A view of Jupiter’s satellite Io from Voyager 1 spacecraft in 1979 provides an example of the variety of planetary bodies. Mottled patches on Io result from active volcanism that constantly modifies the sulfur-rich surface. Doughnut-shaped rings at right center is a cloud of debris being erupted from an active volcanic caldera (black area inside the doughnut). (NASA)
The solar system is commonly said to have nine **planets**, shown in Figure 2-1. In order from the sun, they are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto. A traditional mnemonic device for remembering this sequence is "Men Very Early Made Jars Stand Upright Nicely (Period)." (Surely today's students can do better than this!) Because confusion often sets in at Saturn, Uranus, and Neptune, remember that the **SUN** is in the system too.

The first four planets are sometimes called the **terrestrial planets** because of their nearness to Earth and the similarity of their rocky, metallic compositions. The four planets from Jupiter through Neptune are sometimes called the **giant**, or **Jovian planets** because of their size and similarity to Jupiter.

### What Is a Planet?

You might think that the term **planet** is so clearly defined that any body can be labeled either a planet or a nonplanet. We grew up being told there were nine planets moving around the sun, and nine bodies do seem uniquely distinguished by size, position, orbit, and so on. However, the situation is not really so clear. The word "planet" comes from the Greek term for "wanderer," referring to the fact that planets drift in the night sky among the stars, from night to night. Among the ancients, a "planet" was any of seven bodies that changed position from day to day with respect to the stars. These seven included the sun and the moon, as well as the first five planets (excluding Earth) out to Saturn. The rest had not yet been discovered.

A contemporary definition is that a planet is any body except a **comet**, **asteroid**, or **meteoroid**, orbiting the sun, but this definition is ambiguous unless comets, asteroids, and meteoroids are defined. We beg the question by calling those objects "interplanetary" bodies. And scientifically, how do we justify excluding the asteroid **Ceres**, which orbits between Mars and Jupiter and has the sizable diameter 1000 km, nearly twice as big as the other asteroids in that region?

If we try to define planets by the regular spacing of their nearly circular orbits, we face the fact that Pluto—which is generally pictured as the most remote planet—has a markedly noncircular orbit that crosses inside Neptune's. In fact, Pluto spent much of the 1990s inside Neptune's orbit! This trait, of crossing planet orbits, is generally associated with asteroids and comets, not planets themselves.

If we try to define planets by size alone, we are confounded by the fact that some satellites are larger than the planets Mercury and Pluto, as shown in Figure 2-2. Pluto is only about half the size of our own moon.

Many astronomers are moving toward the view that it makes more semantic sense to say that our own solar system has eight planets, not nine! When Pluto was discovered in 1930, it was hailed as a newly discovered planet. However, today's evidence is that it should be demoted to an asteroid. The arguments include the following:

- Since the 1990s, many bodies up to half the size of Pluto have been discovered in the same region. Called the "Kuiper Belt" objects, they are cataloged as asteroids or comet nuclei.
- Pluto crosses inside Neptune's orbit, like an asteroid or comet.
- Pluto is now known to be only about half the size of our moon, and a bit more than twice the size of the next-largest known asteroid, Ceres. Seven satellites are larger than Pluto.
- Pluto's orbit is considerably more inclined to the plane of the solar system than the orbit of any other planet, but well within the range for asteroids and comets.

Generally, the whole distinction between planets and "asteroids and comets" is vague, because planets formed by the aggregation of smaller bodies; the asteroids and comets are these smaller bodies or their broken debris, so it is hard to say what is the smallest planet and what is the largest asteroid or comet.

To confuse matters more, a number of bodies, mostly around the size of Jupiter, were detected during the 1990s, orbiting around other stars. They are too small to be stars themselves—that is, to have nuclear reactions inside. Are they planets, in the same sense as Jupiter or Earth? Most astronomers initially said yes, but we might ask if they
formed in the same way as the planets in our system. This is more than a semantic question because planet-sized bodies might form in different ways, and some of the extrasolar systems may be different from ours. For example, some roughly Earth-sized “planets” have been found around neutron stars—remnants of stars that exploded as supernovae. These might not be planets like ours but may have something to do with the debris from the explosion.

Operationally, we now define a planet as a nonstellar body larger than a certain size (1,000–3,000 km?), orbiting around a star. If we knew more about the orbits and other characteristics of recently discovered extrasolar planets, we might have a better answer to the question of whether they formed in the same way our system did.

Some additional terms can give more flexibility. Planetary body or planetary material: Includes planets and smaller objects, as used in Chapter 1. Planetary bodies are usually solid (with some liquid or gas components possible) and mostly composed of silicates or ices. Planetary bodies include the dust grains observed around some stars, asteroids, comets, and the planets orbiting other stars.

Planetary: One of the relatively small planetary bodies. Usually this word refers to one of the small planetary bodies in the early solar system, which aggregated into planets. The term usually implies a size between that of a microscopic dust grain (less than 1 mm in diameter) and a large asteroid (about 1,000 km in diameter).

Satellite: Any planetary body in orbit around a larger planetary body. At least 63 are known.

Asteroid: A small planetary body composed mostly of rock or metals; most orbit the sun between Mars and Jupiter. All known asteroids have diameters of less than 1,000 km. Usually the term is used only for bodies down to about 10 m in diameter, but there is no firm cutoff.

Comet: An ice-rich planetesimal that can emit an observable gaseous halo when its ice is warmed by the sun. Most comets spend most of their time in the outer solar system far beyond the asteroid belt. The term comet is
Figure 2-2. Relative sizes of the terrestrial planets and selected smaller bodies, drawn to scale. Diameters are given in km. Giant planets' satellites are indicated by letters J, S, U, and N and a number code, as well as names. (The number code is a traditional usage, indicating either the order outward from the planet, usually for larger numbers, or the order of discovery.) Asteroids have a number and a name. The three objects with numbers $\geq 20,000$ are the largest known Kuiper Belt "asteroids" in the outermost solar system.

THE SOLAR SYSTEM: AN OVERVIEW
<table>
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<tr>
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<th>Mercury</th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
<th>Asteroids</th>
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<td>192</td>
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**Predicted distance (AU)**
- 0.4
- 0.7
- 1.0
- 1.6
- 2.8
- 5.2
- 10.0
- 19.6
- 38.8

**Actual distance (AU)**
- 0.4
- 0.7
- 1.0
- 1.5
- 2.8
- 5.2
- 9.5
- 19.2
- 30.0
- 39.4

**Symbol**
- ☉
- ☉
- ☉
- ☉
- ☉
- ☉
- ☉
- ☉
- ☉
- ☉

**No. known satellites**
- 0
- 0
- 1
- 2
- 7
- 16
- 18
- 17
- 8
- 1

*The well-observed asteroids (roughly 2000 known) are numbered; the symbol is the encoded number.

**Voyagers 1 and 2 discovered several small satellites on the outskirts of the ring systems of Jupiter, Saturn, Uranus, and Neptune. The smallest may grade into the largest ring particles. At least four more probable moons were seen by Voyagers near Saturn.*

ambiguous in that region because those comets are too far from the sun to be heated enough to make the ice turn into gas; thus they are inactive or dormant comets and are hard to distinguish observationally from asteroids. Many of the inactive comets have been catalogued as asteroids. In a sense, the “comet-asteroid” language breaks down beyond Saturn, where the bodies are surely icy but rarely give off gas. Planetesimals might be a better general term in that region.

**World:** A term useful in referring to any planetary body—planet or satellite—that is larger than 1,000 km in diameter. Bodies larger than that typically have enough internal energy to have individual geological “personalities.” This term gained increased use in 1979 when the Voyager probes revealed that the four large satellites of Jupiter, originally assumed to be dead iceballs, instead had four distinct geologic characters, ranging from craters to smooth ice to erupting volcanoes.

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**Bode’s Rule**

In 1772, the German astronomer Johann Bode* popularized a simple empirical rule, Bode’s rule, which is a helpful tool for remembering the distances of the planets from the sun. This rule should be memorized. Write down a sequence of 4s, one for each planet except Neptune and one for the asteroids, and add the sequence 0, 3, 6, 12, 24, . . . (see Table 2-1). Dividing by 10 gives the relative distances of the planets from the sun in terms of the mean distance from Earth to the sun. The latter distance is called the **astronomical unit** (AU). Thus, Jupiter is 5.2 AU from the sun.

