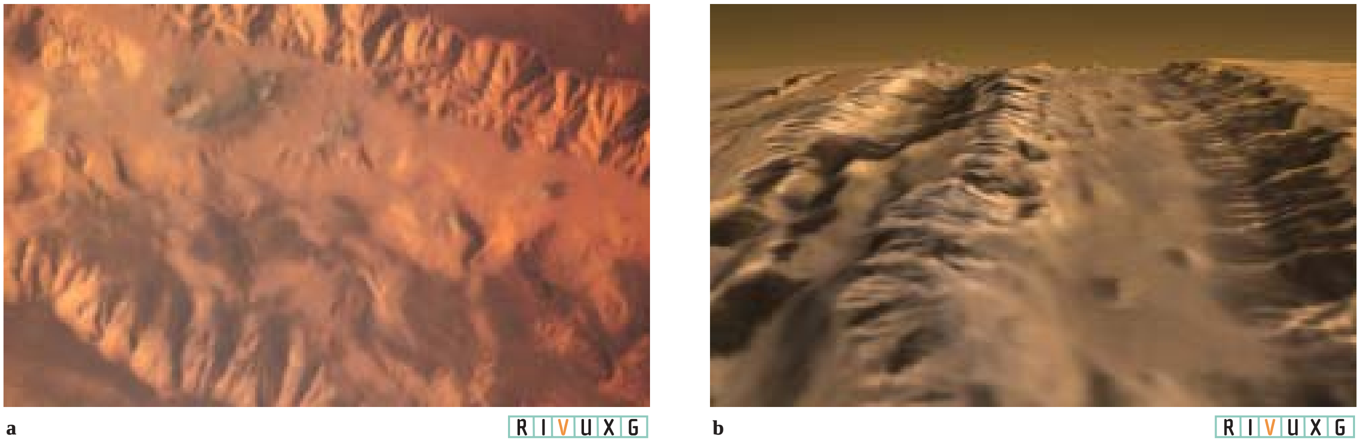

FIGURE 6-24 A Segment of Valles Marineris (a) This mosaic of *Viking Orbiter* photographs shows a segment of Valles Marineris. The canyon is about 100 km (60 mi) wide in this region. The canyon floor has two major levels. The northern (upper) canyon floor is 8 km (5 mi) beneath the surrounding plateau, whereas the southern canyon floor is only 5 km (3 mi) below the plateau. (b) This westward-looking view of the Valles Marineris was created using altitude data from *Mars Global Surveyor.* (a: NASA; b: MOLA Science Team/NASA)

6-12 Surface features indicate that water once flowed on Mars

Despite disproving the theory that Mars has broad canals, Mars-orbiting spacecraft did reveal many features that look like dried-up riverbeds (Figure 6-25), lakes, and other water-related features. Some of the riverbeds include intricate branched patterns and delicate channels meandering among flat-bottomed craters. Rivers on Earth invariably follow similarly winding courses (Figure 6-26).

The Martian riverbeds were totally unexpected because liquid water cannot exist today on Mars. Water is liquid 4

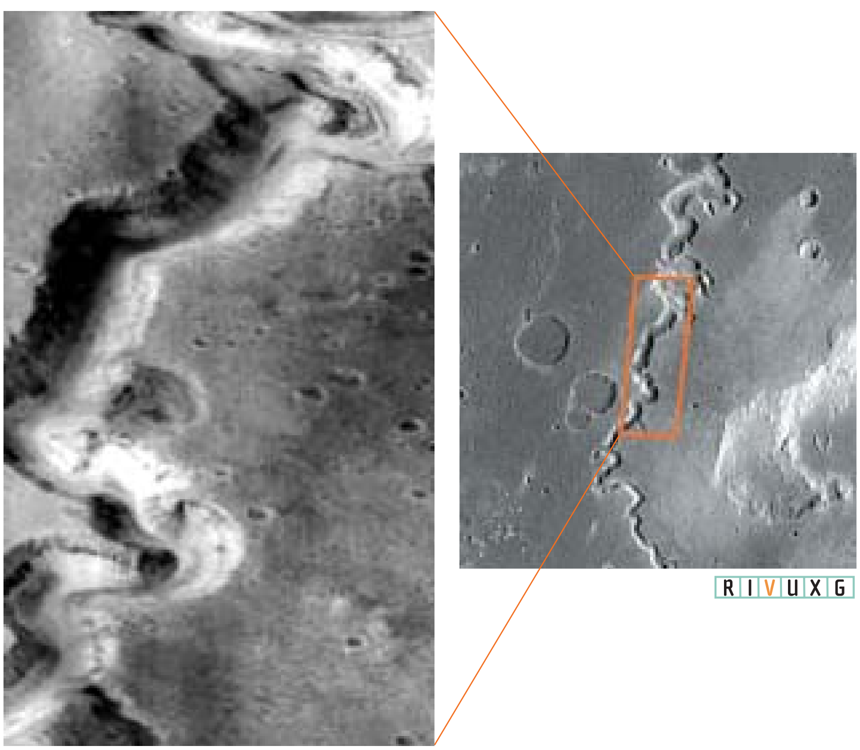

FIGURE 6-25 Ancient River Channel on Mars Winding canyons on Mars, such as the one in this *Viking Orbiter I* image (on the right) appear to be at least partly due to sustained water flow. This belief is supported by the terraces seen on the canyon walls in the high resolution *Mars Orbiter* image (inset). Long periods of water flow require that the planet's atmosphere was once thicker and its climate more Earthlike. (NASA)

