PLANETARY GEOLOGY

by Diana Siemens

Understanding Earth focuses on the geology of Earth. This is natural, for Earth is the planet we know most about and the one we are most interested in. More broadly, however, geology includes the study of all the worlds in our solar system: how planets and their satellites are born and how they evolve. Geologists are interested in other worlds for the sake of the knowledge itself and because the things we learn about other planets give us new insights into Earth's geologic history and the processes that still continue today.

Mars, for example, has huge shield volcanoes, much like those on Earth but much larger. Venus, too, has shield volcanoes and also displays unique forms of volcanism in its pancake domes and coronae. Yet despite the evidence of volcanism, neither planet seems to have developed a system of plates like that on Earth. Why not? On Io, a satellite of Jupiter, volcanoes erupt spectacular plumes of sulfur and sulfur dioxide rather than the water vapor and carbon dioxide emitted by Earth's volcanoes. Triton, Neptune's main satellite, displays cryovolcanism in which plumes of nitrogen fountain far above the surface. Discovering the differences and similarities among these various manifestations of volcanism helps scientists better understand the processes that produce volcanoes on Earth.

The fascinating and useful information to be gained from a study of the other planets is almost endless. Moonquakes have been recorded on the lunar surface; studying them gives us information about the makeup of our nearest neighbor that we will need if we ever decide to establish colonies on the Moon or mine the lunar crust. Titan, Saturn's giant satellite, has an extensive atmosphere very different from that of Earth; examining Titan's atmosphere and its evolution provides insights into Earth's atmosphere now and in the past. The atmosphere of Venus has much to teach us about the greenhouse effect here on Earth, a critical issue as we head into the next century.

Comparing and contrasting the geological features on Earth and elsewhere in the solar system yields a wealth of valuable information. The information gained from planetary studies increases our total sum of knowledge, equips us for our eventual visits to our neighbors, and may help us find better ways to protect humans from the consequences of such geologic phenomena as earthquakes and volcanoes.

This special section provides a brief overview of what we know about the other planets and their moons, with an emphasis on their geology. Because a planet's geology is inextricably linked to such basic attributes as its size, density, distance from the Sun, and period of rotation, facts about these attributes are also included. It is hoped that students will gain a better understanding of the complexity of geological processes and their relationship to the physical characteristics of the planets on which they operate. Planetary geology can also give students insight into the scientific method, by showing how researchers are able to infer from raw data a great deal of information about a planet's characteristics and geology.

METEOROIDS

Meteoroids play an important role in our understanding of the solar system. These particles of interplanetary debris strike planets and their satellites, and one of the ways scientists can tell the age of a planetary surface is by how heavily cratered it is. Old surfaces are pocked with craters caused by meteoroid impacts, but on planets where geological activity is continually reshaping the surface, the craters are erased and little evidence of their presence remains.

Three separate terms are used to describe these fragments of debris. Before a particle enters the atmosphere, it is called a meteoroid. The flash of light seen in the sky when a meteoroid enters Earth's atmosphere is called a meteor. If the particle does not burn up in the atmosphere but reaches Earth's surface, it is called a meteorite.

Most meteoroids appear to be debris from comets or chips of rock broken off from asteroids. A few are probably material blasted off the Moon and Mars by huge impacts. When the particles pass close to Earth, they are captured by its gravity. They are traveling at a velocity of several kilometers per hour, and most burn up from friction with the atmosphere. Only the very largest pieces of material survive their entry through the atmosphere to strike the surface. Large meteorites have collided with Earth, however, leaving giant craters at the point of impact. One of the largest and most famous is Barringer Meteorite Crater in northern Arizona (Figure 36.1).

Meteorites are classified as stony, stony-iron, and iron. About 95 percent of meteorites are stony meteorites (Figure 36.2). Most meteorites you will see in museums, however, are stony-iron or iron, because they are easy to find with metal detectors.

MOON

The Moon, with a diameter of 3476 km, is approximately one-quarter Earth's size and about one-eightieth its mass. The Moon moves around Earth in a slightly elliptical orbit, at an average distance of 384,400 km. It completes an orbit around Earth and returns to the same position in the sky with respect to the distant stars every 27.32 days, the sidereal month. Because Earth orbits the Sun in the same direction as the Moon, the time needed to return to the same phase—the synodic month—is longer: 29.53 days. The Moon also rotates on its axis over one sidereal month, so it always keeps approximately the same side toward Earth. Because of slight oscillations in its orbital motion and the inclination of the orbit to the ecliptic (the Earth-Sun orbital plane), 59 percent of the Moon's surface is visible from Earth at one time or another. The remaining 41 percent has since been thoroughly mapped by spacecraft.

Internal Structure

The Moon is less dense than Earth (3.34 g/cm^3 versus 5.52 g/cm^3). The lunar surface rocks brought back by the *Apollo* missions were close to the average density, which means that the Moon's interior is probably about the same density as the surface. Seismometers installed by the *Apollo* astronauts showed that the Moon is much less seismically active than Earth. The moonquakes recorded were deep-focus quakes, with centers 600 to 900 km beneath the surface. Seismographic records provided further evidence that the lunar interior is rigid and also indicated that the Moon's surface layers must be highly fractured. The absence of a dipolar magnetic field on the Moon indicates that it does not have a metallic core.

Composition

The most abundant element in the Moon's crust is oxygen (60 percent), followed by 16 to 17 percent silicon, 6 to 10 percent aluminum, 4 to 6 percent calcium, 3 to 6 percent magnesium, 2 to 5 percent iron, and 1 to 2 percent titanium (all percentages by weight). All other elements are present only in trace amounts (less than 1 percent by weight). The amounts of oxygen, silicon, and aluminum on the Moon are comparable to their abundance in Earth's crust. There is more iron and titanium in the Moon's crust than in Earth's, and the alkali metals, carbon, and nitrogen are less abundant than on Earth. Of the compounds formed by these elements, silica constitutes between 40 and 50 percent by weight of the Moon's crust, compared to 48.5 percent by weight of Earth's crust.

Surface Features

There are two distinct types of terrain on the lunar surface. The highlands are rough, relatively bright, and occupy 83 percent of the Moon's surface. The maria (Latin for "seas"), which make up the other 17 percent, are darker and smoother. The old, heavily cratered highlands formed during a heavy bombardment period early in the Moon's history, when huge meteoroids and asteroids were striking the surface. These collisions also created giant impact basins, which were later flooded with lava to become the maria.

Both terrains are pocked with craters (Figure 36.3) formed by the impacts of asteroids, comets, meteoroids, and interplanetary dust. These craters range in size from more than 1000 km across—Mare Imbrium (Figure 36.4) and Mare Orientale—to tiny microscopic pits found on crystalline rocks brought back to Earth by the *Apollo* missions. Because the Moon has no atmosphere to slow down meteoroids, they strike the surface at velocities of several kilometers per second. A particle moving at such velocities possesses a great deal of kinetic energy. When the kinetic energy is dissipated on impact, material is excavated and a surface scar remains. This is how small craters formed.

For craters more than about 100 km in diameter, enough heat was released by the impact to flood the crater floor with molten material. In the largest impact formations, the excavation of the initial basin appears to have been followed by lava flooding after a few hundred million years. Bright rays up to 16 km wide extend outward for hundreds of kilometers from some of the very largest lunar craters. They consist of lighter colored materials ejected by the force of the impacts that formed the craters.

Rilles are another notable surface feature. Some of these narrow lunar valleys extend for several hundred kilometers. They may have been formed early in the Moon's history by subsurface flows of lava, leaving hollow tubes into which surface materials eventually collapsed. The lunar surface is covered with a layer of fine powder and rock fragments called the regolith.