Bode’s rule lacked any theoretical justification, but it passed its first test in 1781 when the English astronomer William Herschel discovered Uranus at 19.2 AU. Afterward, a search was made for the “missing planet,” which was supposed to lie between Mars and Jupiter. This led to the discovery of the first asteroid, Ceres, on the first night of the new century, January 1, 1801, by the Italian astronomer Giuseppe Piazzi, exactly at the predicted solar distance of 2.8 AU. Discoveries of more asteroids followed in subsequent years, mostly having solar distances around 2.8 AU.

Notice that from Bode’s rule, planets are not evenly spaced, but each one tends to be nearly twice as far from the sun as the previous one. Modern work suggests that this spacing has to do with the way the aggregating planetesimals partitioned the solar system into zones, with each zone dominated gravitationally by one large body that grew by sweeping up the rest of the bodies.

A set of symbols for designating the planets is the one useful contribution of astrology. The symbols, listed in Table 2-1, form convenient subscripts and datum-point symbols in theoretical discussions and graphs.

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**A Survey of the Planets**

Before proceeding to the chapters describing the dynamics, origin, and nature of the planets, we give a thumbnail sketch of each planet in order from the sun. These sketches emphasize a basic observational description of each planet; the interpretations appear in later chapters.

**Mercury**

**Mercury** is the second smallest planet and the closest to the sun. It has essentially no detectable atmosphere. Its surface has a slightly pinkish cast; Earth-based telescopes reveal only faint mothlings reminiscent of the appearance of the moon to the naked eye. Most of these dark regions are believed to be lava-covered areas similar to the dark lava plains of the moon. Like the dark regions on the moon and Mars, these dark regions are called maria (singular...
Venus

Venus is sometimes called Earth's sister planet. It most nearly matches Earth in size, and its orbit is closest to Earth's orbit. Its very dense atmosphere is composed mostly of carbon dioxide (CO₂). Opaque white or yellowish clouds hide its surface.

Because of the highly reflecting clouds and its close approaches to Earth, Venus is very bright when it appears in our sky. Like Mercury, it moves only a small angular distance from the sun as seen from Earth (see Figure 2-3). When it moves into a position to be our evening star or morning star (setting or rising a few hours after or before the sun), it is brighter than any other planet and is some 15 times brighter than the brightest star (Sirius); it can even cast shadows.

Through a telescope, Venus appears as a nearly blank disk, occasionally mottled by barely visible dusky bands or patches. These cloud patterns are much more prominent in ultraviolet light because some of the cloud or atmospheric constituents absorb the ultraviolet (Figure 2-6). Spacecraft photographs taken with ultraviolet filters clearly reveal the roughly banded cloud patterns, which lack the great cyclonic whirls characteristic of Earth's low-level clouds.

Because of Venus's cloud cover, we cannot watch the rotation of the solid surface of the planet, and until the 1960s, the rotation period was a mystery. Repeated attempts...
to determine the rotation by watching motions of the cloud markings on Earth-based ultraviolet photographs were frustrated by rapid changes in the clouds and their ill-defined patterns.

In the early 1960s, radar techniques yielded the totally unexpected finding that Venus rotates in 243.1 d, not in the same direction as Earth and most other bodies rotate, but backward, from east to west (Dyce, Pettengill, and Shapiro, 1967)! This peculiar situation may be abetted by dynamical resonance between Earth and Venus (Goldreich and Peale, 1967), although the resonance is apparently not exact. This east-to-west motion (clockwise as seen from the north side of the planet), whether in a planetary body’s orbit or spin, is called retrograde motion, as contrasted to the usual west-to-east or prograde motion (counterclockwise as seen from the north).

Ultraviolet photos show that the high-atmosphere clouds circulate east to west in roughly 4 d (Smith, 1967), a result confirmed by spectroscopic studies from Earth (Betz and others, 1977) and by spacecraft photography (Murray and others, 1974). This movement corresponds to a circulating wind near the cloud tops (40 to 60 km above the surface) of about 100 m/s (meters/second). Other winds have been measured by spacecraft and spectroscopy, ranging from very gentle surface breezes to a 125 m/s wind from daytime to nighttime hemispheres at an altitude of around 115 km (Betz and others, 1977).

What lies hidden beneath the clouds of Venus? Decades of speculation have produced many theories. Many early 20th century scientists thought the clouds were composed of water droplets and that the surface must be a steamy jungle of vegetation swept by torrential rains. Others suggested a windy, dry desert or an ocean of oily liquid. Decades of speculation were ended by spacecraft encounters with the planet and new techniques of intensive Earth-based observation in the 1960s. Venus was first observed at close range on December 14, 1962, by the U.S. spacecraft Mariner 2, which passed 38,854 km (21,645 mi) from the surface of the planet. The first contact with the planet was achieved October 18, 1967, when the Soviet spacecraft Venera 4 parachuted into the atmosphere and radioted back data. On December 15, 1970, Venera 7 made the first successful unmanned landing on Venus, sending back more atmospheric data. Finally, on October 22 and October 25, 1975, Veneras 9 and 10 sent back the first photos of the surface (Chapter 10), which reveal a desolate, dry, rock-strewn landscape (Florensky, Basilevsky, and Pronin, 1977; Keldysh, 1977). The atmosphere at ground level is surprisingly clear. Gravel and rounded bedrock outcrops give evidence of erosive and weathering processes.

Earth-based instruments and the Soviet landers showed that the surface temperature and pressure are extremely high, about 750 K (890°F) and 90 atmospheres (90 times the sea level air pressure on Earth), respectively.
The mystery of the cloud composition was solved when Sill (1973) and Young (1973) independently found that the cloud properties could be explained by droplets of concentrated sulfuric acid ($H_2SO_4$ dissolved in water). The droplets are typically 2 $\mu$m across, with an acid concentration of 78% to 90% (Pollack and others, 1978). Venus is thus a fearsome place—hot and dry with a dense CO$_2$ atmosphere and sulfuric acid clouds.

Space probes orbiting around Venus have bounced radar waves through the clouds and off the surface, yielding detailed images and topographic maps of surface features (Figure 2-7). Global mapping was first done by the Soviet Venera 15 and 16 probes starting in 1983, and with more detail by the American Magellan probe in 1990-1992. The results reveal a volcanically active sister to planet Earth. Venus’s volcanic plains are broken by a few Australia-size uplands 2 km to 5 km high, with a few volcanic peaks as high as 11 km above the plains, exceeding Mt. Everest’s 8 km above sea level (Figure 2-8). Meteorite impact craters, sparsely scattered on the plains, suggest a surface nearly as young as Earth’s, with a fairly uniform age of about 500 My to 800 My. With some surprise, geologists have interpreted this as suggesting a global resurfacing event at that time, perhaps due to major turnover in the planet’s mantle. Fractures testify to seismic unrest, and some of the volcanoes may be active today. Circular features called coronas, a few hundred km across, may be caused by local upwelling currents in Venus’s mantle (Phillips, Grimm, and Malin, 1991; Saunders and Pettengill, 1991).

**Earth**

The next planet from the sun is characterized by shifting white clouds and a blush color resulting from sunlight scattered by molecules in its atmosphere. Different from the CO$_2$-dominated atmospheres of its neighbor planets, Venus and Mars, its atmosphere is mostly molecular nitrogen ($N_2$) and molecular oxygen (O$_2$), with variable traces of water vapor (H$_2$O). Its surface is very unusual, being temperate and 71% covered with liquid water.

The most important and unique characteristic of this planet—Earth (Figure 2-9)—is its widespread life, both on land and in the oceans. Protecting this life appears to be a major challenge to Earth’s current civilization.