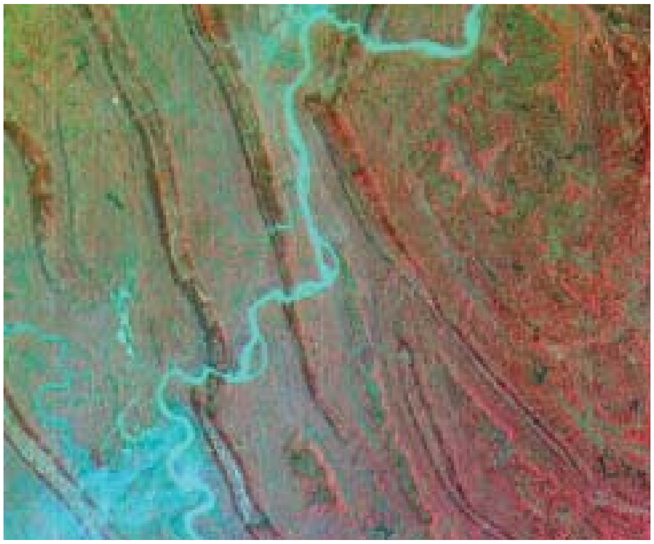
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FIGURE 6-26 **River Flow on Earth** This image of the Yangzi river near Chongqing, China, as is typical of rivers on Earth, shows the same snakelike curve as the river channels on Mars. (TMSC/NASA)

over a limited range of temperature and pressure. At low temperatures, water becomes ice; at high temperatures, it becomes steam. The atmospheric pressure also affects the state of water. If the pressure is very low, molecules easily escape from the liquid's surface, causing the water to vaporize. Because the pressure of Mars's atmosphere is only 0.6% that of the Earth's atmosphere, any liquid water on Mars today would furiously boil and rapidly evaporate into the thin Martian air. If the gravitational attraction of any planet (or moon) to various gases in its atmosphere is too low, these gases will eventually escape into space. Calculations reveal that water escapes from Mars's atmosphere.

Further evidence that water once flowed on Mars comes from so-called *SNC meteorites* found on Earth (Figure 6-27a). These space rocks are believed to have once been pieces of Mars because their chemistries are consistent with those of rocks studied on Mars's surface and because they contain trace gases in amounts found only in the current Martian atmosphere. The meteorites were ejected into space during especially powerful impacts on that planet's surface. They also contain water-soaked clay, which is not expected to be found on any objects in the solar system besides Mars, Earth, and perhaps Europa. At least 22 Mars meteorites have been identified.

Where did the water on Mars come from and go to? Some of it was (and still is) frozen in the Martian polar caps, although their seasonal variations today are created by the freezing and evaporating of dry ice (carbon dioxide). The temperature at Mars's poles, typically 160 K (–170°F), keeps the water there permanently frozen, like the permafrost found in northern Asia and on Antarctica. Other frozen water probably lies elsewhere under the Martian surface. Heat from meteoritic impacts or from volcanic activity occasionally melted this layer of permafrost on Mars. The ground then collapsed, and millions of tons of rock pushed the water to the surface. These flash floods could account for the riverbeds we see there today.

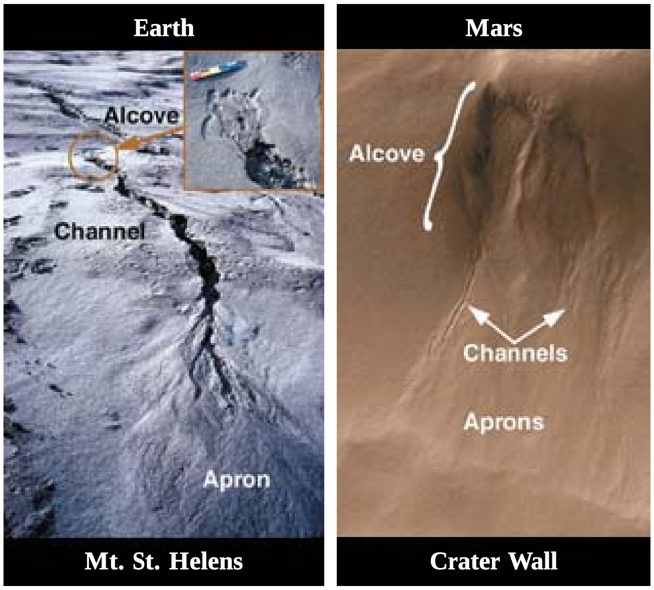
In 2001, astronomers reported evidence that volcanic activity may still be causing episodic flows of both water and lava on Mars's surface. *Mars Global Surveyor* images


a

b

R I V U X G

FIGURE 6-27 **A Piece of Mars on Earth** Mars's thin atmosphere does little to protect it from impacts. Some of the debris ejected from impact craters there apparently traveled to Earth. (a) This SNC meteorite was recovered in Antarctica. It shows strong evidence of having been exposed to liquid water on Mars, perhaps for hundreds of years. (b) These may be the fossil remains of primitive bacterial life on Mars. (a: NASA; b: NASA/JPL)



a b R I V U X G

FIGURE 6-28 Water Flow on Earth and Mars (a) When underground water flows on the Earth, the surface can become unstable and slide (creating what geologists call an *alcove*). The water reaching the surface runs down, gouging out *channels* and carrying debris that creates the *apron.* (b) This image from the *Mars Global Surveyor* shows the same features, suggesting that liquid water has come from under Mars's surface. When this event occurred is not yet known. (JPL/Malin Space Science Systems/NASA)

show channels apparently carved by water flowing down the walls of pits or craters (Figure 6-28). What makes these observations especially intriguing is that they appear to be geologically young, indicating that liquid water may still exist under the Martian surface.