Mineralogy

The dark crystalline materials filling the basins of lunar maria are basalts, similar to Earth's lavas but enriched with iron and titanium (Figure 36.5). The highlands consist of feldspathic rocks similar to terrestrial granites, including anorthosite (gabbro), a nearly pure feldspar. The existence of anorthosites on the Moon implies chemical differentiation of the crust, in which heavier elements such as iron were separated from lighter elements. Because anorthosites consist mostly of coarse-grained minerals, they must have cooled slowly from the melt (at depth rather than on the lunar surface). The physical texture of lunar rocks reveals information about the origin of the surface formations. Many of the materials found in the highlands are breccias made up of grains of various minerals (Figure 36.6). Breccias are conglomerates of preexisting crystalline rocks in which angular fragments of diverse origin were welded together by events that occurred after they first solidified. The structure of lunar breccias indicates that they were formed by metamorphism that occurred during meteoroid impacts.

Geologic History

Many scientists now think that the Moon was formed by the collision of a Mars-sized body with Earth about 4.5 billion years ago. They hypothesize that the gigantic impact propelled a shower of debris into space; the debris then aggregated to form the Moon. Radiometric dating of the rocks brought back by the *Apollo* missions has revealed that the oldest rocks are about 4.44 billion years old, which is close to the proposed time of the giant impact event.

Radiometric dating also indicates that most of the crater-forming impacts on the mountainous parts of the Moon occurred in the first half-billion years of its history. The largest of these impacts, which created the maria, occurred 400 to 800 million years after the Moon was formed. The basins excavated by these impacts were flooded with basaltic magmas some 400 to 700 million years later, or 3.3 to 3.8 billion years ago.

In the past 3 billion years, nothing much has happened on the lunar surface. Although the Moon keeps accumulating scars of new meteoroid impacts, these are occurring at a diminishing rate.

MERCURY

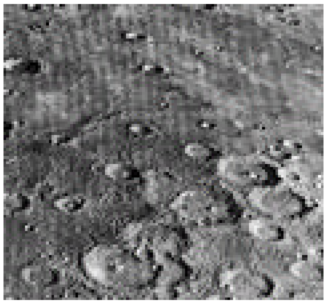
Mercury is the second smallest planet (after Pluto), being only 4880 km in diameter. Its small size can probably be attributed to the fact that the heat of the nearby Sun as Mercury formed, about 4.6 billion years ago, prevented most of the gases present from becoming part of the protoplanet. Mercury's surface is very hot, sometimes reaching extremes of more than 470°C. Because of the heat and the planet's low gravity, Mercury did not retain a significant atmosphere. Trace amounts of hydrogen, helium, and oxygen above the surface are probably derived from the solar wind; traces of sodium and potassium atoms may represent gases diffusing up through the planet's crust.

Mercury orbits the Sun once every 88 days at a distance of 46 to 70 million km. Because it is very difficult to observe this planet, which rises and sets within two hours of the Sun, it was thought as late as 1962 that Mercury also rotates with an 88-day period, so that one hemisphere always faces the Sun. Radar observations have since shown that the true rotation period is 58.6 days. Mercury rotates three times for every two trips around the Sun, so that during every other perihelion (closest approach to the Sun), the same face points directly at the Sun.

Internal Structure

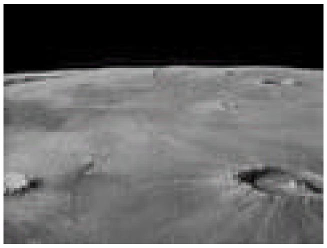
Mercury's high density (5.4 g/cm^3) suggests a large iron or nickel-iron core. Computer models indicate that Mercury's core has a radius of 1800 km—75 percent of the planetary radius. (Earth's core has a radius of only about 55 percent of the planetary radius.) This large iron core, part of which is probably molten, is responsible for Mercury's magnetic field. Although it is only about 1 percent as strong as Earth's magnetic field at the surface, it is substantial enough to disturb the solar wind as it streams past the planet.

Surface Features



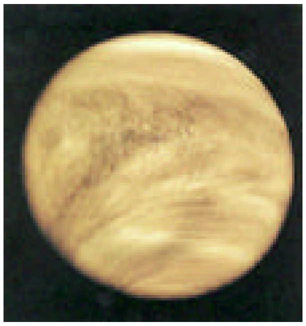
Mariner 10 photographed about 40 percent of Mercury's surface in detail. Ancient cratered highlands (estimated to be about 4 billion years old) cover much of the observed surface. Smooth, dark plains that look like those on the Moon were also seen. They are probably younger than the highlands, although old enough to be pocked with craters (Figure 36.7). The largest plain, Caloris Basin, is 1300 km wide and is surrounded by mountains that rise

to 2 km. It was probably created by the impact of a large meteoroid during the time when Mercury was forming. On the opposite side of Mercury, there is an area of hilly, lineated terrain that probably resulted from seismic waves caused by the same impact. The surface also has areas of smooth, flat plains with few craters, indicating a younger age; these areas may be of volcanic origin. Radar observations of the north polar area in 1991—an area not photographed by *Mariner 10* —suggest that some water ice may exist there at protected sites. Although heavily cratered, Mercury's highlands are not saturated with craters like the Moon's. The extensive gently rolling plains, which may be the original crust, predominate. Mercury's higher surface gravity prevents meteoroid impacts from spreading ejecta as far as they do on the Moon, so some of the precratered surface may have remained intact.



At some time between the formation of the older plains and the formation of the smooth younger plains, the whole planet may have shrunk as it cooled, causing the crust to buckle and form the long scarps that wind across the surface of the cratered highlands for hundreds of kilometers (Figure 36.8). Although Mercury looks like the Moon on the surface (Figure 36.9), internally it is more like Earth, with its large iron core and related magnetic field. The formation and development of this core distinguishes the evolution of Mercury from that of the Moon.

VENUS



Venus, the second planet from the Sun, lies an average of about 108 million km from the Sun. It has a diameter of about 12,100 km. Venus completes one trip around the Sun every 224.7 days and rotates on its axis once every 243 days. Its rotation is retrograde, or "backward" compared to Earth and most of the other objects in the solar system.

Traditionally, Venus and Earth have been considered sister planets because of their similar diameter, mass, density, and composition. Venus, however, has no satellites, nor does it have a magnetic field. The planet is covered by a thick, reflective cloud layer (Figure 36.10) that produces very high surface temperatures (about 475°C) and pressures (about 90 atmospheres). Because Venus is shrouded in clouds, our views of the surface are obtained by radar.

Atmosphere and Clouds

The atmosphere of Venus is composed mainly of carbon dioxide (about 98 percent). Below Venus's clouds, which are made up of sulfuric acid droplets and solid sulfur particles, the atmosphere contains about 0.1 to 0.4 percent water vapor and 60 parts per million of free oxygen. The presence of water and free oxygen indicates that Venus may have had abundant water early in its history, which was later lost.

Venus has a very pronounced greenhouse effect. Sunlight filtering through the clouds heats the surface, which radiates the heat back into the lower atmosphere. Rather than escaping to space, the heat is easily absorbed by the carbon dioxide in the atmosphere and radiated back to the surface. This process is called the greenhouse effect because it is similar to the warming of a greenhouse. The glass of a greenhouse lets in visible light but lets little heat escape. Earth has a much less extreme greenhouse effect. If it had none, its surface temperature would be well below freezing and the oceans would be a solid mass of ice. There is concern, however, that Earth's greenhouse effect may be intensifying because of increased carbon dioxide released into the atmosphere by the burning of fossil fuels. The increased carbon dioxide could result in global warming, which would have serious effects on climate and weather patterns and would result in a small but significant rise in global sea level. Studying Venus's more extreme greenhouse effect can give us insights into what might happen here on Earth.

Winds

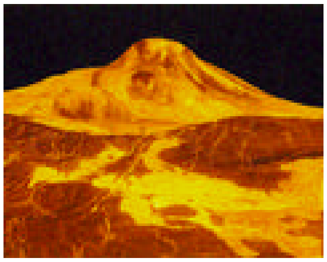
Winds of about 13 km/hr have been measured at the surface. Winds of 175 km/hr have been recorded 45 km above the surface, and strong vertical winds have also been detected. Several Venus probes returned data indicating lightning activity in the atmosphere.

Features produced by the wind include long streaks that extend behind obstacles such as low-lying ridges and small volcanic shields on the planet's plains. Sand dunes occur near several of the large impact craters; it is thought that the sand particles were produced when the craters were formed.