*Figure 2-6.* Ultraviolet image of Venus from Pioneer Orbiter in 1978 shows faint patterns of cloud bands in the opaque atmosphere. (NASA)

*Figure 2-7.* Radar image of impact crater on volcanic terrain of Venus. Dark background material is an old lava plain, cut by tectonic fractures (bright lines), typical of Venus. The impact crater (center circle) was formed on this surface, but was partly filled in by lavas. Tongues of new lava flow extend toward the crater from the southwest; they are bright because rough, young lavas reflect more radar than old, eroded lavas. (NASA Magellan mission image)
Figure 2-8. Comparative relief maps of (a) Venus, (b) Earth, and (c) Mars. Altitude data have been digitized and presented as shaded relief with light from the left. Venus has broader expanses of rolling plains than Earth but also has some elevated, continentlike masses (such as Aphrodite Terra) and features resembling sea-floor trenches (such as Artemis Chasma). Mars retains a more primitive topography with traces of old impact basins (such as Hellas). Martian relief is also dominated by large domes of volcanic lavas surmounted by high volcanic peaks (such as Olympus Mons atop the Tharsis Dome). (Images courtesy Michael Kobrick, Jet Propulsion Laboratory)

Moon

Earth has one natural satellite, the moon, whose character remained rather mysterious during centuries of telescopic study. The broad dark patches composing the “man in the moon” were first thought to be seas and were given the Latin name maria (MAH-ree-a, singular mare, pronounced MAH-ray); these dark patches were finally found to be plains formed by lava flows about 3,500 My ago. Early observers gave these plains Latin names such as Mare Tranquillitatis (Sea of Tranquility) and Mare Imbrium (Sea of Rains). As on Mercury, the cratered regions of lighter color are called uplands.

After a century of debate, researchers concluded that most of the craters are caused not by volcanism, but by meteorite impact. As shown in Figure 2-10, craters and lava plains have been mapped in detail on both sides of the moon.

Unmanned landers in the 1960s first revealed that the lunar surface is covered by a dusty layer called a regolith—a layer of powdery soil and scattered rock fragments created by eons of bombardment by meteorites.

The moon’s history remained enigmatic until 1969, when astronauts explored the ghostly lunar landscape and brought back the first rock and soil samples. In 1969–1972, lunar samples were returned from six Apollo
landing expeditions and three sites visited by Soviet unmanned vehicles. These samples indicate that the moon has a bulk chemical composition roughly similar to that of Earth's outer mantle layers, with many rock types known to terrestrial geologists. However, the moon lacks water and other volatile compounds. These chemical differences are clues to the moon's origin and history and are the subject of much vigorous research. The rocks show that the moon, like Earth, formed about 4500 My (million years), or 4.5 Gy* ago. The mode of formation is uncertain. The early moon underwent intense bombardment by meteorites, forming most of the many craters shown in Figure 2-11 by 4.0 Gy ago. The early moon was volcanically active, and about 3.5 Gy ago, massive lava flows created the dark plains or maria. Most lunar volcanism ceased about 2 Gy ago. Most of the Apollo astronaut landings occurred on the maria, whose dusty, rock-strewn landscapes became familiar when the lunar exploration was broadcast live from the moon's surface into our living rooms.

**Mars**

If Venus is Earth's sister planet, Mars is a smaller brother, half the size of Earth. It has many Earth-like features, including an atmosphere with clouds and ice deposits at its poles, called **polar caps**. It rotates in 24 1/2 h (hours), about the length of Earth's day. Unfortunately for the proposed family resemblance as well as for future manned exploration, the atmosphere is very thin, cold, and dry. Compared to Earth's sea level surface pressure of 1000 mbar (millibars), Mars's surface pressure in most regions is about 5 to 8 mbar and would require visitors to wear a spacesuit. Martian ground temperature exceeds freezing only on the warmest summer days (though the air temperature usually stays below freezing), and the air has only minuscule traces of water vapor. There is no liquid water; all the water of the planet is in the form of ice and water molecules trapped in the minerals. The famous red **surface coloration** is caused by oxidized iron minerals, or rust-like

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*In the SI (International System) system of metric units, the prefix "giga," abbreviated G, stands for 10^9. The figure 4.5 Gy is also commonly referred to as 4.5 billion years.*
material. This color is prominent even when Mars is viewed with the naked eye from Earth.

As shown in Figure 2-12, dusky markings have been mapped on Mars since 1659. They intrigued early astronomers because they change shape and intensity from season to season and year to year. Observers in the 1800s interpreted the seasonal changes as strong evidence that the dark markings were Martian vegetation.

When observers such as William Herschel discovered clouds and white polar ice caps around 1800, they thought these features bolstered the philosophical idea called the plurality of worlds—the idea that other planets were like Earth, and probably inhabited with other of God’s creatures. By the late 1800s, astronomers began to realize that the Martian climate was inhospitable, but Darwin’s 1859 theory of evolution and adaptation made it reasonable to suppose that Martian creatures might have evolved and adapted to their planet’s conditions.

During the 1877 approach of Mars, the Italian observer Giovanni Schiaparelli called attention to the streaky Martian markings, which he called by the Italian term, canali. Contrary to common belief, Schiaparelli did not discover these streaks; they had been drawn earlier, as shown in Figure 2-12b. However, Schiaparelli drew them differently, as straight or curved narrow lines, as can be seen in Figure 2-12c.

In the 1890s, Percival Lowell, a flamboyant American astronomer, pulled these discoveries into a radically new conception of Mars that influenced many 20th-century ideas. Lowell saw the lines, which he called canals, as very sharply defined, like steel engraving lines. He said they really were canals, built by a civilization of intelligent Martians. The Martians, said Lowell, were having trouble surviving because the weak gravity of their planet was allowing its water to leak off slowly into space. Therefore, the Martians had constructed a vast network of canals to

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*This idea of gases escaping into space more easily on weak-gravity planets is scientifically correct, as we see in Chapter 12.
Figure 2-11. The moon is dominated by rugged regions covered by craters mostly formed during intense meteorite bombardment about 4.5 to 3.5 Gy ago. In the upper left are dark, smooth lava plains called mare, dating back to about 3.5 Gy. (NASA, Apollo 16)

carry the spring runoff from the melting polar ice down to the warmer equatorial regions, where they could cultivate the vegetation.

Lowell's theory was wonderful, but it was all wrong. Its underpinnings, the canals, essentially do not exist as he drew them; they are only wispy streaks and splotches, as shown in Figures 2-13 and 2-14. The Martian canal affair occurred because the human eye tends to interpret rough alignments as linear streaks. Lowell was especially inclined toward this and even saw lines on Venus.
Figure 2-12. Drawings of Mars through telescopes. (a) One of the earliest known sketches of Mars was drawn by Christian Huygens on November 28, 1659. The northward-extending triangle is probably a dark region known as Syrtis Major. (After Huygens) (b) In a drawing by English observer W.R. Dawes during the 1864–1865 opposition, Syrtis Major extends northward but with a streaky extension of a type later called a canal. Clouds covering the north polar ice cap are outlined by a dotted line at the top. (After Dawes) (c) Italian observer Giovanni Schiaparelli drew Mars in 1888 with the dark triangle of Syrtis Major again visible with a streaky, dark tail. Schiaparelli first popularized the canals, shown by him here as nearly straight lines and line pairs covering Mars. However, spacecraft show that the canals do not exist in this form. Because we see Mars from different angles in different years, Syrtis Major may appear above or below the disk center. (After Schiaparelli)

Lowell's ideas, though disproven, forced scientists and intellectuals to recognize that theories of planetary and biological evolution raise the possibility of life on other worlds if the conditions are suitable. This idea shook intellectuals and the public at large and remains exciting today.*

On July 15, 1965, the first close-up spacecraft photos of Mars were taken by the American spacecraft Mariner 4. There were no signs of dying Martian cities or canals—only a moonlike cratered surface. In 1969, Mariners 6 and 7 flew by, showing more craters and jumbled, collapsed depressions that geologists called chaotic terrain. Although the nature of the changing dark markings was still unknown, many astronomers now concluded that Mars was dead and moonlike—similar to the moon but with a little wind to blow the dust around.