Evidence that water existed as recently as a few million years ago (and possibly still today) just meters below Mars's equator also comes in the form of clusters of cones on the planet's surface. These cones are created when lava flows over water-rich terrain. The lava vaporizes the water, which eventually bursts through the lava, creating the cones. Similar clusters of cones on Earth created by this mechanism are found in Iceland. We present further evidence for water on Mars in section 6-14.

6-13 Martian air is thin and often filled with dust

As on Venus, some 95% of Mars's thin atmosphere is composed of carbon dioxide. The remaining 5% consists of nitrogen, argon, and some traces of oxygen. The planet's gravitational force is just strong enough to hold all its gases but as noted above, it is too weak to prevent most water vapor from evaporating into space. Consequently, the concentration of water vapor in Mars's atmosphere is 30 times lower than the concentration above the Earth. If all the water vapor could somehow be squeezed out of the Martian atmosphere, it would not fill even one of the five Great Lakes of North America.

Mars experiences Earthlike seasons because of a striking coincidence, first noted in the late 1700s by the German-born English astronomer William Herschel. Just as the Earth's equatorial plane is tilted $23\frac{1}{2}$° from the plane of its orbit, Mars's equator makes an angle of about 25° with its orbit. However, the Martian seasons last nearly twice as long as Earth's, because Mars takes nearly two Earth years to orbit the Sun.

Unlike our blue sky, Mars's atmosphere is often pastel red, sometimes turning shades of pink and russet (Figure 6-29). All these colors are due to the fine dust blown from the planet's desertlike surface during windstorms. The dust is iron oxide, familiar here on Earth as rust. Mars's sky also changes color because the amount of dust in the air varies with the season. During the winter, carbon dioxide ice adheres to the dust particles and drags them to the ground. This helps clear and lighten the air. In the summer months, the carbon dioxide is not frozen, and the dust blown by surface winds remains aloft longer.

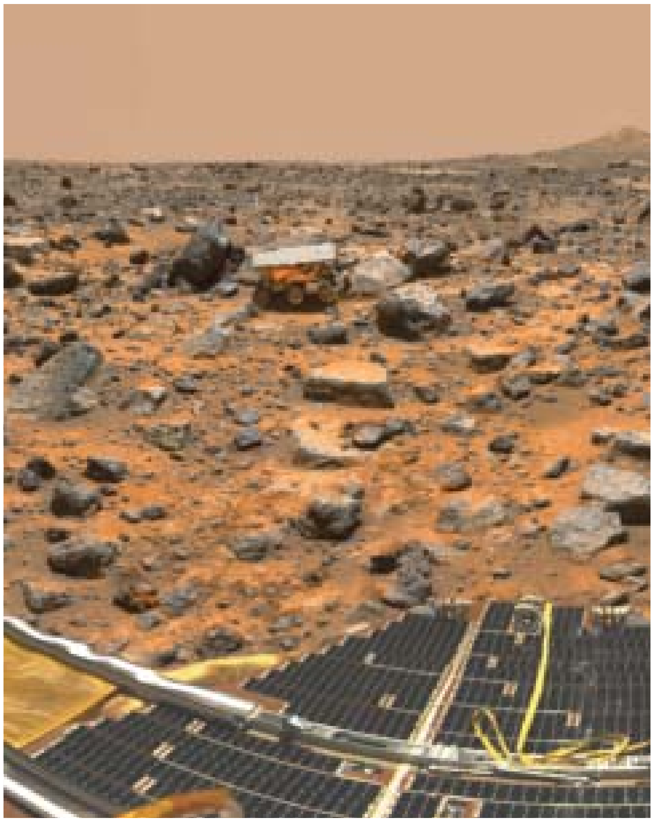
The sky color also changes over periods of many years. In 1995, for example, the amount of dust was observed to have dropped dramatically compared to that observed in the 1970s. The reason for such long-term changes is still under investigation.

6-14 Surface exploration reveals an antiseptic surface and even more signs of water

The discovery in the 1960s that water once existed on the surface of Mars rekindled speculation about Martian life. Although it was clear that Mars has neither civilizations nor fields of plants, microbial life-forms still seemed possible. Searching for signs of organic matter was one of the main objectives of the ambitious and highly successful *Viking* missions.

The two *Viking* spacecraft were launched during the summer of 1975. Each spacecraft consisted of two modules—an orbiter and a lander. Almost a year later, both *Viking* landers set down on rocky plains north of the Martian equator (see Figure 6-22).

The landers confirmed the long-held suspicion that the red color of the planet is due to large quantities of iron in its soil. Despite the high iron content of its crust, Mars has a lower average density (3950 kg/m^3) than that of other ter-



R I V U X G

FIGURE 6-29 Mars's Rust-Colored Sky Taken by the *Mars Pathfinder,* this stunning photograph of another world shows the *Sojourner* rover snuggled against a rock named Moe on the Ares Vallis. At the top of the image, the pink color of the Martian sky is evident. One of the "Twin Peaks" can be seen in the background, about 1 km away. (NASA)

restrial planets (more than 5000 kg/m^3 for Mercury, Venus, and Earth). Mars must therefore contain overall a lower percentage of iron than these other planets.

Each *Viking* lander was able to dig into the Martian regolith and retrieve rock samples for analysis (Figure 6-30). Bits of the regolith were observed to cling to a magnet mounted on the scoop, indicating that the regolith contains iron (consistent with the assertion above that Mars is rich in iron oxides). Indeed, further analysis showed the rocks at both sites to be rich in iron, silicon, and sulfur. The Martian regolith can best be described as an iron-rich clay.