Composition

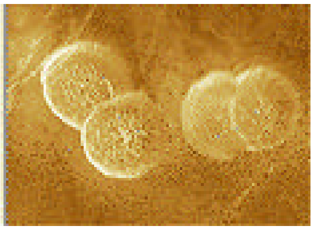
The composition of the surface was measured by spacecraft at several landing sites. *Venera 8* detected materials similar to the granitic rocks on Earth's continents, along with radioactive isotopes of uranium, thorium, and potassium. *Venera 9* and *Venera 10* found basaltic rock compositions at two other sites. *Venera 13* and *Venera 14* also measured the electrical conductivity of rocks, drilled holes to retrieve material from deeper surface layers, and scooped up samples of the soil. These probes also detected basaltic compositions.

Geology

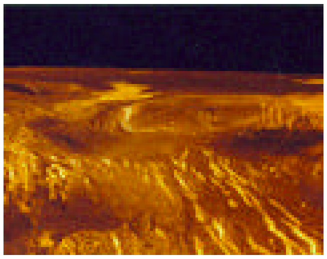


Venus and Earth share many geological surface features. There are three basic types of surface on Venus: lowland plains (20 percent), rolling uplands (70 percent), and highlands (10 percent). All three areas show evidence of extensive volcanism. Much of the volcanic activity on Venus occurs as basaltic eruptions that flood large areas. In addition, Venus has several large shield volcanoes, some of which are thought to be currently active (Figure

36.11, on previous page). Recently announced findings indicate that Venus is still volcanically active, but only in a few hot spots. Generally, it has been geologically quiet for the past few hundred million years.



Venus also displays unique forms of volcanism. One such form is pancake domes, which are almost perfectly circular, flat domes with steep sides (Figure 36.12). The domes appear to be made of highly viscous lava erupted suddenly from a single vent. There are also rivers of extremely fluid lava, some of them hundreds or even thousands of kilometers long.



The most distinctive volcanic features on Venus are coronae (Figure 36.13), large circular structures with a slightly raised interior surrounded by a low circular ridge and a trough. They are typically 200 to 500 km in diameter, although the largest (Artemis) has a diameter of 2000 km. Coronae are thought to be hot spots formed over mantle plumes that became inactive before they could form a true shield volcano.

Impact craters are distributed randomly but uniformly over the surface. From the number of craters and their sharp, uneroded condition, we deduce that Venus was resurfaced about 300 to 500 million years ago. The majority of Venusian craters appear pristine because they were formed after this resurfacing, and there has been little geologic activity and weathering since to degrade and destroy the craters. There are far fewer small craters on Venus than on other planets, because small meteoroids vaporize or break up in the Venusian atmosphere before they reach the surface.

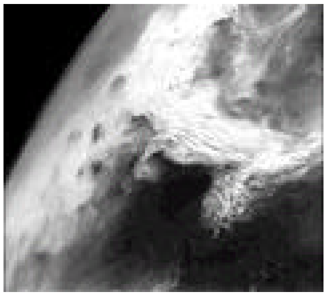
The highland regions have mountain ranges, volcanoes, and rift systems. Mountain ranges, long faults, and deep troughs indicate that horizontal surface movement has occurred. Among the most complex types of terrain identified on Venus are raised regions of the surface characterized by intersecting sets of faults and ridges. These regions, called tesserae from the Latin word for “tile,” may result from long episodes of compression and extension of the surface.

Although its surface has been very geologically active in the past, Venus appears to lack plate tectonics. Heat generated in the interior drives the abundant volcanic activity. Features found at plate boundaries on Earth also occur on Venus, such as deep asymmetrical troughs associated with subduction zones and rifts typical of spreading centers. But these features do not appear to link up in an integrated system of plates as on Earth.

MARS

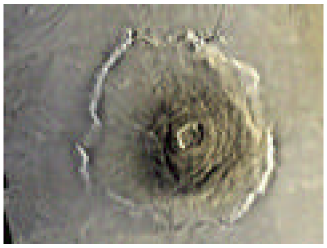
Mars is the fourth planet from the Sun. It orbits the Sun at a distance varying from 206.7 million km to 249.2 million km. Its year is 687 days long, and it rotates on its axis once every 1.026 Earth days. The planet’s axis is tilted at about 25 degrees, which produces seasonal changes similar to those on Earth. Because the orbit is elliptical, summer in the southern hemisphere and winter in the northern hemisphere occur at perihelion (when the planet is nearest the Sun). The diameter of Mars is about 6780 km, about half the size of Earth and nearly twice the size of the Moon. It is less dense than Earth (3.95 g/cm^3 versus 5.52 g/cm^3). No measurable magnetic field has been detected, which indicates that the core is solid and explains why Mars has no radiation belt. The soil of Mars was sampled by *Viking* and found to consist of clays and iron oxides. This was expected because of its red color.

Atmosphere and Climate



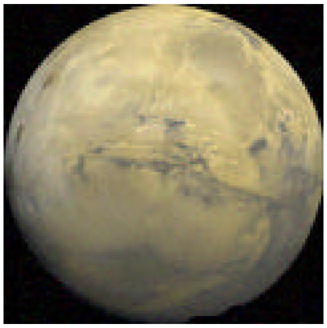
The major constituents of the Martian atmosphere are carbon dioxide (95.3 percent), nitrogen (2.7 percent), and argon (1.6 percent). The average atmospheric surface pressure is less than 1 percent of Earth’s, and it varies with season and elevation. The surface temperature fluctuates greatly between day and night and between seasons, but even at the equator temperatures are below freezing most of the time. The average temperature is about –53°C. Although thin and frigid, the Martian atmosphere is very active and complex. Mars and Earth have similar global atmospheric circulation patterns. In the Martian atmosphere, as in Earth’s, warm air rises at the equator, moves poleward, is deflected to the east, and then descends at middle latitudes and returns to the equator. At middle to high latitudes, jet streams blowing from the west produce storm systems near the surface. Mars also has seasonal climate changes caused by solar heating and by the exchange of carbon dioxide between polar ice and frost and the atmosphere. The polar caps grow and shrink seasonally. The strong southern summer winds lift vast amounts of dust into great storms that cover the entire planet (Figure 36.14).

Geology



Although the overall geology of Mars is unique in the solar system, it shares some characteristics with Earth. Many geologic features on Mars are much larger than the same kinds of features on Earth, however. For example, the shield volcano Olympus Mons (Figure 36.15), the largest volcano in the solar system, is three times as tall (24 km) as Mount Everest (the tallest mountain on Earth) and 20 times larger in cubic content than Mauna Loa (Earth’s largest shield volcano). Several factors contribute to the size of geological features on Mars. The lack of plate tectonics means that centers of volcanic activity persist longer in the same place, rather than moving with the changing plate boundaries as on Earth. These more static conditions allow volcanoes to grow for longer periods of time. The surface gravity of Mars is only about a third that of Earth, which allows volcanoes to grow much higher before they reach their limiting heights. Mars also has a much less erosive atmosphere and climate, so volcanoes are worn down much more slowly.

Olympus Mons is one of four huge volcanoes in the Tharsis region, an immense area uplifted by tectonic forces and marked by volcanism. Many geologists believe that the Tharsis bulge resulted from a large mantle plume. Tharsis straddles and overlies the two major terrains on Mars: the southern hemisphere consists of ancient cratered uplands; the northern hemisphere of younger, relatively uncratered, volcanic lowlands. How the surface of Mars came to be divided into these two disparate terrains is not completely understood, but it is thought that the crust in the northern hemisphere probably collapsed as a result of internal forces present billions of years ago.



Stretching more than 3000 km from the Tharsis slopes out across the old uplands is the Valles Marineris system (Figure 36.16). The system is up to 8 km deep and 200 km wide in places. The deep linear canyons of Valles Marineris were produced by the same tremendous tectonic forces that produced Tharsis. Although these canyons were not carved by running water, geologists believe that they were widened by catastrophic outbursts of water, ice, and debris released from artesian aquifers.