On November 14, 1971, Mariner 9 became the first spacecraft to go into orbit around Mars. This mission mapped the whole planet in detail for the first time, as shown in Figure 2-14, and proved that the vision of a moonlike Mars was too pessimistic. To everyone's surprise, Mariner 9 photographed young volcanoes, sand dunes, and many examples of dry riverbeds! Examples of the

Figure 2-13. Mars viewed from the Mars Global Surveyor spacecraft in 1997 shortly before it went into orbit. This image, sharper than any Earth-based pictures, shows bright clouds (right) and the types of dark streaky markings (lower third) that were mistaken for linear "canals" by many early observers. (NASA and Malin Space Science Systems)

* A more detailed, nontechnical history of the changing theories is given by Hartmann (2003). An excellent biography of the colorful Percival Lowell is given by Hoyt (1976).
Figure 2-14. Map of Mars. The prominent dark and light markings are semipermanent features seen from Earth, created mostly by dust deposits. The underlying topographic features, such as craters and mountains, were first mapped in the 1970s by spacecraft. (Courtesy R. M. Batson, U.S. Geological Survey)

riverbeds appear in Figure 2-13. Some of them emanate from the previously discovered chaotic terrain. After much controversy, most planetary geologists concluded that these features, called channels (not to be confused with the semi-illusory canals!), really were carved by running water. As discussed in more detail in Chapters 11 and 12, this finding suggests that the climate of Mars may have been more clement in the ancient past.

Mariner 9 also indicated that substantial amounts of H₂O are frozen at the poles under a transient winter cap of CO₂ snow and accompanied by stratified polar sedimentary deposits. The evidence for abundant ice and past liquid water raised profound questions. If liquid water existed on Mars in the past, did life evolve at that time? If so, what happened to that life? If not, why not?

Because no one had yet seen Martian details smaller than a couple hundred meters, astronomers still wondered if the surface supported plants or even animals! The next step was to land cameras on the surface to see what was there. The first human-made devices on Mars were Soviet probes that failed before or after touchdown. Mars 2 crashed in November 1971; Mars 3 landed but failed 20 s (seconds) after touchdown in December 1971; Mars 6 failed moments before touchdown in February 1974.

July 20, 1976, the seventh anniversary of the first lunar landing, was a better day. The Viking 1 lander made the first successful touchdown on the planet (Figure 2-16). In the following months, Viking 1 and its sister ship, Viking 2 (which landed September 3, 1976) found a striking desert landscape devoid of any obvious life. There was not even any organic material in the Martian soil, measured to a precision of a few parts per billion. Although three experiments designed to seek life found peculiar reactions in the soil at both landing sites, most
scientists relate those reactions to unusual soil chemistry. Mars Pathfinder landed at a third site on July 4, 1997, and photographed a similar terrain strewn with lava-like rocks. In the 1980s–90s, scientists identified meteoritic rocks on Earth that were blown off Mars by asteroid impact. These priceless rocks confirm excitingly young volcanic and magmatic activity on Mars—as recently as 0.17 Gy ago.

Mars has two small satellites, Phobos and Deimos, discovered in 1877 by the American astronomer Asaph Hall. Curiously, literary works such as Swift's *Gulliver's Travels* (1720) and Voltaire's *Micromégas* (1750) referred to two moons of Mars years earlier. This led some pseudo-science writers to suggest occult knowledge of the two moons centuries ago, but the explanation is simpler. Johann Kepler, who discovered the laws of planetary motion around 1610, believed in numerology and suggested that if Earth had one moon and Jupiter four (the four discovered by Galileo at that time), then Mars should have two to maintain the progression. Later spacecraft have searched for smaller satellites and found none down to diameters of 1.6 km (Pollack, 1973).

Close-up photos of Phobos and Deimos show irregularly shaped satellites about 20 × 28 km and 10 × 16 km, respectively, with heavily cratered surfaces and brownish-black surface material, as shown in Figure 2-17 on page 24. In color and appearance, these two satellites resemble certain dark asteroids composed of carbon-rich minerals.

**Jupiter**

Jupiter is by far the largest planet, having more mass than all the other planets put together. It has more than three times the mass of the next largest planet, Saturn, and about a 20% larger diameter. Dynamically the solar system can be thought of as composed of two main bodies, the sun and Jupiter; Jupiter has 0.001 the mass of the sun, and the other bodies are negligible.

Jupiter has a dense atmosphere of molecular hydrogen (H₂, 79% by mass), helium (19%), and trace amounts of
such as dark, oval-shaped clouds that may last for years, are called disturbances.

Another long-lived feature is the Great Red Spot, prominent in Figures 2-18 and 2-19. Probably first seen by Robert Hooke in 1664 or Giovanni D. Cassini in 1665, it was named in 1878 when it became very prominent and was rediscovered (Peek, 1958; Chapman, 1968). Time-lapse movies by Voyagers 1 and 2 in 1979 showed that the Great Red Spot is characterized by circulating currents—small clouds caught in the Red Spot will spiral around counterclockwise like a leaf caught in a whirlpool. It is a giant whirlpool indeed; somewhat variable in size, it can reach 4 Earth diameters!

Telescopic observers in the last century estimated the rotation rate of the planet by watching the cloud features as the planet turned, but they found that different cloud features circulate at different rates, due to zonal winds. The basic rotation rate of the underlying planet is probably about 9 h (hours) 55 m (minutes) 30 s (seconds), a value associated with radio pulses associated with the planet's magnetic field. The equatorial clouds move faster than this because of jet streamlike winds, and give a rotation period of only 9 h 50 m 30 s, the so-called "System I" period. High latitude clouds also show a "System II" rotation, or circulation period of 9 h 55 m 41 s, closer to the planetary value. The Great Red Spot drifts along with a variable period, drifting sometimes ahead of and sometimes behind other features in System I; Peek (1958) gives values 9° 55′ 31″ to 9° 55′ 44″ over a 76 y (year) period.

The first spacecraft to Jupiter was the American probe Pioneer 10, which made some crude images and measurements during a fast flyby on December 4, 1973. It was followed by a similar probe, Pioneer 11, in December, 1974. The first detailed images of Jupiter and its four large moons were made by the U.S. probes Voyager 1 (March 1979) and Voyager 2 (July 1979) as they flew through the Jupiter system on their way to the outer planets (Figure 2-20). These were followed by the U.S. Galileo probe that went into orbit around Jupiter in 1995 and spent several years cruising from one moon to another, returning a wealth of data about the system. These vehicles took superb photos of Jupiter and the moons and gathered abundant additional data. Voyager 1 also discovered a ring around Jupiter, fainter and narrower than the famous rings of Saturn and probably composed of fine, rocky particles.

Jupiter has a complex system of at least 28 satellites outside the rings, somewhat resembling a small solar system. The four large moons are called the Galilean satellites because they were discovered by Galileo. The discovery date was January 7, 1610; on the next night they were independently discovered by the German astronomer Marius, who named them Io, Europa, Ganymede, and Callisto (in order outward from Jupiter) after associates and parameters of Zeus, the Greek version of the Roman god Jupiter. Jupiter's moons are also labeled with numerals; the Galilean satellites are J1, J2, J3, and J4 in the order given above. Subsequent numbers are assigned in order of discovery.

water vapor (H₂O), methane (CH₄), and ammonia (NH₃). The planet is covered by clouds, arranged in dark belts and bright zones, parallel to the equator (Figure 2-18). The belts and zones are semipermanent and have been named, as shown in Figure 2-19. The clouds show a variety of colors—browns, tans, yellows, and reds. Large irregularities,
Within the orbits of the Galilean moons is the largest remaining moon, Amalthea (numbered J5), about $155 \times 270$ km in size, dark reddish-gray in color, and heavily cratered. The Voyagers discovered three other small moons in this region. Two are about 30 to 40 km across, very dark in color, and located between the rings and Amalthea (Jewitt, 1979). The other is about 75 km across and is located between Amalthea and Io.