The *Viking* landers each carried a compact biological laboratory designed to test for microorganisms in the Martian soil. Three biological experiments were conducted, each based on the idea that living things alter their environment: They eat, they breathe, and they give off waste products. In each experiment, a sample of the Martian regolith was placed in a closed container, with or without a nutrient substance. The container was then examined for any changes in its contents.

The first data returned by the *Viking* biological experiments caused great excitement. In almost every case, rapid and extensive changes were detected inside the sealed containers. However, further analysis showed that these changes were due solely to nonbiological chemical processes. Apparently, the Martian regolith is rich in chemicals that effervesce (fizz) when moistened. A large amount of oxygen is apparently tied up in the regolith in the form of unstable chemicals called *peroxides* and *superoxides,* which break down in the presence of water to release oxygen gas.

The chemical reactivity of the Martian regolith probably comes from ultraviolet radiation that beats down on the planet's surface. Ultraviolet photons easily break apart molecules of carbon dioxide (CO_2) and water vapor (H_2O) by

R I V U X G

VIDEO 6.6

FIGURE 6-30 Digging in the Martian Regolith *Viking*'s mechanical arm with its small scoop protrudes from the right side of this view of the *Viking 1* landing site. Several small trenches dug by the scoop in the Martian regolith appear near the left side of the picture. (NASA) knocking off oxygen atoms, which then become loosely attached to chemicals in the regolith. Ultraviolet photons also produce ozone (O_3) and hydrogen peroxide (H_2O_2), which become incorporated in the regolith. In all these cases, the loosely attached oxygen atoms make the regolith extremely reactive.

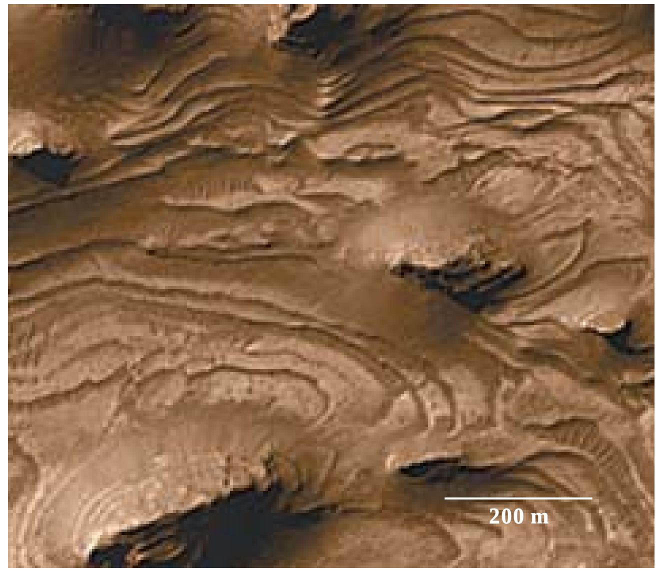
Here on Earth, hydrogen peroxide is commonly used as an antiseptic. When you pour this liquid on a wound, it fizzes and froths as the loosely attached oxygen atoms chemically combine with organic material and destroy germs. The *Viking* landers *may* have failed to detect any organic compounds on Mars, because the superoxides and peroxides in the Martian regolith make it antiseptic today.

Okay, if there is no sign of life on Mars now, are there
5 signs of ancient life from the days when water flowed? Curiously, the best evidence may lie on Earth. When cut open, several of the Martian meteorites (section 6-12) have shown microscopic features that could be fossils of Martian bacterial life and their excretions (see Figure 6-27b). These features, no larger than 500 nm (1/100th the diameter of a human hair), are 30 times smaller than bacteria found on Earth. Detailed analysis of the meteorites in 2001 revealed the presence of several organically created features, including tiny spheres found with some of Earth's bacteria, and magnetite crystals, which are also used by some bacteria on Earth as compasses to find food. It is worth noting that claims of fossils from Mars in the 1960s have been disproved. While the present meteorite evidence is not yet conclusive evidence that life existed there, it has withstood over five years of rigorous analysis and the studies continue.

The 1997 visit by *Pathfinder* and its little rover, *Sojourner* (see Figure 6-29), to the Ares Vallis has revealed evidence of several floods at the mouth of a dried flood plain. The evidence includes layers of sediment, clumps of rock and sand stuck together like similar groupings created by water on Earth, rounded rocks worn down as they were dragged by the water, and rocks aligned by water flow. The rover performed some 20 chemical analyses of rocks in the landing area. Results indicate chemical compositions consistent with those of the SNC meteorites, supporting the belief that these latter bodies came from Mars. The soil is a rusty color, laden with sulfur. The source of this sulfur is a mystery, as is the large amount of silicon-rich silica discovered on rocks such as Barnacle Bill.

Further evidence for the existence of standing water on Mars comes from layered terrain, similar to that found in Earth's Grand Canyon, located in several places on the red planet (Figure 6-31). The most plausible explanation of these formations is layers of sediment laid down by large bodies of water.