The surface of Mars shows features that resemble dry riverbeds and gullies (Figure 36.17). These might have been created by rainfall and runoff, but they might also have been made by subsurface water that seeped to the surface. In either case, the channels are evidence that temperatures were warmer in the past—warm enough for water to exist in liquid form. The higher temperatures probably were caused by heat released from the interior and by the thicker atmosphere.

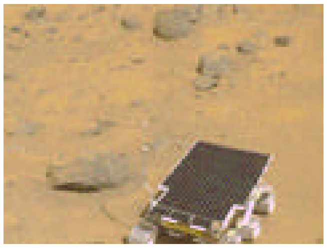
Life on Mars?

A small number of meteorites found on Earth are known to have originated on Mars. In August 1996, a NASA research team announced that they had identified organic compounds in a Martian meteorite found in the Antarctic. They also found several mineral features characteristic of biological activity and identified possible microscopic fossils of primitive, bacteria-like organisms. This evidence suggests that primitive life may have existed on Mars more than 3.6 billion years ago.

The announcement set off a wave of research on this and other Martian meteorites. Some researchers have supported the original conclusion, while others have remained skeptical. Exciting as this discovery is, the evidence so far does not establish the fact of extraterrestrial life beyond a doubt. Much work remains to be done before we can be confident of this extraordinary claim. Ultimately, we will probably need to send a probe to Mars to scoop up samples of the rock and soil there and return them to Earth for study.

Recent Missions

Mars Pathfinder, a mission to explore the atmosphere, weather, and surface of Mars, landed on the planet's surface on July 4, 1997. The mission consists of a stationary lan-



der (Sagan Memorial Station) and a small rover (Sojourner) that has examined rocks and soil on the surface (Figure 36.18).

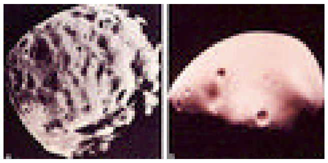
As a result of the mission, scientists are refining some of their ideas about Mars. For example, the *Pathfinder* results indicate much more differentiation of volcanic materials than was previously thought. The high silica content of one of the rocks measured suggests that there was more crustal activity (heating and recycling of materials) early in Mars's history than scientists previously believed.

Color panoramas of the Martian landscape show clear evidence that the surface has been altered by winds and flowing water. Mars in its infancy appears to have been very like Earth, with weathering processes and flowing water that created a variety of rock types and a warmer atmosphere that generated clouds, winds, and seasonal cycles. Mars appears to have conglomerates that were worn down by water and surface features that were created by liquid water. Close-up images of dunes around the landing site show that there is sand on the surface of Mars. The presence of sand, as opposed to dust or pebbles, helps to establish that weathering by wind and water helped to shape Mars's present landscape.

Mars Global Surveyor reached orbit on September 7, 1997. Currently, *Surveyor* is in an "aerobraking" phase to lower the high point of its orbit from 56,000 km to near 400 km. This phase will last until January 1998. In mid-March 1998, *Surveyor* will begin mapping the surface of Mars. The spacecraft will orbit Mars and collect scientific data continuously for almost two years. *Surveyor* is expected to return an unprecedented amount of data on Mars's surface features, atmosphere, and magnetic properties. After the mapping phase is finished in late January 2000, *Surveyor* will function as a communications satellite to relay data back to Earth from surface landers launched as part of future Mars missions.

The *1998 Mars Surveyor* program consists of an orbiter mission and a lander mission. The orbiter will be launched in December 1998 and the lander in January 1999. The orbiter will map the surface of Mars for two years and relay data for five years. The lander, which will have a 90-day primary mission, will land near Mars's south pole. The primary objectives of the *1998 Mars Surveyor* program are to search for evidence of life, past or present; collect data on weather processes and climate history; understand how Mars evolved; and assess its possibilities for future exploration.

Phobos



Phobos (Figure 36.19) is the larger and closer of Mars's two satellites, both of which were discovered in 1877. The orbit of Phobos lies only 9378 km from the center of Mars, or less than two Mars radii above the planet's surface. It orbits so close to Mars that gravitational tidal forces are dragging it down. In 100 million years or so, it could crash into the surface or be shattered by the tidal stress, the debris forming a ring around Mars. Phobos’s period of revolution is less than one-third of Mars’s rotation period, and the moon appears to rise in the west and set in the east as seen from Mars. Phobos was first photographed in some detail by *Mariner 9* in 1969, and photographic and infrared studies were made by the *Viking* orbiter in 1977. Phobos is very small (about 20 km by 28 km) and irregular, and it always keeps it long axis pointed toward Mars. It has a very low density and low reflectivity. The surface is covered with craters and exhibits elongated depressions, peculiar parallel linear striations, and chains of craters, all tending to parallel the orbital plane. Stickney, the largest crater (10 km in diameter), is so big that it is surprising that Phobos survived the impact that formed the crater. Phobos is generally thought to be a captured asteroid rather than a natural satellite of Mars.

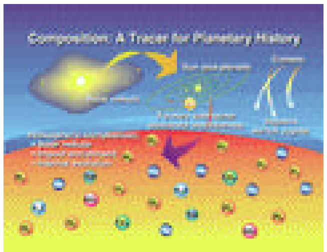
Deimos

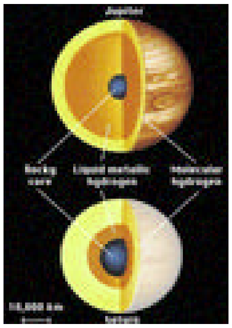
Deimos (see Figure 36.19), the smaller and more distant of Mars’s two satellites, is about 12 by 16 km and is roughly ellipsoidal. It orbits Mars at a mean distance of 23,500 km and is gradually moving away from the planet. Deimos has a low reflectivity; its surface is as dark as the Moon’s darkest regions. In 1971, *Mariner 9* first revealed that the surface is sprinkled with craters, though it is not so heavily cratered as Phobos. Deimos is also believed to be a captured asteroid.

JUPITER

Jupiter, the fifth planet from the Sun, is by far the largest in the solar system (Figure 36.20). It is 318 times more massive than Earth, and its diameter of 142,800 km is about 11 times that of Earth. It orbits the Sun once every 11.9 years at a distance of 778.3 million km. Its rotation period is 0.410 Earth day (about 10 hours).

Composition and Structure

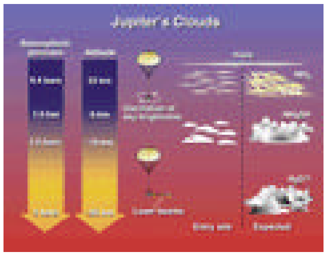




Jupiter has a low density (1.3 g/cm^3), being composed primarily of hydrogen and helium. Its composition indicates that, like the Sun, it formed by gravitational collapse of part of the primeval solar nebula (Figure 36.21). It is so hot that there is no solid surface under the atmosphere, just a gradual transition from gas to liquid. Jupiter has a rocky core about 10 to 15 times Earth’s mass, surrounded by a massive mantle of liquid metallic hydrogen (Figure 36.22). (At the temperature and pressure of Jupiter’s interior, hydrogen is a liquid.) Liquid metallic hydrogen consists of ionized protons and electrons, so it is an electrical conductor. Jupiter’s rotation and currents within the metallic hydrogen interior generate a dipolar magnetic field 4000 times stronger than Earth’s. The mantle probably also contains some helium and traces of water, ammonia, methane, and other organic compounds.

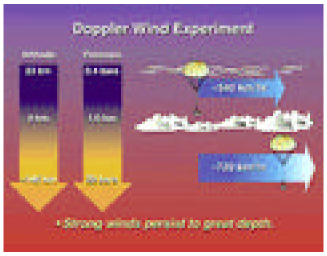
Clouds

Jupiter has spectacular bands of clouds ranging in color from white to orange to blue to brown. The vivid colors are thought to result from chemical reactions of the trace elements in Jupiter's atmosphere. The colors correlate with the clouds' altitude: blue lowest, followed by browns and whites, with reds highest. Sometimes we see the lower layers through holes in the upper ones.