Beyond the Galilean moons are two peculiar groups of small moons. The inner group includes J13, J6, J10, and J7, in orbits from about 11,000 km to 12,000 km from Jupiter, and all inclined between 24° and 29° to the
Figure 2-20. Jupiter looms beyond two of its satellites. Europa is the lighter moon (right), and Io the darker moon silhouetted against the Great Red Spot. Numerous other cloud formations on Jupiter are prominent in this Voyager 1 view from a distance of 20 million kilometers. Europa and Io are about the size of our moon. (NASA)

planet's equator. The second group, including J12, J11, J8, and J9, all lie at distances of about 21,000 km to 24,000 km with inclinations of 147° to 164°. (The use of an inclination figure greater than 90° is a convention for indicating a retrograde direction of revolution. Thus, an inclination of 147° is equivalent to an inclination of 180° - 147° = 33° but with retrograde orbital motion.) Why the outer satellites of Jupiter should be arranged in two such tidy groups rather than randomly scattered is a mystery to which we return in Chapter 5. The surfaces of at least some of these moons are black, owing to a soil rich in carbonaceous minerals like those in certain dark asteroids and meteorites. In addition to the eight moons mentioned above, many other captured moons have been found since 2000.

The "total number of moons" of a giant planet has become a semantic question. Ultra-sensitive telescopes routinely turn up new kilometer-scale moonlets, and 100-meter-scale objects may exist by the hundreds. Many are not original, but captured. This book concentrates on "world-class" examples.

Orbital calculations (for example, Carusi, Valecchi, and Kresak, 1981) suggested that cometary or asteroidal bodies are sometimes captured by Jupiter into temporary satellite orbits lasting months or years. A moonlet photographed several times in 1975 by Charles Kowal may have been one of these. The concept of temporary captures by Jupiter was confirmed in spectacular fashion in 1993 when astronomers Carolyn and Gene Shoemaker and David Levy discovered a cometary body caught in a loose, temporary orbit around Jupiter. Because of dynamical forces during the close pass by Jupiter, when it had been captured into orbit, the weak cometary body had been broken into a string of fragments that were destined to make a wide orbit around Jupiter and then crash into the planet. The spectacle climaxed in 1994 when the string of fragments struck Jupiter, making explosions that were visible from Earth, as seen in Figure 2-21 (Beatty and Goldman, 1994). This episode reminds us that throughout geologic time, the planets have been interacting with the smaller interplanetary bodies, resulting in explosions, impact craters, and occasional climatic disturbances.
Small Worlds of the Outer Solar System: A Simplified Overview

Telescopic views of even the largest satellites of the outer solar system revealed only pinhead-sized disks (less than 2 arc seconds across) on which visual observers in the mid-20th century reported dusky shadings. Spectroscopists, by the 1970s, reported H₂O ice with admixtures of soil. Astronomers tended to assume that these worlds would be rather alike—cratered, dead iceballs resembling icy versions of our own moon. Close-up photos of Jupiter’s and Saturn’s moons by Voyagers 1 and 2 revealed the opposite—an astounding variety from one world to the next, as if each were attempting to assert its own uniqueness!

The variety might make theorists throw up their hands and conclude that each world is governed by laws unto itself. But we can make some sense of the pattern by keeping in mind the following simple model. Theories of mineral condensation in the primordial solar system (which we discuss in more detail in Chapter 5) suggest that the main materials formed in the cold, outer parts of the system would be frozen water and a type of sooty-black dust rich in carbon minerals. Spectrophotometric observations seem to confirm that either ice or dark soil, or a mixture of the two, are the main constituents visible on the surfaces of most moons and all interplanetary bodies from the outer asteroid belt outward. Note that a chunk of frozen water is relatively stable against sublimation by solar heating only beyond about 4 AU (Lebofsky, 1975). If mixtures of ice and black soil are finely powdered and mixed in a regolith soil layer, the resulting material will look dark if the soil content is more than a few percent, because the opaque black minerals efficiently absorb the light. Thus, a primitive surface of, say, 50% ice and 50% carbonaceous soil would look dark. Similarly, any surface in which the carbonaceous component had been concentrated would look like dark soil (even though it might have some ice content). On the other hand, if heating occurred, the denser soil would sink and watery “lava” could coat the surface with regions of relatively pure bright ice or ice/soil layers (Hartmann, 1980). If enough heating occurred to evaporate most of the water, components such

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as sulfur compounds could be left on the surface (Fanale, Johnson, and Matson, 1974).

As we now see, this “salt-and-pepper” model (“salt”—bright ices; “pepper”—black soils) gives a first-order explanation of the range of surfaces that have evolved in the outer solar system. It is easiest to apply this idea if we describe the four Galilean moons, starting with the outermost and working our way inward.

**Callisto**

Of the four large Galilean moons of Jupiter, the outermost one, **Callisto**, most closely resembles a terrestrial planet.* At 5,000 km across, it is about 2% larger than Mercury. The surface is moderately dark and composed of silicate-like soil mixed with 30% to 90% H₂O ice by mass (Clark, 1980). The soil component is probably black carbonaceous material that may contain further water chemically bound in its minerals. The Voyager flybys in 1979 revealed a heavily cratered surface resembling the uplands of the moon or Mercury, as is seen in later chapters. The low mean density, 1,790 kg/m³ (compared with 1,000 for water and ice, and about 3,000 for rock) is the lowest of the Galilean moons, indicating that the interior consists of about one-fourth ice by mass. The lack of volcanic/tectonic features suggests little internal heating. Similarly, magnetic and dynamic measurements of the Galileo orbiter as it passed Callisto in 1996–1997 indicate no magnetic field and a homogeneous interior that never melted or formed a dense core. Bright rims and rays of some craters suggest that impacts have blown away a dark soil surface and exposed brighter icy material underneath. The largest feature is an enormous multiring bulls-eye, with outer rings spanning 2,400 km. This and other smaller, similar features are probably caused by impacts on the icy crust, later modified by isostatic leveling involving a watery substrate (McKinnon and Melosh, 1980).

**Ganymede**

**Ganymede**, the largest and next moon inward from Callisto, has different properties. With a 5,270-km diameter, it is 8% larger than Mercury and 75% of Mars. It has a moderately bright surface containing an average of 90% frozen water or frost by mass (Clark, 1980). Voyager close-ups reveal some provinces of old, cratered, dark, terrain like Callisto's but these are broken by broad, bright fracture zones that appear to have fresher ice. Olistolites have occurred on some fractures, but overlying undeformed craters indi-

*Discussions of the various Galilean worlds include Voyager 1 and 2 results described by Smith and Voyager Imaging Team (1979), along with other papers in Science, 204, No. 4390 (June 1, 1979) and Science, 212, No. 4491 (April 10, 1979), and Galileo probe results in Science, 274, No. 5286 (October 18, 1996).

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**Europa**

**Europa**, the smallest Galilean moon, is different from the others. Twelve percent smaller than our moon, it has a bright, featureless surface except for a system of shallow, dusky grooves. It looks like an icy billiard ball with smudges and scratches (Figure 2-22). Paradoxically, the very blandness is cause for great excitement among scientists. The near absence of impact craters shows that the surface is relatively young and that resurfacing processes have operated in recent times. The bright surface is more than 90% ice by mass, but the bulk density of 3,030 kg/m³ implies that the interior is composed mostly of rocky material. The Galileo orbiter found evidence of a denser core and a possible weak magnetic field. Photos from the probe showed clearly that the ice, like pack ice in Earth's arctic, is a thin layer (hundreds of meters thick?) floating on an
underlying ocean, and that it fractures and breaks into ice rafts, with new ice filling in the gaps. All the evidence, taken together, indicates continued heating by an uncertain mechanism; some heat source is keeping the underlying water melted. Two mysteries are (1) the source of the heat and (2) the nature of the underlying ocean. As Arthur C. Clarke, author of 2001, suggested after Voyager, a water ocean on Europa could conceivably harbor life.

**Io**

Io, the innermost Galilean moon, is one of the strangest worlds in the solar system. At 2,640 km across, it is only 2% larger than our moon. Its density is 3,530 kg/m³, highest of the Galilean worlds, implying an interior of rocky material with very little or no ice content.