The temperature at *Pathfinder*'s (see Figure 6-22) site ranged from 197 K (–105° F) just before dawn to 263 K (14°F) at the warmest time of day. During the afternoons, heat from the planet's surface warmed the air and created



R I V U X G

FIGURE 6-31 Ancient Oceans and Lakes on Mars This *Mars Global Surveyor* images of a portion of *Valles Marineris* reveals terrain with "stair step layers." Such terrain is likely to have been created by sedimentation at the bottom of an ancient body of water. (Malin Space Science Systems/JPL/NASA)

whirlwinds called **dust devils.** A similar phenomenon occurs in dry or desert terrain on Earth. Martian dust devils reach altitudes of 6 km (20,000 ft). All three landers detected drops in air pressure as dust devils swept past. Dust devils are large enough to be seen by orbiting spacecraft (Figure 6-32)

WEB LINK 6.12 The *Mars Global Surveyor*'s images have greatly strengthened the belief that Mars once had liquid water, as seen in Figure 6-33. The total amount of water that existed on Mars's surface is not known. By studying flood channels that exist there, geologists estimate that there was enough water to cover the planet to a depth of 500 meters (1500 ft). For comparison, Earth has enough water to cover our planet to a depth of 2700 meters (8900 ft), assuming that the Earth's surface was everywhere a uniform height. The evidence is very strong now that Mars once had lakes, rivers, and perhaps even oceans of liquid water. There is observational evidence of ancient shoreline encircling the northern lowlands of Mars. The belief that the northern lowlands were an ocean is supported by the analysis of a 1.2 billion-year-old meteorite from Mars. It has remnants of salt believed to have been deposited there when the Martian ocean dried up.

The *Mars Global Surveyor* has taken visible light images of Mars's surface, seeing objects as small as 1.5 m across. Its laser has mapped the planet to a resolution of 330 m along

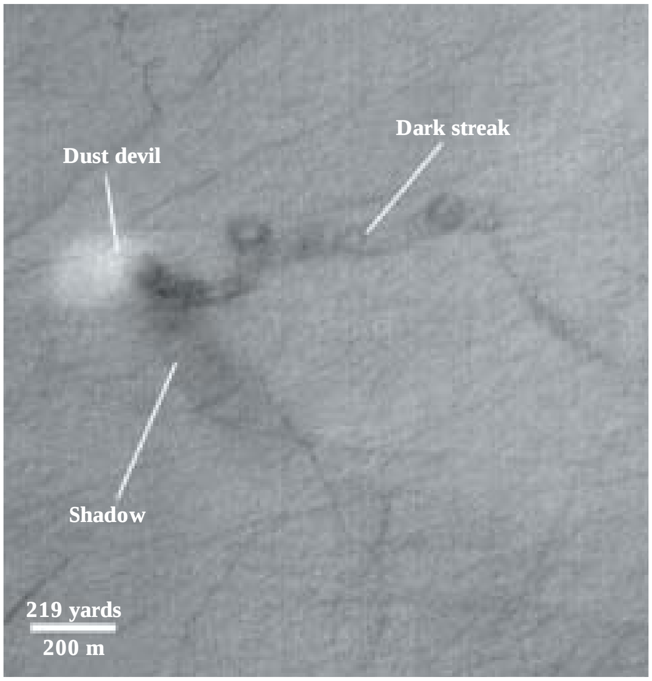


FIGURE 6-32 Martian Dust Devil This *Mars Global Surveyor* image shows a dust devil as seen from almost directly above. This tower of swirling air and dust casts a long shadow in the afternoon Sun. The dust devil had been moving from right to left before the picture was taken, leaving a dark curlicue-shaped trail in its wake. The area shown is about 1.5 × 1.7 km (about 1 mile on a side). (NASA/JPL/Malin Space Science Systems)

FIGURE 6-33 Evidence of Water on Mars A dry Martian lake, photographed by the *Mars Global Surveyor* with a resolution of 1.5 m. An excellent example of how geology and astronomy overlap, the features of this dry lake are consistent with those found on lakebeds on Earth. (NASA/JPL)

the surface and 1 m in height (see Figure 6-22). *Surveyor* has also mapped heat emitted from Mars and mineral deposits on its surface, along with the planet's strange magnetic fields, discussed earlier. This remotely sensed information is invaluable in helping space scientists decide where to explore Mars's surface in upcoming missions such as the *Mars Odyssey* spacecraft, which is now collecting information about the planet's surface composition, radiation environment, and underground water.

6-15 Mars's two moons look more like potatoes than spheres

Two tiny moons orbit close to Mars's surface. Phobos (meaning "fear") and Deimos ("panic") are so small that they were not discovered until 1877. Potato-shaped Phobos is the inner and larger of the two (Figure 6-34a). It rises in the west and races across the sky in only $5^{1/2}$ hours, as seen from Mars's equator. It is heavily cratered, and observations by *Mars Global Surveyor* indicate that its surface has been transformed into dust at least 1 meter thick by countless tiny impacts over the eons. Football-shaped Deimos is less cratered than Phobos (Figure 6-34b). As seen from Mars, Deimos rises in the east and takes about three Earth days to creep from one horizon to the other.

Phobos and Deimos were not formed like our Moon, by splashing off Mars. Rather, they are captured planetesimals. Both moons are in synchronous rotation as they orbit the red planet.

Insight into Science **Imagine the Moon** The definitions we use for words based on our everyday experience often fail us in astronomy. For example, the word "moon" usually creates an image of a spherical body, like our Moon. In reality, most of the moons in the solar system are unsymmetrical, like Phobos and Deimos.

WEB LINK 6.13

FIGURE 6-34 Phobos and Deimos (a) Phobos, the larger of Mars's two moons, is potato-shaped and measures approximately 28 × 23 × 20 km. It is dominated by crater Stickney, seen on the left. (b) Deimos is less cratered than Phobos and measures roughly 16 × 12 × 10 km. (a & b: NASA)

6-16 Frontiers yet to be discovered

All three other terrestrial planets have much to reveal. We have yet to see all of Mercury's surface. What is the chemical composition of its surface rocks? What is Mercury's cooling history and how much of its core is molten? Is there really ice at its poles? If so, how did it get there? What will its internal structure reveal?