Scientists think that there are three layers of clouds, separated by about 30 km in altitude. The lowest layer is believed to be made of water ice, the next layer of crystals of a compound of ammonia and hydrogen sulfide, and the highest layer of ammonia ice. The primary clouds that we see when we look at Jupiter are composed of crystals of frozen ammonia. The recent *Galileo* probe, however, found no evidence of the lower layer of water ice clouds. Figure 36.23 and its caption give a more complete picture of the probe results and what they might mean.

Winds



Jupiter has high-velocity winds confined in wide bands of latitude. The winds blow in opposite directions in adjacent bands. Slight chemical and temperature differences between the bands are responsible for the broad, colored stripes that dominate the planet's appearance. Data from the *Galileo* probe indicate that the winds are even faster than expected (more than 600 km/hr) and extend down as far as the probe was able to observe; they may extend thousands of kilometers into the interior (Figure 36.24). Jupiter's atmosphere was also found to be turbulent, which indicates that its winds are driven mostly by the planet's internal heat rather than by solar energy as on Earth.

Eddies and storms form and dissipate, some lasting only a few days, others much longer. Larger eddies, such as long-lived white spots and the Great Red Spot (see Figure 36.20), last for decades or centuries. These storms survive so long because there is no solid surface to slow them down, and their huge size tends to make them stable. Both *Voyager* spacecraft observed lightning as well as auroras on Jupiter's night side. The *Galileo* probe data indicated far less lightning activity (about 10 percent of that found in an equal area on Earth) than anticipated. This is puzzling, but consistent with the absence of water clouds.

Rings

In 1979, *Voyager 1* photographed two narrow rings associated with the two tiny innermost satellites. These rings are extremely tenuous, made up of tiny particles presumably eroded from the surfaces of these two satellites by the constant bombardment of micrometeoroids and charged particles in the planet's magnetosphere.

Comet Shoemaker-Levy

Fragments of comet Shoemaker-Levy 9 collided with Jupiter on July 16–22, 1994, with spectacular results. At least 20 large fragments impacted the planet at 60 km/s, causing plumes thousands of kilometers high. They left hot bubbles of gas in the atmosphere and great dark scars that lasted for months after the collision. The effects were clearly visible even with amateur telescopes, and debris from the collisions was visible for nearly a year afterward from the Hubble Space Telescope.

Observations of the impacts shed new light on Jupiter's atmospheric winds and magnetic field. Observations made a week and a month after impact were used to make global maps of Jupiter for tracking changes in the dark debris caught up in the high-speed winds at Jupiter's cloud tops. This debris is a natural tracer of wind patterns and allows astronomers a better understanding of the physics of the Jovian atmosphere.

Galileo Mission

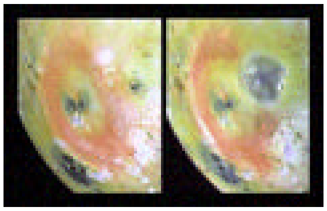
The *Galileo* mission, launched on October 18, 1989, consists of an orbiter designed to observe Jupiter, its moons, and its radiation belts and an atmospheric entry probe designed to enter Jupiter's atmosphere. The spacecraft entered orbit around Jupiter on December 7, 1995, and is currently observing the Jupiter system. The *Galileo* probe descended into Jupiter's atmosphere on the same day and directly measured the atmosphere of a gas giant for the first time.

Satellites

Although Jupiter was not large enough to begin nuclear fusion, its gravitational compression generated a tremendous amount of heat when the planet formed. Even now, 4.5 billion years later, Jupiter radiates nearly twice as much heat as it receives from the Sun. When satellites were forming around Jupiter, the heat radiating from the planet was much greater. Hence, Jupiter's satellites are rockier near Jupiter and icier farther away. The four large Moon-sized satellites—Io, Europa, Ganymede, and Callisto—were discovered by Galileo in 1610 and named the Galilean satellites after him. Their regular, circular orbits around Jupiter's equator suggest that they formed from a cloud of small particles circling Jupiter.

Jupiter also has 12 smaller satellites. Four of these lie close to Jupiter, well inside Io's orbit. Amalthea has been known for about a century; it is irregularly shaped, about 265 km long and 150 km wide. Its dark red surface is continually bombarded by the energetic particles of Jupiter's magnetosphere. *Voyager* found the other three inner satellites: Metis, Adrastea, and Thebe. The eight outer satellites are small, dark, stony objects that are believed to be captured asteroids.

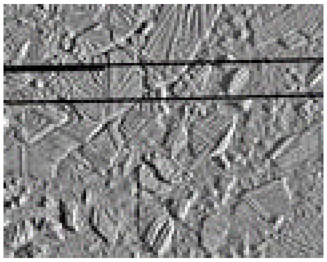
Io



Of the Galilean satellites, Io lies closest to Jupiter, at an average distance of about 421,600 km. Io completes one revolution of Jupiter in about 42 hours 27 minutes. Slightly smaller than Earth's Moon, it has a diameter of 3630 km. It has a high density (3.55 g/cm^3). The interior consists of molten rock. Io is the most geologically active body in the solar system. Its erupting volcanoes were first sighted by *Voyager 2* in 1979. Recent images from the *Galileo* mission indicate that major changes in the surface of Io took place just in the five months between *Galileo* 's seventh and tenth orbits of Jupiter (Figure 36.25). Io has a sulfurous crust with white and dark markings. Several volcanoes send dust and gas high above the surface, leaving a trail of ions and molecules in the satellite's orbit. Calderas and flows of molten material are observed, as well as nonvolcanic mountains about 10 km high. Because the surface is constantly being renewed by geological activity, no meteoroid craters exist. The surface temperatures are around –148°C, although near eruptions they may reach 27°C.

Europa

Europa, with a diameter of 3138 km, is the smallest of the four Galilean satellites. Compared to most solid planets and satellites, Europa is extraordinarily smooth. Its bright surface is crisscrossed by darker lines up to 70 km wide and 1000 km long. Some are flat; others are shallow ridges or grooves. There are also smaller streaks and regions of mottled terrain. There are only a few low craters, which means that the surface is relatively young. Europa has a density of 3.04 g/cm^3 and probably consists mostly of rock, with a 75- to 100-km-thick mantle of water ice. The lack of craters has led to speculation that Europa was covered with an ocean of water until its frozen surface formed. Some scientists suggest that Europa will remain warm enough for a few hundred million more years to maintain a liquid sea sandwiched between the surface and the core.

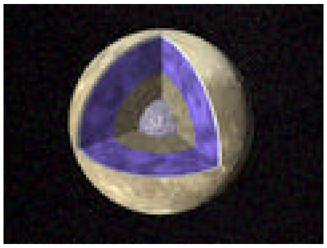


Recent images captured during *Galileo* 's flyby of Europa on February 20, 1997, have supported the idea that there are hidden, subsurface oceans on Europa. Images of ice rafts (Figure 36.26) reveal that Europa had, and may still have, a very thin ice crust covering either liquid water or slush. The rafts appear to be floating and may be comparable to icebergs on Earth.

Galileo 's final flyby of Europa during its primary mission occurred on November 6, 1997. At press time, the pictures and other information gathered during this flyby were being transmitted to Earth. Up-to-date images from *Galileo* will be posted at

http://www.jpl.nasa.gov/galileo/images.html

Ganymede



With a diameter of 5262 km, Ganymede is the largest satellite in the solar system—it is larger than the planet Mercury. Its average distance from Jupiter's center is 1,070,000 km, and it takes a little more than a week to complete one orbit of the planet. Ganymede's density is about 2.0 g/cm^3; it probably has a rocky core and thick icy mantle (Figure 36.27). Parts of the surface are dark and heavily cratered. Interspersed are lighter regions filled with bands of parallel grooves a few hundred meters deep and several kilometers apart. Some grooves extend for thousands of kilometers, and the bands sometimes intertwine with other bands in complicated patterns. Although less heavily cratered than the dark areas, the bands have enough craters to indicate that they formed fairly early in Ganymede's history. The grooves are thought to be cracks that formed as areas of the old, dark crust were pulled apart.