A history of mystifying discoveries indicated Io's strange nature even before the Voyager photos revealed Io's unique properties. In 1964, observers reported Io to be anomalously bright for about 15 minutes after some, but not all, eclipses (Binder and Cruikshank, 1964). This effect was seen occasionally in later years. Also in 1964, radio observers discovered that bursts of radio radiation from Jupiter were correlated with the position of Io in its orbit relative to Earth (Bigg, 1964). Spectral observers in the next few years found that unlike the other satellites, Io lacks water frost or ice on its surface. High-resolution telescopic photos taken in 1973 show reddish and white patches (Minton, 1973). Observers then discovered that Io is surrounded by a thin, yellow-glowing cloud of sodium atoms knocked off the surface (Brown, 1973; Trafton, Parkinson, and Macy, 1974). This cloud, many Io diameters across and extending along Io's orbit, is too faint to be seen through telescopes but is probably bright enough to be seen as an aura by an observer on Io. Sulfur and oxygen atoms have subsequently been found spread along Io's orbit. Some months before Voyager 1 reached Jupiter and Io, telescopic observers noted mysterious flare-ups of infrared (5μm wavelength) emission, but the observers did not guess the real cause (Witteborn, Bregman, and Pollack, 1979).

Many of these findings have now been clarified. For example, Io orbits within Jupiter's intense magnetic field and is coupled to Jupiter by electric currents through this field. This connection explains its influence on the directions of radio emissions arising in Jupiter's magnetic field.

A notable triumph of the scientific method came in 1979 when California dynamosist Stanton Peale and colleagues calculated the heat produced inside Io by a certain dynamical effect called tidal heating (see also Chapter 3). They found that Io's interior must be hot and predicted that Io might have active volcanoes. The prediction was published a few days before Voyager 1 reached Jupiter, and a few days later, active volcanoes were discovered on Io by Linda Morabito, an engineer in the Voyager program (Figure 2-23). This was the first discovery of active volcanoes outside Earth. The chapter opener photograph for this chapter also shows an active Io volcano from "above," with a black caldera at the center, surrounded by a doughnut-shaped bright ring of debris.

"Predicted" is the key word in the above discussion because it is the key strength of the scientific method. What other system of thought has this ability to predict phenomena around us?

The Voyager and Galileo close-up photos reveal an extraordinary world of mottled patches in colors of red, orange, yellow, white, and black. When the first photos came in, one Voyager investigator quipped that he didn't know what was wrong with Io, but it looked as if it might be cured by a shot of penicillin. Reporters compared Io to a pizza.

Temperature measurements confirm that the volcanoes are hot (500 K or 440°F) and their outbursts account for infrared flare-ups seen from Earth. The heating is severe enough that it has driven off water and other volatile compounds, leaving a rocky/sulfurous composition without the ice that characterizes other moons of the outer solar system. The Galileo orbiter discovered that Io has a large metallic core, interpreted to be a mix of iron and iron sulfide (Anderson, Sjogren, and Schubert, 1996). The surface is dominated by sulfurous lavas, explaining the high density and unusual colors. Ions striking the surface dislodge atoms of sulfur and sodium that are excited by sunlight, explaining the yellow auroral glow around Io. Condensations of compounds such as sulfur dioxide (SO₂) when
cooling occurs during eclipses may explain some of Io's reported changes in brightness. In short, Io is an amazing world, with a colorful red, yellow-orange, and white surface, an intermittent yellow-aurora sky, and volcanoes ejecting vast fountains of gas and sulfur-ash debris.

**Saturn**

The globe of Saturn is rather like Jupiter but smaller, more flattened, with less-prominent cloud markings (Figure 2-24). Yellowish and tan cloud belts parallel the equator as seen in Figures 2-24 and 2-25. Occasional bright and dark markings disturb these belts, but a greater depth of overlying haze makes them less visible than on Jupiter. Spectroscopic studies from Earth and Voyagers 1 and 2 identified the main gases as molecular hydrogen (88.2% by mass) and helium (11%); an atmosphere similar to that of Jupiter. Minor identified components include methane (CH₄), ammonia (NH₃), and ethane (C₂H₆).

Saturn has the lowest mean density of all the planets, 710 kg/m³, indicating a very hydrogen-rich interior with few rocky materials. Given a sufficiently immense ocean, Saturn would float!

Saturn is best known for its rings, shown in Figure 2-25. When Galileo first turned his crude telescope on Saturn in 1610, he could not see the rings clearly. He saw only fuzzy appendages on each side of the globe, and drew Saturn as a triple planet. Saturn's true nature remained controversial until the 1660s, when the rings were clearly seen to encircle the planet (Alexander, 1862). In 1899, the Scottish physicist James Clerk Maxwell showed that they could not be a solid plate but must be made up of innumerable particles, each moving in an independent orbit around Saturn. The American astronomer James Keeler (1895) was the first person to prove this when he used the Doppler shift to detect the varying orbital velocities of different parts of the rings; it was one of the first great successes of spectroscopic astronomy. Although the rings are 270,000 km (170,000 mi) in diameter, they are extremely thin, probably no more than a few hundred meters thick. Spectra show that the ring particles are composed of, or covered by, frozen water (Pilcher and others, 1970; Kuiper, Cruikshank, and Fink, 1970), possibly with traces of silicate or carbon minerals (Lebofsky, Johnson, and McCord, 1970; Pollack, 1975; Cuzzi and Pollack, 1978). Various studies show that the common ring particles range from a few centimeters to a few decameters across; they are hailstones from the size of a Ping-Pong ball to the size of a house. A Voyager search for larger ring moonlets yielded negative results at sizes larger than a few kilometers.**

The rings are divided as sketched in Figure 2-24. The dusky outer ring, called ring A, is separated by a gap from the brighter ring B. The gap is called Cassini's division. A narrower division, called Encke's division, cuts ring A. On the inner side of ring B is a very faint, tenuous ring, C. The French observer Guerin (1970) announced a still fainter

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*Measuring the composition of the rings illustrates the vicissitudes of planetary research. Kuiper, Cruikshank, and Fink (1970) obtained the first infrared spectrum of the rings, and although Kuiper as early as 1956 hypothesized that the rings are water ice, the spectrum matched lab samples of frozen ammonia at ~20°C, and so they published the conclusion that the rings are made of ammonia ice. Immediately, Pilcher and others (1970) and Lebofsky and others (1970) pointed out that under the actual ring temperatures of ~178°C, water ice spectra are altered, and do match the spectrum of Saturn's rings. Kuiper and his coworkers concurred at once that the spectra indicate water ice.

**Important Voyager results on Saturn, the rings, and the satellites have been published in Science, 212, no. 4491 (April 10, 1981) and Science, 215, no. 4532 (Jan 29, 1982). See also Beatty and others (1981).
Figure 2-25. Varying aspects of Saturn during its 29-\text{y} orbit around the sun, as photographed with Earth-based telescopes. Because the rings maintain a fixed tilt to the ecliptic, the Earth-based observer sometimes sees them from "above" and sometimes from "below" the ring plane. This series shows half of the 29-\text{y} cycle, including two views of the apparent disappearance of the rings as Earth passes through the ring plane. (Lowell Observatory)
and more tenuous innermost ring, D, which extends from the planet toward ring C; the Voyagers confirmed a D ring here but not bright enough to have been seen from Earth (Smith, 1990). Rings A through D, together with the Cassini and Encke divisions, have been called the classical ring elements (Smith and others, 1981); they were charted from Earth. Pioneer 11, flying by in 1979, discovered a narrow ring just outside the A ring; it came to be called the F ring. Beyond it lies a thin G ring and a very diffuse E ring that extends beyond the orbit of Enceladus.

Saturn’s Satellites

Thirty Saturnian moons were known by 2001. The system, like Jupiter’s, includes a host of small moons near the rings, and a grouping of larger moons at intermediate distance, including the giant moon, Titan. As with Jupiter’s Galilean system, we gain some insights by starting with the outermost moons and working inward.

The outermost sizable moon is the small, dark satellite Phoebe, about 220 km across. Its orbit is retrograde and the most highly inclined of the satellite family. It is surely a captured interplanetary body rather than a native Saturn satellite. In 2001 another dozen, smaller, captured moons, both prograde and retrograde, were found (Gladman et al. 2001).