Does Venus have active volcanoes? If not, what supplies its atmosphere with sulfur compounds? Can we find observational evidence of what caused Venus's rotation axis to flip over? Likewise, can we find further evidence that its surface periodically undergoes significant recovering?

Perhaps one of the most significant discoveries that lies in store in our solar system is confirmation that life once existed on Mars and if there actually is liquid water under the red planet's surface, whether there is still life there. If so, how far did life evolve? What are the similarities and differences between such life and life on Earth? Significant similarities might imply a common origin. Furthermore, what is the surface water history of that world? What causes its local magnetic fields? What does its interior look like? How did its axis get tilted? Where did its moons come from? It is likely that we will have answers to many of these questions in the coming few decades.

Further Reading on These Topics

WHAT DID YOU KNOW?

1 *Is the temperature on Mercury, the closest planet to the Sun, higher than the temperature on Earth?* The temperature on the daytime side of Mercury is much higher than on Earth, but the temperature on the nighttime side of Mercury is much lower than on Earth, because Mercury rotates so slowly and has little atmosphere to retain heat.

2 *What planet is most similar to Earth?* Venus is most similar to Earth in size, chemistry, and distance from the Sun. Mars is more similar to Earth (than Venus) only in its length of day and in having seasons.

3 *What is the composition of the clouds surrounding Venus?* The clouds are made primarily of sulfuric acid.

4 *Does Mars have liquid water on its surface today?* No, but there are strong indications that it had liquid water on its surface in the past.

5 *Is life known to exist on Mars today?* No current life has yet been discovered on Mars.

KEY WORDS

3-to-2 spin-orbit coupling, 167
caldera, 177
dust devil, 182
greenhouse effect, 169
hot-spot volcanism, 176
northern vastness (northern lowlands), 177
retrograde rotation, 173
scarp, 165
southern highlands, 177

KEY IDEAS

All four inner planets are composed primarily of rock and metal, and thus they are classified as terrestrial.

Mercury

• Even at its greatest orbital elongations, Mercury can be seen from Earth only briefly after sunset or before sunrise.

• The *Mariner 10* spacecraft passed near Mercury in the mid-1970s, providing pictures of its surface. The Mercurian surface is pocked with craters like the Moon's, but extensive, smooth plains lie between these craters. Long cliffs meander across the surface of Mercury. These scarps probably formed as the planet cooled, solidified, and shrank.

• The long-ago impact of a large object formed the huge Caloris Basin on Mercury and shoved up jumbled hills on the opposite side of the planet.

• Mercury has an iron core much like that of the Earth.

Venus

• Venus is similar to the Earth in size, mass, and average density, but it is covered by unbroken, highly reflective clouds that conceal its other features from Earth-based observers.

• While most of Venus's atmosphere is carbon dioxide, its dense clouds contain droplets of concentrated sulfuric acid mixed with yellowish sulfur dust. Active volcanoes on Venus may be a constant source of this sulfurous veil.

• Venus's exceptionally high temperature is caused by the greenhouse effect, as the dense carbon dioxide atmosphere traps and retains heat emitted by the planet. The surface pressure on Venus is 90 atm, and the surface temperature is 750 K. Both temperature and pressure decrease as altitude increases.

• The surface of Venus is surprisingly flat, mostly covered with gently rolling hills. There are two major "continents" and several large volcanoes. The surface of Venus shows evidence of local tectonic activity but not the large-scale motions that play a major role in continually reshaping the Earth's surface.

Mars

• Earth-based observers found that the Martian solar day is nearly the same as that of the Earth, that Mars has polar caps that expand and shrink with the seasons, and that the Martian surface undergoes seasonal color changes.

• A century ago observers reported networks of linear features that many perceived as canals. These observations led to speculation about self-aware life on Mars.

• The Martian surface has many flat-bottomed craters, several huge volcanoes, a vast equatorial canyon, and dried-up riverbeds—but no canals formed by intelligent life. Flash-flood features and dry riverbeds on the Martian surface indicate that large amounts of water once flowed there.

• Liquid water would quickly boil away in Mars's thin present-day atmosphere, but the planet's polar caps contain some frozen water, and a layer of permafrost may exist beneath the regolith.

• The Martian atmosphere is composed mostly of carbon dioxide. The surface pressure is less than 0.01 atm.

• Chemical reactions in the regolith together with ultraviolet radiation from the Sun apparently act to sterilize the Martian surface.

• Mars has no global magnetic fields, but local fields pierce its surface in at least nine places.

• Features that may be fossil remains of bacteria have been found in several meteorites that are believed to have come from Mars.

• Mars has two potato-shaped moons, the captured planetesimals Phobos and Deimos. Both are in synchronous rotation with Mars.

REVIEW QUESTIONS

1 Why is Mercury so difficult to observe? When is the best time to see the planet? *Hint:* The Guided Discovery box, "The Inner Solar System," on page 176 can help.

2 Compare the surfaces of Mercury and our Moon. How are they similar? How are they different?

3 Compare the interiors of Mercury and Earth. How are they similar? How are they different?

4 To better understand the interiors of Mercury and Earth, do Interactive Exercise 6-1 on the Web or CD-ROM. You can print out the result, if requested.

5 What are the longest features found on Mercury? Why are the examples of this feature probably much older than tectonic features on the Earth?

6 Briefly describe at least one theory explaining why Mercury has such a large iron core.

7 Astronomers often refer to Venus as the Earth's twin. What physical properties do the two planets have in common? In what ways are the two planets dissimilar?