In June 1996, *Galileo* returned stunning close-ups of Ganymede revealing that its surface has been extensively bombarded by comets and asteroids and dramatically wrinkled and torn by tectonic forces. Scientists studying data from the spacecraft have discovered that Ganymede possesses its own magnetosphere—a bubble-shaped region of charged particles that surrounds many of the planets but has never been found to exist around a moon. Possible sources of a magnetic field include a molten iron core or even a thin layer of conducting salty water underneath its icy crust.

Callisto

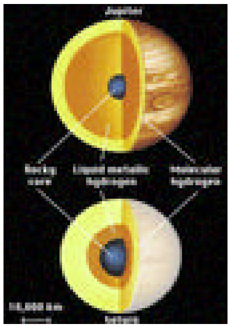
Callisto lies 1,880,000 km from Jupiter's center and is 4800 km in diameter. It is the outermost and the least geologically active of the Galilean satellites. Its density (1.8 g/cm^3) indicates a core of rock and a thick mantle of ice. The dark surface is probably dirty ice or a thin rock layer. Callisto is heavily cratered, exposing brighter ice. The shallowness of most craters is probably a result of flattening of their rims by the flow of ice. The most prominent feature is Valhalla, a bright central area some 300 km wide that is surrounded by sets of concentric ridges extending to 1500 km from the center.

SATURN

Saturn, the sixth planet from the Sun, orbits the Sun at a mean distance of 1.427 billion km and completes one orbit every 29.456 years. With a diameter of 120,536 km, Saturn is second in size only to Jupiter. Saturn rotates once on its axis about every 10.7 hours. Its axis of rotation is tilted by about 27 degrees, which causes seasons. The average density is only 0.69 g/cm^3, indicating a deep atmosphere and a small core. Even when viewed through a small telescope, Saturn is one of the most striking objects in the sky, with its spectacular ring system. Through a large modern telescope, the planet appears as a light yellow and gray banded oblate spheroid. Like the other gas giants—Jupiter, Uranus, and Neptune—the visible planet is the cloud top of an extensive gaseous atmosphere.

Figure 36.28 is a montage of Saturn with six of its satellites.

Composition and Structure



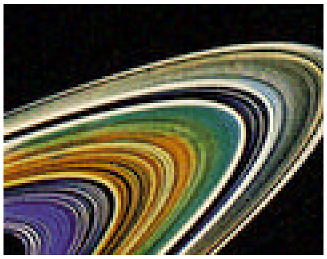
Saturn, like Jupiter, is composed primarily of hydrogen and helium. Current models of the interior indicate that below the relatively thin, opaque cloud layers is a large, clear hydrogen-helium atmosphere. The cloud layers are similar to those on Jupiter: ammonia ice in the upper layer, crystals of a compound of ammonia and hydrogen sulfide in the middle layer, and water ice in the lower layer. As on Jupiter, the density of the atmosphere gradually increases toward the surface, and the gas transforms into a liquid. At the center, the hydrogen becomes metallic; Saturn, however, with its lower mass and internal pressure, has a much smaller region of metallic hydrogen than Jupiter (see Figure 36.22). Saturn has a strong dipolar magnetic field similar to Jupiter's, but it is only about one-third the size. Saturn's magnetic field traps charged particles coming from the solar wind, which impinge on the ionosphere and create airglow emissions. The core is much like Jupiter's, consisting of metal, rock, and ice.

Atmosphere

There are easterly blowing jet streams that, at the equator, can reach speeds of 1700 km/hr. The jet streams do not change appreciably over time, but *Voyager* recorded changes in smaller scale spots, waves, and eddies over a period of hours. Such smaller features are usually hard to observe because of the obscuring haze layer above the planet's cloud surface.

A feature in the northern hemisphere known as the Great White Spot becomes visible to Earth-based observers about every 29 years. The spot is apparently an upwelling of ammonia-rich materials; the ammonia then crystallizes at the greater height, producing the white color. The spot sometimes expands until it becomes a band of clouds girdling the planet. Various colors that have been observed probably result from the interaction of such trace elements as sulfur and carbon compounds with charged particles in the ionosphere and lightning.

Rings



Saturn's spectacular rings (Figure 36.29) were first seen by Galileo in 1610; his small, primitive telescope showed the planetary disk flanked by what he first interpreted as two smaller bodies. Later scientists correctly theorized that these bodies were rings.

Saturn’s rings are extraordinarily thin; although they are 250,000 km or more in diameter, the ring plane has a maximum thickness of 1 to 2 km, and the main rings themselves are only about 20 m thick. The particles that make up the rings are composed primarily of water ice and range in size from sand grains to large boulders.

The *Voyager* probes showed that the ring system is highly structured. The main rings are broad and flat, with few gaps. There are also a few narrow rings, between 10 and 100 km wide. Finally, there are the ring gaps, which are about 100 km wide. The dynamics of the rings are not yet well understood. Their origin also remains a mystery. Most scientists think that the rings are composed of the remnants of shattered small satellites, dating from the early history of the solar system. Others hypothesize that the rings may be relatively young.

Cassini Mission

The *Cassini* mission to explore the Saturn system was launched on October 15, 1997. It will arrive at Saturn on July 1, 2004. The mission includes an orbiter and an atmospheric probe. Upon arrival, the *Cassini* spacecraft will take up an orbit around Saturn. Then the probe will separate from the orbiter and descend through the atmosphere of Titan, Saturn’s largest moon. The orbiter will relay probe data to Earth for about 3 hours while the probe enters and traverses the cloudy atmosphere to the surface. After completion of the probe mission, the orbiter will continue touring the Saturn system for three and a half years, including flybys of Titan, Iapetus, Dione, and Enceladus. The objectives of the mission are to conduct detailed studies of Saturn’s atmosphere, rings, and magnetosphere; conduct close-up studies of Saturn’s satellites; and characterize Titan’s atmosphere and surface.

Satellites

Saturn has 18 named satellites, more than any other planet, and there may also be several small ones yet to be discovered. Only Titan is as large as the Galilean satellites of Jupiter. Except for Titan, Saturn’s satellites have low densities (1 to 1.5 g/cm^3) and high surface reflectivities, indicating that they are composed of water ice. All the satellites, except Enceladus, have old, highly cratered surfaces.

Titan

Titan lies 1,222,000 km from the center of Saturn and takes nearly 16 days to orbit the planet. With a diameter of 5150 km, it is the largest satellite of Saturn. In fact, it is the second largest satellite in the solar system (only Jupiter’s satellite Ganymede is larger). Titan’s average density of 1.9 g/cm^3 indicates that it has a rocky core with a thick mantle of various ices—probably water, ammonia, and methane. It is the only satellite with a substantial atmosphere. Titan’s atmosphere consists mostly of nitrogen, with a small amount of hydrogen and argon. The surface pressure is 1.6 bars, the highest of any terrestrial planet but Venus, and the surface temperature is about –180°C.

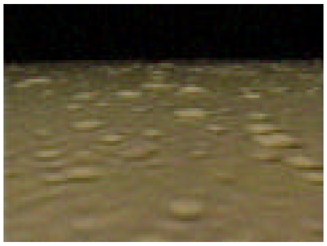
The main clouds on Titan are found in the bottom 10 km of the atmosphere and probably consist of condensed methane. Much higher, at an altitude of several hundred kilometers, is a reddish haze composed of complex organic chemicals (hydrocarbons). The particles in this haze gradually fall to the surface, where they presumably collect as a deep tarlike layer of deposits. Despite the presence of abundant organic chemicals, life could not have evolved in Titan's extreme cold.

Because organic compounds are stable at the low temperatures on Titan, the surface probably records a chemical history going back billions of years. Many scientists believe that Titan will provide great insight into the early history of Earth's atmosphere.

Mimas

Mimas, heavily cratered and icy, is dominated by a crater 130 km in diameter (one-third of its own diameter). The impact that produced this gigantic crater must have come close to destroying the satellite. The surface of Mimas has some grooves that may have formed during the impact that created the large crater or may have developed by tidal interactions when Mimas was still warm from accretion. Density measurements gathered by *Voyager 2* indicate that Mimas probably has a small rocky core with a thick mantle of water ice.