Next inward from Phoebe is the curious moon, Iapetus. It is a moderate-sized body, about 40% the size of our moon. Its diameter is 1,440 km. Its strangeness was recognized as early as 1671 when G. D. Cassini discovered that he could see it easily when it was on the west side of the planet, but not when it was on the east side! This oddity was explained when large telescopes revealed that Iapetus keeps one face toward Saturn so that one hemisphere leads and one trails, and that the leading hemisphere is covered with very dark soil whereas the trailing hemisphere is covered with frost and nearly five times as bright. Voyager 2 photos in 1981 revealed that the boundary between the dark and light sides is irregular and sharp (Figure 2-26). One possible explanation is that dark dust knocked off Phoebe by meteorites spirals in toward Saturn and hits Iapetus’s leading side, enriching that side’s soil with dark material and altering the native material.

As if to reemphasize the rule that each world is unique, the next satellite is again different. Hyperion is a biscuit-shaped chunk about 350 km across and 200 km thick. Voyager 2 photos (Figure 2-27) showed its irregular, cratered shape. Its long axis does not remain lined up with Saturn, as would be expected if gravitational tidal forces

Figure 2-26. Saturn’s unusual satellite Iapetus has dark soil on its leading hemisphere (left) and bright icy material on its trailing hemisphere (right). A dark circular crater rim is seen on the right side. Cause of the strange soil/ice distribution is uncertain. (NASA Voyager 1)

Figure 2-27. (a) Top view and side-on view of Saturn’s biscuit-shaped satellite, Hyperion. The irregular shape may have occurred during impact fragmentation. Hyperion is about 360 km long. The side-on view (b) was made from a greater distance and is less sharp. (NASA Voyager 2 photo)
Figure 2-28. A rogue's gallery of Saturn's major icy moons. (a) An unusual view of Dione shows it against a background of Saturn's clouds; Dione, at 1,118 km diameter, has darker markings on its trailing hemisphere (left). (b) Rhea, at 1,530 km diameter, shows craters and dark patches. (c) Tethys, 1,048 km in diameter, shows a cratered surface and a linear canyonlike fracture. (d) Mimas, at 390 km, has an impact crater almost big enough to have shattered the satellite. (NASA Voyager photos)

had acted for a long time. Instead, Hyperion has an irregular and chaotic spin that is a result of gravitational forces and rotational dynamics acting in concert with Hyperion’s irregular shape and eccentric orbit.

Because the next satellite inward, Titan, is unique and one of the largest moons in the solar system, we discuss it separately in a moment.

The next three moons, Tethys, Dione, and Rhea, are around 1,000 to 1,500 km across and have bright, icy surfaces, as seen in Figure 2-28a-c. Tethys, Dione and Rhea have densities of around 1,210 to 1,430 kg/m³, and probably have some rocky material mixed with their ice. These worlds are moderately to heavily cratered. Tethys's surface is broken by a huge canyon system and Dione's by swaths of lighter-toned material, reminiscent again of Ganymede. Cracking of the surfaces and resurfacing by water (quickly frozen to form bright ice plains and flows) may have occurred because of some source of internal heat, possibly tidal heating.

In 1980, Earth-based observers discovered interesting additional small moons perhaps 20 km to 50 km across in the orbits of Tethys and Dione. One orbits 60° behind Tethys, one is 60° ahead of Tethys, and the third is 60° ahead of Dione. At least two others, associated with Tethys and Dione, are suspected from Voyager photos. Gravitational forces make this 60° point—a called a Lagrangian point—a stable location for small objects. Certain asteroids are known in similar 60° points ahead of and behind Jupiter. These discoveries expand the list of similarities between satellite families and the solar system as a whole—supporting the analogy of satellite families as miniature solar systems.

The next satellite, Enceladus, is especially fascinating as a “missing link” between Jupiter's moons Europa and Ganymede. Enceladus (Figure 2-29) has the linear grooves and bright, sparsely cratered, icy surface of Europa, but it also has some moderately cratered, fractured regions that resemble Ganymede. Voyager analysts suspect that Enceladus has a fairly young surface created by eruptions of water and ice from an interior heated by tidal interactions with other Saturnian moons. This mechanism would resemble the heating that keeps Io's volcanoes erupting, but calculations have failed to show how the heating mechanism would be adequate. The bulk density of 1,200 kg/m³ indicates that Enceladus is mostly icy throughout, so that radioactivity from rock minerals (such as the process that heats Earth's interior) also appears minimal. A concentration of material in Saturn's E ring at the position of Enceladus's orbit also leads to suspicions of (volcanic or geyserlike?) eruptions of material off Enceladus. However, the mystery of Enceladus's heat sources and degree of geologic activity remains unsolved.

The next moon inward is Mimas, 390 km across, round, icy, and heavily cratered. Mimas's bright surface and low bulk density (1,190 kg/m³) indicate that it is composed mostly of ice. As seen in Figure 2-28d, Mimas has a crater so large that it was almost big enough to shatter the moon.

On the outskirts of the rings are at least five small moons with diameters of 30 to 330 km. Most were discovered by Voyager 1 and by intense Earth-based observations during a period of a few weeks when the rings were seen edge on and thus did not obscure the satellites by their glare. Voyager photos show that at least some of these moons are lumpy and cratered, but their composition is uncertain.

Titan

In the middle of the Saturn satellite system is the giant, Titan, with a diameter of 5,120 km. It is the solar system's second-largest moon, ranking just smaller than Ganymede. Titan rivals Io as the solar system's most bizarre world. It is the only moon with a thick atmosphere, discovered in 1944 when spectra of Titan revealed methane gas (CH₄). Observations in 1973 showed that Titan's sky is
not clear, but is filled with a reddish haze, creating a nearly featureless globe as seen from a distance. Later observations showed that this haze is photochemical smog produced by reactions of the methane and other compounds when they are exposed to sunlight—like the smog produced by the action of sunlight on hydrocarbons over Los Angeles. Titan is the smoggiest world in the solar system.

The Voyager probes showed that methane and smog are no more than 10% of Titan’s atmosphere. The main constituent is nitrogen, as on Earth. The atmosphere is so dense that the surface air pressure is 1.6 times that on Earth! The main difference is that Titan’s air is very cold, around 93 K (−292° F). Minor constituents include organic molecules such as ethane (C₂H₆), acetylene (C₂H₂), ethylene (C₂H₄), and hydrogen cyanide (HCN). Since Earth’s air is also mostly nitrogen, Titan’s atmosphere offers fascinating comparisons; the abundance of organic molecules suggests that Titan offers a natural laboratory for research on the origins of life.

Under conditions on Titan’s surface, pools of liquid methane and liquid nitrogen may exist. If the methane content exceeds some 8%, methane may also rain out of the clouds and exist as snow or ice, playing the same triple role of gas, liquid, and icy solid as water does on Earth. The smog may even produce gasolinelike compounds that rain out of the hazy clouds. The strange surface may be revealed by the Cassini/Huygens parachute probe in 2004.

**Uranus**

Now we come to the outer three planets, which were not known to the ancients. **Uranus** was discovered accidentally on March 13, 1781, by the English musician-turned-astronomer William Herschel. Herschel was observing star fields at the time with his telescope; later studies showed that other accidental observations of Uranus had been made earlier but the observers had mistakenly plotted the planet as a star.
While Uranus is nearly four times the size of Earth, it is only 41% the size of Saturn. It is so remote that it presents only a tiny, somewhat bluish disk in large telescopes. Voyager 2 photos were the first high-resolution images, but revealed only a nearly featureless disk, with only faint traces of cloud bands and polar haze. Voyager 2 is the only spacecraft to have reached Uranus and Neptune; Voyager 1, after departing Saturn, flew on a different course out of the solar system. Spectroscopic studies indicate a dense atmosphere consisting of roughly the same mix of hydrogen to helium found on Jupiter and Saturn (Ingersoll, 1990). The planet rotates in 17.9 hours.

The bland appearance of Uranus (Figure 2-30) results from colder temperatures and lesser inner thermal activity, so that the atmosphere is less restless than those of Jupiter and Saturn. The color comes from Rayleigh scattering of blue light (see Chapter 11), as in our own atmosphere, plus a strong absorption of red light by methane gas (CH₄), which constitutes a few percent by mass. The net result is a bland, ethereal blue globe, with a slight greenish cast.