8 Why is it hotter on Venus than on Mercury?

9 What is the greenhouse effect? What role does it play in the atmospheres of Venus and the Earth?

10 What evidence exists for active volcanoes on Venus?

11 Describe the Venusian surface. What kinds of geological features would you see if you could travel around the planet?

12 Why do astronomers believe that Venus's surface was not molded by the kind of tectonic activity that shaped the Earth's surface?

13 Why is Mars red?

14 When is the best time to observe Mars from Earth? *Hint:* The Guided Discovery box, "The Inner Solar System," on page 176 can help.

15 Compare the cratered regions of Mercury, the Moon, and Mars. Assuming that the craters on all three worlds originally had equally sharp rims, what can you conclude about the environmental histories of these worlds?

16 How would you tell which craters on Mars were formed by meteoritic impacts and which by volcanic activity?

17 Compare the volcanoes of Venus, Earth, and Mars. Do you think hot-spot volcanism is or was active on all three worlds? Explain.

18 What geologic features indicate plate tectonic activity once occurred on Mars? What features created by tectonic activity on Earth are not found on Mars?

19 To better understand the surface features of Mars, do Interactive Exercise 6-2 on the Web or CD-ROM. You can print out your results, if requested.

20 What is the current knowledge concerning life on Mars? Do you think that today Mars is as barren and sterile as the Moon? Why or why not?

21 To compare the surfaces of Mercury, Venus, and Mars, do Interactive Exercise 6-3 on the Web or CD-ROM. You can print out your results, if requested.

22 What evidence have astronomer's accumulated that liquid water once existed in large quantitites on Mars's surface? What evidence is there that water is still there, under the surface?

ADVANCED QUESTIONS

23 What evidence do we have that the surface features on Mercury were not formed during recent geologic history?

24 Venus takes 440 days to move from greatest western elongation to greatest eastern elongation, but it needs only 144 days to go from greatest eastern elongation to greatest western elongation. With the aid of a diagram, explain why.

25 As seen from Earth, the brightness of Venus changes as it moves along its orbit. Describe the main factors that determine Venus's variations in brightness as seen from Earth. *Hint:* See the discussion of Venus in Chapter 2.

26 How might Venus's cloud cover change if all of Venus's volcanic activity suddenly stopped? How might these changes affect the overall Venusian environment?

27 Compare Venus's continents with those on the Earth. What do they have in common? How are they different?

28 Explain why Mars has the longest synodic period of all the planets, although its sidereal period is only 687 days.

29 With carbon dioxide accounting for about 95% of the atmospheres of both Mars and Venus, why do you think there is little greenhouse effect on Mars today?

30 Could the polar regions of Mars reasonably be expected to harbor life-forms, even though the Martian regolith is sterile at the *Viking* lander sites?

DISCUSSION QUESTIONS

31 If you were planning a return mission to Mercury, what features and observations would be of particular interest to you and why?

32 If you were designing a space vehicle to land on Venus, what special features would be necessary? In what ways would this mission and landing craft differ from a spacecraft designed for a similar mission to Mercury?

33 Suppose someone told you that the *Viking* mission failed to detect life on Mars simply because the tests were designed to detect terrestrial life-forms, not Martian life-forms. How would you respond?

34 Compare the scientific opportunities for long-term exploration offered by the Moon and Mars. What difficulties would there be in establishing a permanent base or colony on each of these two worlds?

35 Imagine you are an astronaut living at a base on Mars. Describe your day's activities, what you see, the weather, the spacesuit you are wearing, and so on.

WHAT IF ...

36 Mercury had synchronous rotation? How would the temperatures on such a planet be different than they are today? Where would humans set up camp on such a world?

37 Venus had the same rotation rate, surface, and atmosphere as the Earth? In what ways would life there be different than it is here? How would their perceptions of the cosmos be different from ours?

38 Mars had the same mass, surface, and atmosphere as the Earth? In what ways would life there be different than it is here? How would their perceptions of the cosmos be different from ours?

39 Mars rotated once every 20 days rather than once every 1.026 days? What would be different?

40 The carbon dioxide content of the Earth's atmosphere increased? What would happen to the Earth? This is not a completely hypothetical question, because carbon dioxide levels are increasing today.

WEB/CD-ROM QUESTIONS

41 Search the Web for the latest information about upcoming space missions to Mercury. When are they scheduled to be launched and when are they scheduled to arrive at Mercury? What scientific experiments will they carry? What scientific issues are these instruments intended to resolve?

ANIMATION 6.1

42 **Elongations of Mercury** Access the animation "Elongations of Mercury" in Chapter 6 of the *Discovering the Universe* Web site or CD-ROM. (a) Note the dates of the greatest eastern and western elongations in the animation. Which time interval is greater: from a greatest eastern elongation to a greatest western elongation or vice versa? (b) Based on what you observe in the animation, draw a diagram to explain your answer to the question in (a).

43 Search the Web for the latest information about proposed future missions to Venus. What scientific experiments will they carry? What scientific issues are these instruments intended to resolve?

AIMM 6.1

44 **Surface Temperature of Venus** Access the Active Integrated Media Module "Wien's Law" in Chapter 4 of the *Discovering the Universe* Web site or CD-ROM. (a) Using the Wien's law calculator, determine Venus's approximate temperature if it emits blackbody radiation with a peak wavelength of 3866nm. (b) By trial and error, find the wavelength of maximum emission for a surface temperature of 750 K (for present-day Venus) and a surface temperature of 850 K (as it might become if its greenhouse gas density increases). In what part of the electromagnetic spectrum do these wavelengths lie?