Enceladus



Enceladus displays at least five different types of terrain (Figure 36.30). Parts of Enceladus shows small craters (less than 35 km in diameter), while other areas show no craters at all, indicating major resurfacing in the geologically recent past. The surface may be undergoing modification by the release of water from "water volcanoes." There are fissures, plains, corrugated terrain, and other crustal deformations. These features all indicate that the interior may be liquid today, even though it should have frozen long ago. Its orbit is perturbed by Saturn's gravitational field and by the large neighboring satellites Tethys and Dione. This orbital eccentricity produces strong tides and tidal heating, which may have kept the ice in a more fluid state after the satellite accreted. The smoother regions have groove and ridge terrain that is very similar to regions on Ganymede.

Tethys

Tethys is heavily cratered and has an approximately 1000-km-long valley running roughly north and south. The terraced walls of the valley suggest layering of the crust. With a density of 1.0 g/cm^3, Tethys is mostly water ice. The expansion forces caused by freezing of the water ice might have created the valley.

Dione

Dione is about the same size as Tethys but has a higher density. Highly reflective streaks or wisps on the dark trailing hemisphere may be frost deposits produced by water escaping from the interior through linear fractures. The crater density is generally lower than on Mimas.

Rhea

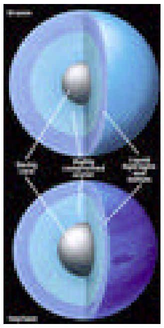
Rhea also shows large variations in surface reflectivity and has wispy markings like those seen on Dione. Differences in the size and frequency of craters in bright and dark terrains indicate that the darker terrain is older.

URANUS

Uranus, the seventh planet from the Sun, was the first to be discovered since ancient times. It was first observed through a telescope in 1781, appearing as a featureless bluish green disk. In *Voyager 2* photos, Uranus appears as a generally featureless disk with darkening toward the edges (Figure 36.31). Faint banding and transitory cloud plumes can be seen in contrast-enhanced images. Uranus orbits the Sun at an average distance of 2.87 billion km, completing one revolution every 84 years. Uranus rotates on its axis once every 17.9 hours. The planet has a very unusual rotation, with its axis tilted on its side. This results in very strange seasons. Despite the exaggerated seasons, Uranus's winds blow parallel to the equator, as do Jupiter's and Saturn's. The atmosphere has such a great capacity to store heat that the alternating 42-year periods of sunlight and dark have practically no effect on Uranus's temperature.

Uranus has a diameter of 52,400 km, four times that of Earth, and a mass 14.58 times that of Earth. Its density is 1.21 g/cm^3. In 1932, red absorption bands in the spectrum of Uranus were identified as being caused by methane gas in the atmosphere. This red absorption is responsible for the planet's blue green color.

Composition and Structure



Hydrogen and helium make up more than 99 percent of Uranus's atmosphere, which is about 8000 km thick. A layer of methane ice clouds was detected by *Voyager 2*. Uranus has a rocky and icy core nearly as large as those of Jupiter and Saturn, but a much thinner envelope of hydrogen and helium (Figure 36.32). We don't know much about the lower atmosphere of Uranus.

The magnetic field is tilted 60 degrees to the rotation axis and is also offset from the center of the planet—by about one-third of Uranus's radius—toward the north pole. Because of the large offset, the surface magnetic field strength is not constant across the planet.

Infrared measurements from *Voyager 2* indicate that Uranus has a surface temperature of –214°C. Unlike the other giant planets, there is no evidence of any significant internal heat source. The absence of an internal heat source contributes to the featureless exterior.

Rings

Scientists were excited by the unexpected discovery in 1977 that Uranus has rings. Subsequent observations have revealed 10 narrow rings of dark particles and one broad, diffuse ring, in addition to 100 or more possibly transient ringlets of dust-sized particles seen only in *Voyager 2* images of the backlighted rings. The rings of Uranus are strikingly different from Saturn's rings. They are a million times less massive than Saturn's rings; they are made up of dark carbonaceous particles rather than water ice; and they are slender and narrow, with large gaps between them, rather than broad and flat like the main rings of Saturn. The outermost ring of Uranus, also unlike the rings of Saturn, has almost no particles smaller than about 20 cm in diameter. The other rings also seem to lack small particles.

Satellites

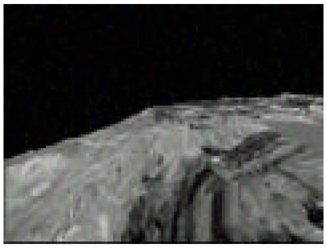
Uranus has five major satellites: Miranda, Ariel, Umbriel, Titania, and Oberon. *Voyager 2* found 10 small satellites as well. The smaller satellites have very dark surfaces. The major satellites are somewhat brighter, reflecting from 19 percent (Umbriel) to 40 percent (Ariel) of the sunlight that falls on them. Umbriel is the darkest of the major satellites and has the fewest geological features. The other four satellites display increasingly complex geologies corresponding with decreasing distance from Uranus. Oberon and Titania are remarkably similar in size, density, color, and reflectivity. Titania, however, has many more small craters and surface fractures, which implies that it has a geologically younger surface. Oberon has one mountain that rises at least 20 km above the surface.

Ariel

Although Umbriel and Ariel have similar diameters and densities, they differ dramatically in surface appearance. Ariel's surface is covered with fractures and fault systems. In several areas, parallel fractures bound valleys that appear to have glacierlike flows along their floors. Ices of water and ammonia melt at much lower temperatures than pure water ice and might form the observed glaciers.

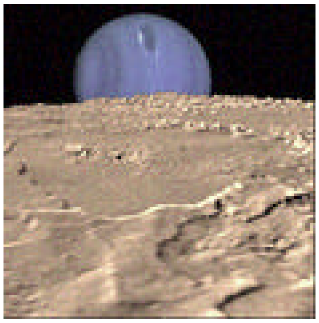
Miranda

Miranda is the innermost and smallest of Uranus's major satellites. It orbits Uranus at a distance of 104,350 km, taking 1.41 days to complete a trip around the planet. Through a piece of good luck, Miranda was the satellite *Voyager 2* approached most closely. (The



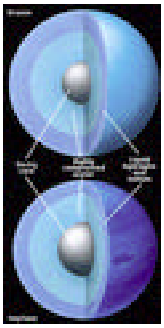
spacecraft had to fly close to Uranus, and thus Miranda, to get the boost it needed to go on to Neptune.) Miranda turned out to be the most interesting of all the satellites. Its surface is unlike anything else in the solar system, with features jumbled together haphazardly (Figure 36.33). Miranda consists of huge fault canyons as deep as 20 km, terraced layers, and a mixture of old and young surfaces. There are several theories about Miranda's bizarre appearance, but the real reason is still unknown. The younger regions might have been produced by incomplete differentiation of the moon, or Miranda may have been shattered several times by ancient collisions with satellite fragments, then reassembled. Possibly, the materials out of which Miranda was formed may not have melded together into a uniform surface. Miranda's bizarre appearance may be a frozen record of the late stages in its development.

NEPTUNE



Neptune, the eighth planet from the Sun, is the most remote of the gas giants, lying an average of 4.497 billion km from the Sun. Neptune is too faint to be seen from Earth by the naked eye. In a large telescope, the planet appears as a small blue disk. Figure 36.34 shows a composite image of Neptune as seen from its large moon Triton. Neptune completes one trip around the Sun every 164.79 years in an orbit even more nearly circular than Earth's. The rotation period of Neptune's magnetic field, which presumably traces the rotation of the planet's core, is 16.05 hours. Most of the clouds on Neptune have longer rotation periods, however, ranging from about 16 hours near the south pole to more than 18 hours near the equator. This means that winds on Neptune reach 1100 km/hr and move opposite to the direction of rotation. These are the strongest retrograde winds seen on any planet in the solar system.