45 Search the Web for the latest information about upcoming space missions to Mars, including the European Space Agency's *Mars Express* and the Japanese orbiter *Nozomi*. When are they scheduled to be launched and when are they scheduled to arrive at Mars? What scientific experiments will they carry? What scientific issues are these instruments intended to resolve?

46 In 1999, two NASA spacecraft—*Mars Climate Orbiter* and *Mars Polar Orbiter*—failed to reach their destinations. Search the Web for information on these missions. What were their scientific goals? How and why did the missions fail? Which current and future missions, if any, are intended to replace these missions?

47 Search the Web for information about possible manned missions to Mars. How long would such a mission take? How expensive would they be? What are some advantages and disadvantages of a manned mission compared to an unmanned one?

ANIMATION 6.8

48 **Conjunctions of Mars** Access and view the animation "The Orbits of Earth and Mars" in Chapter 6 of the *Discovering the Universe* Web site or CD-ROM. (a) The animation highlights three dates when Mars is in opposition, so that the Earth lies directly between Mars and the Sun. By using the "Stop" and

"Play" buttons in the animation, find two times during the animation when Mars is in *conjunction*, so that the Sun lies directly between Mars and the Earth (see Figure 2-3). For each conjunction, make a drawing showing the positions of the Sun, the Earth, and Mars, and record the month and year when the conjunction occurs. (b) When Mars is in conjunction, at approximately what time of day does it rise as seen from Earth? At what time of day does it set? Is Mars suitably placed for telescopic observations when it is in conjunction?

OBSERVING PROJECTS

49 Refer to the accompanying table to determine the dates of the next two or three greatest elongations of Mercury. Consult such magazines as *Sky & Telescope* and *Astronomy*, or use your *Starry Night Backyard*™ planetarium software to see if any of these greatest elongations is going to be especially favorable for viewing the planet. If so, make plans to be one of those rare individuals who has actually seen the innermost planet of the solar system. Set aside several evenings (or mornings) around the date of the favorable elongation to reduce the chances of being "clouded out." Select an observing site that has a clear, unobstructed view of the horizon where the Sun sets (or rises). Make arrangements to have a telescope at your disposal. Search for the planet on the dates you have selected and make a drawing of its appearance through your telescope.

Greatest Elongations of Mercury

Evening	2002 Sep 1	27.2°E
Morning	2002 Oct 13	18.1°W
Evening	2002 Dec 26	19.9°E
Morning	2003 Feb 4	25.4°W
Evening	2003 Apr 16	19.8°E
Morning	2003 Jun 3	24.4°W
Evening	2003 Aug 14	27.4°E
Morning	2003 Sep 26	17.9°W
Evening	2003 Dec 9	20.9°E
Morning	2004 Jan 17	23.9°W
Evening	2004 Mar 29	18.9°E
Morning	2004 May 14	26.0°W
Evening	2004 Jul 27	27.1°E
Morning	2004 Sep 9	18.0°W
Evening	2004 Nov 21	22.2°E
Morning	2004 Dec 29	22.4°W
Evening	2005 Mar 12	18.3°E
Morning	2005 Apr 26	27.2°W
Evening	2005 Jul 9	26.3°E
Morning	2005 Aug 23	18.4°W
Evening	2005 Nov 3	23.5°E
Morning	2005 Dec 12	21.1°W

50 Refer to the following table in the next column to see if Venus is currently near a greatest elongation. If so, view the planet through a telescope. Make a sketch of the planet's appearance. From your sketch, can you determine whether Venus is closer to us or farther from us than the Sun?

Greatest Elongations of Venus

Evening	2002 Aug 22	46.0°E
Morning	2003 Jan 11	47.0°W
Evening	2004 Mar 29	46.0°E
Morning	2004 Aug 17	45.8°W
Evening	2005 Nov 3	47.1°E

51 Observe Venus through a telescope once a week for a month and make a sketch of the planet's appearance on each occasion. From your sketches, can you determine whether Venus is approaching us or moving away from us?

52 Consult such magazines as *Sky & Telescope* and *Astronomy*, or use your *Starry Night Backyard*™ planetarium software to determine Mars's location among the constellations. If Mars is suitably placed for observation, arrange to view the planet through a telescope. Draw a picture of what you see. What magnifying power seems to give you the best image? Can you distinguish any surface features? Can you see a polar cap or dark markings? If not, can you offer an explanation for Mars's bland appearance?

53 Using your *Starry Night Backyard*™ software, try the activities in this chapter's Guided Discovery box, "The Inner Solar System," to follow Mercury's orbit as it nears the Sun. With the timestep still set at 1 sidereal day, describe the motion of Mercury relative to the equatorial coordinate grid (that is, the celestial sphere). What can you say about the maximum and minimum angles on the celestial sphere between Mercury and the Sun? Periodically stop the motion, zoom in on Mercury, and determine its phase. Can you find a pattern of phases?

54 The Guided Discovery box on page 176 will introduce you to Mars's motion. In *Starry Night Backyard*™ go into Atlas mode (*Go/Atlas*), find Mars (*Edit/Find/Mars*), set the sky at 60°, and lock on Mars. Run the program with a timestep of 2 sidereal days. Notice that the equatorial coordinate system usually flows smoothly past Mars. When the stars behind Mars begin to slow down, stop the motion by pressing the ■ icon. Unlock Mars by moving it to the left quarter of the screen. Then run the program again. Describe how Mars now moves relative to the coordinate system. Stop the program, run it backward through this entire period, and stop it. Set the timestep at 1 sidereal day and rerun it forward in time, this time using the single-step feature. Make a day-by-day drawing of Mars's motion during this time. What is the name of this motion?