Composition and Structure



Neptune has a diameter of 49,500 km and a mass 17.22 times that of Earth, making the planet slightly smaller and heavier than Uranus. It has an average density of 1.67/cm^3. Like Uranus, Neptune is believed to have a rocky core surrounded by a liquid water mantle, which is surrounded in turn by liquid hydrogen and helium (see Figure 36.32). The atmosphere consists mainly of hydrogen and helium, with about 2.5 to 3 percent by weight of methane. The cirruslike clouds in Neptune's atmosphere are composed of crystals of methane. Methane's strong absorption band dominates the planet's spectrum, giving Neptune its deep blue color. Ammonia is probably also present.

Temperatures on Neptune rise with increasing depth, as on Uranus. Scientists had expected Neptune's temperature to be about –228°C, but measurements made by *Voyager 2* indicated a higher temperature of at least –218°C. Thus Neptune, like Jupiter and Saturn but unlike Uranus, appears to have an internal heat source.

Voyager 2 discovered that the magnetic field of Neptune is tilted more than 50 degrees from the rotation axis and is offset from the center of the planet. This means that the magnetic field strength varies across the surface. This unexpected orientation resembles that of Uranus's magnetic field. The orientation of Uranus's magnetic field had been thought to be linked to that planet's unusual orientation, with a rotation axis nearly parallel to the plane of the ecliptic. Now scientists must find some other explanation for this shared characteristic.

Atmosphere and Clouds

The best pictures of Neptune from Earth show discrete bright clouds and a bright haze over Neptune's south pole.*Voyager 2* confirmed these sightings when it reached Neptune. The spacecraft's cameras revealed many atmospheric features, including a large storm system the size of Earth named the Great Dark Spot for its resemblance to the Great Red Spot of Jupiter. In 1994, the Great Dark Spot disappeared. Perhaps it simply dissipated, or maybe it is being masked by other aspects of the atmosphere. A few months later, a new dark spot was discovered in Neptune's northern hemisphere. Apparently, Neptune's atmosphere changes rapidly, perhaps because of slight changes in the temperature differences between the tops and bottoms of the clouds. *Voyager 2* also saw a smaller dark storm system with a bright core of feathery clouds, a small bright cloud feature named the "Scooter," well-defined banding, and numerous wispy, cirruslike clouds. Some of these clouds cast shadows on deeper cloud decks below, and this observation marked the first detection of vertical relief in the atmosphere of an outer planet. The cirruslike clouds changed rapidly, often forming and dissipating over several hours. These surprisingly fast changes imply that Neptune's weather may be as dynamic and variable as Earth's.

Rings

The presence of rings around Neptune had been debated before the *Voyager* encounter. Several ground-based observations had suggested that irregular arcs of partial rings orbited the planet. Studies of *Voyager* 's photographs eventually revealed that five rings surround Neptune: two bright, narrow rings and three fainter, fuzzier rings. Some sections of the bright rings are denser than others, and it was these areas of higher density that had first been detected by Earth telescopes. The bright rings are roughly 53,000 km and 63,000 km from the center of Neptune. Like Uranus's rings, they are made up of dark carbonaceous particles and are much less substantial than the rings of Saturn.

Satellites

The only two satellites discovered before *Voyager* 's visit were Triton, Neptune's largest satellite, and Nereid. Both have unusual orbits. Triton is the only large satellite in the solar system to move in a retrograde direction around its planet, and Nereid has the most eccentric orbit of any satellite in the solar system. Nereid's distance from Neptune varies from 1,400,000 to 9,700,000 km. *Voyager 2* found that Nereid is about 340 km in diameter and reflects about 12 percent of the sunlight that falls on it. *Voyager 2* also discovered six new satellites. Proteus, the largest of these, has an irregular shape with an average diameter of about 400 km, making it slightly larger than Nereid. It is much darker, however, reflecting only about 6 percent of the sunlight that strikes it. It is also closer to Neptune, which is why it remained undiscovered before *Voyager.* Nereid is gray in color, and hints of craterlike forms and groovelike lineations are seen on its surface.

Triton

Triton's surface is remarkably diverse and reveals a long geological evolution (Figure 36.35). Some areas are smooth and free of craters, suggesting a young surface. Grooves and ridges cut across the icy landscape. Unusual features include a terrain of roughly circular depressions with raised rims. The depressions are probably not impact craters, because they are too similar in size and too regularly spaced. It is more likely that they are associated with local melting and collapse. Other regions have dark gray markings with sharply defined bright borders. The slightly pinkish south polar cap covers much of the southern hemisphere and is apparently evaporating along its northern edge. The polar cap may consist of nitrogen ice deposited during the previous winter. The evaporation of nitrogen ice seems to generate geysers or volcanic plumes of nitrogen that rise to altitudes of 10 km above the surface. This cryovolcanism is driven by sunlight warming the surface rather than by internal heat and tidal effects, as on Io.

Triton has a thin atmosphere composed mainly of nitrogen, with some methane, and it may extend as high as 800 km. A thin haze appears to be concentrated about 3 km above the surface but may extend upward to at least 14 km. Its composition is unknown, but it may be either condensed atmospheric gases or complex organic molecules produced by irradiation of methane in the atmosphere. About 50 elongated dark streaks seem to be composed of particulate materials blown and deposited by prevailing winds. They originate from small, dark, circular vents and may represent deposits of geyserlike emissions of materials under the surface. Because Triton has a relatively high overall density (2.1 g/cm^3), it is thought that up to 75 percent of the inner core may be rocky material.

Triton has turned out to be an object of great interest to scientists because of its active and varied geology. Many would rank it with Io and Titan as the most interesting satellites in the outer solar system.

PLUTO

Pluto, the outermost planet, is also the smallest, with a diameter of about 2280 km. Because of its small size, it was not discovered until 1930. Pluto can be seen only as a faint point of light even by the largest Earth-based telescopes. Much of what we know about Pluto is deduced from the presence of its satellite, Charon, discovered in 1978. Pluto is the only planet that hasn't been visited by a spacecraft. Figure 36.36 is a Hubble Space Telescope image of Pluto and Charon.

Pluto’s average distance from the Sun is 5.9 billion km, but because of its high orbital eccentricity (0.249), it comes as close as 4.42 billion km and travels as far as 7.40 billion km from the Sun. This unusual orbit brings Pluto inside the orbit of Neptune during its close approach to the Sun; we are currently in such a period of close approach (between January 1979 and March 1999). The actual orbital paths do not cross, however, because Pluto’s orbit is inclined 17 degrees to the ecliptic. Pluto revolves around the Sun once every 248.4 years. In 1988, a computer simulation showed that the orbit of Pluto is chaotic (that is, not completely predictable). Pluto rotates once on its axis every 6.39 Earth days; its motion is retrograde.

Pluto’s composition is unknown, but its density (about 2 g/cm^3) indicates that it is probably a mixture of 70 percent rock and 30 percent water ice, much like Triton. The bright areas of the surface seem to be covered with ices of nitrogen with smaller amounts of (solid) methane and carbon monoxide. The composition of the darker areas of Pluto’s surface is unknown. Consistent variations in brightness that have been observed indicate that the surface is irregular.

Little is known about Pluto’s very thin atmosphere, but it probably consists primarily of nitrogen with some carbon monoxide and methane. Pluto’s atmosphere may exist as a gas only when Pluto is near perihelion; for most of Pluto’s long year, the atmospheric gases are frozen into ice.

Charon

Charon, Pluto’s grayish satellite, was discovered on June 22, 1978. It is about 1160 km in diameter. It orbits Pluto at a distance of about 19,000 km and at an inclination of 55 degrees to the ecliptic. It completes one revolution in 6.39 days, the same as Pluto’s rotation period. Charon may have a trace atmosphere.

Many of the key questions about Pluto and Charon will only be answered by the close-up observation of a space flight mission. To address these questions, NASA is now developing a robotic reconnaissance mission to Pluto-Charon. The *Pluto Express* mission is being conceived using lightweight advanced-technology hardware components and advanced software technology. The mission plan calls for launch when this technology is ready, with a goal of encounters with Pluto and Charon around 2010 or later.