Uranus has a peculiar dynamical property. As shown in Figure 2-31 on page 36, its axis of rotation, instead of having only a slight tip to the plane of the solar system as is true of the other planets, lies mostly in the plane of the solar system. This means that sometimes the "north" pole of Uranus points toward the sun, whereas half a revolution later the "south" pole points toward the sun. The inclination of the axis to the orbit plane is 82° and the spin direction is retrograde; these two statements are usually combined by saying that the inclination of the axis is 98°, or eight degrees past parallel. This is more than a curiosity; it is a property that must be explained by any theory of the evolution of planets.

The first edition of this book, in 1972, remarked that Uranus resembles a bluish Saturn without rings—a fine analogy until March 10, 1977, when many astronomers watched Uranus pass in front of a relatively bright star, and saw the star dim several times on both sides of Uranus's disk, indicating that it had been obscured by rings that go all the way around Uranus (Elliot, Dunham, and Mink, 1977, and many other papers published that year). When Voyager 2 arrived, it confirmed an elegant system of narrow, faint rings (Figure 2-30) totally unlike Jupiter's broad, tenuous ring, or Saturn's dramatic system of bright rings and narrow gaps. The faint rings are composed of black dust particles. Between some of the narrow rings are broader, still fainter rings. A flurry of subsequent studies indicated that the net gravitational actions of small satellites near the rings confine the ring particles into narrow, tightly defined rings.

Uranus has five substantial satellites discovered from Earth, and ten more small ones, close to the planet, discovered by Voyager 2 and two more small outer moons that may be captured. Voyager provided a surprise. As shown in Figure 2-32 on page 36, the satellites show amazing geologic features and individual personalities. For example, 1,170-km-diameter Umbriel is darker than the others, and 470-km Miranda has extraordinary swaths of grooves and faulted cliffs. The energy source for Miranda's ancient tectonic activity may be tidal heating. Other satellites, such as 1,160-km Ariel, also show tectonic signs of ancient activity (Figure 2-32b). The sixteenth and seventeenth moons were discovered in 1998 from photographs taken with the Palomar 200-inch telescope.

Neptune

After Uranus was discovered in 1781, dynamacists tried to determine its orbit. They found that Uranus's motions were being affected by the gravitational force of another planet beyond Uranus.

An interesting chapter in the history of science then ensued (Lyttleton, 1968). Unknown to each other, an English and a French astronomer set out in the 1840s to predict where the undiscovered planet must be. Based on Bode's rule, which seemed to be confirmed by Uranus, they assumed a solar distance of 38 AU—ironically, as Neptune is the one serious failure of Bode's rule. John Adams, just finishing his undergraduate work at Cambridge, had trouble getting his professors interested in the search. Urbain LeVerrier predicted a position in 1846, and the English astronomers began a desultory search, actually spotting it, but failing to recognize it. Meanwhile, LeVerrier got two young German astronomers interested, and they discovered it within half an hour of starting their search on September 23, 1846. Adams and LeVerrier are
Figure 2-31. Comparison of the sizes and rotations of Earth and Uranus. Earth has an obliquity (or axial tilt) of 23½° and a prograde (west-to-east) rotation. Uranus has a much steeper obliquity and retrograde rotation.

Figure 2-32. Satellites of Uranus (a) The five large moons in order outward from Uranus (left to right). They are reproduced at the same scale and with a uniform brightness scale. The unique, puzzling dark color of Umbriel is well seen, as is the small size of Miranda. (b) Close-up of part of Uranus's satellite, 1,160-km-diameter Ariel, shows old, heavily cratered surface, broken by numerous tectonic rifts. (c) Miranda, at 484 km diameter, surprised scientists by showing an intensely fractured and contorted surface. Origin of the sharply defined sectors of fractured terrain is unknown. (NASA Voyager 2 photos)
A satellite, named Charon (KEHR-on), was discovered in 1978 (Christy and Harrington, 1978). Pluto is the only “planet” not yet visited by a spacecraft, and we have no close-up photos. Pluto and Charon are so far away that even the Hubble Space Telescope shows only a fuzzy image of Pluto with the vaguest shadings. However, observations of spectra, star occultations, and a fortuitous set of eclipses (1985–1990) established many properties of Pluto and Charon. They keep the same face to each other and rotate every 6.39 days on an axis tipped 122° to the orbit plane. Pluto has an atmosphere thinner than that of Mars, probably composed of nitrogen and carbon dioxide (Stern, Weintraub, and Festou, 1993). Pluto’s diameter is 2,302 ± 16 km, and Charon’s is 1,186 ± 26 km. The daytime surface temperature is a frigid 36 ± 2 K (−396°F) (Stern and others, 1993). Pluto and Charon’s mean densities are roughly 2,000 ± 200 kg/m³, suggesting a composition of around 70% rock and 30% ice (Binzel, 1990; Stern, 1992).

An interesting observation is that Pluto is somewhat brighter and pinker (but not nearly as red as Mars) and has a surface rich in methane ice with blue geometric albedo (reflectivity) of 66%; Charon is more neutral gray and has a surface rich in water ice, with a blue geometric albedo of only 38%. Why would the two intimately linked worlds have different surface materials? Researchers think that the lighter molecules, such as methane, have escaped from Charon because of its lower gravity; once the molecules escaped into space within the Pluto/Charon system, some of them collided the surface of Pluto itself. Thus, over time, Charon has lost methane molecules and Pluto has gained some of them. This would explain the difference in surfaces.

Pluto and Charon are a frontier outpost of the solar system. From that distance, the sun would appear only as bright as a bright streetlight seen at night down the street.

“Planet X”?  

Are there any other substantial planetary bodies beyond Pluto? Several astronomers have sought dynamical or photographic evidence of a planet there, sometimes called “Planet X.” Clyde Tombaugh, the discoverer of Pluto, conducted a long search and ruled out any planet as large as Neptune near the plane of the solar system out to a distance of around 100 AU.

However, the mass of Pluto/Charon seems to be too small to account for all the irregularities in the motions of Neptune. This finding has prompted more searches; surveys in 1979, 1988, and following years found no more Pluto-sized objects, but they did turn up many smaller objects in Pluto’s region and beyond, with
**Figure 2-33.** A portion of crescent-lit Neptune (bottom) sets off a view of its satellite, Triton. Crescent lighting and forward scattering of light through haze of Neptune makes its cloud features relatively invisible. (NASA Voyager 2 photo)

**Figure 2-34.** Two photo-mosaics of Neptune's sparsely cratered, largest moon, Triton. Due to the inclined orbit, lighting was mostly on the southern hemisphere, as shown by latitude/longitude grid. Inset shows a view that includes more of the bright southern polar region. Dark streaky smudges (bottom) are associated with geyser-like vents. (NASA Voyager 2 mosaics)
diameters of a few hundred kilometers, approaching a fifth the size of Pluto. These discoveries convinced many astronomers that the outer fringe of the solar system is full of icy bodies, of which Pluto may be only the largest (or one of the largest). Probably no full-fledged Planet X, Earth-size or larger, will be discovered. However, additional Pluto-size bodies may lurk in the outermost solar system.

Telescopic Appearance of the Planets

Though much of the information we will discuss comes from spacecraft, it is still interesting to know what can be seen by examining the planets visually with an earth-based telescope. Except on rare nights, Earth's atmospheric turbulence blurs details with an angular size of less than 0.5 seconds of arc. Rare conditions with little turbulence are called good "seeing." With even fair seeing, amateur astronomers' telescopes of 15 cm to 30 cm (6–12 in.) show most of the details shown in Figure 2-35. Experienced observers can always see much more detail than beginners.

The sizes of the sketches in Figure 2-35 indicate very roughly the apparent sizes of the planets seen from Earth. Note that the inner planets display the largest apparent size when they are in crescent phase between Earth and the sun. A good rule of thumb is that the east-west ("horizontal") thickness of Venus in most of its phases is roughly 10 (10 seconds of arc) across. Jupiter and the Saturn ring system are typically around 45 seconds of arc. When passing near Earth, Mars reaches as much as 25 seconds across. Jupiter's four Galilean satellites and some satellites of the giant planets are easily visible in small telescopes; but only the four large moons of Jupiter approach even one second in angular diameter, so that vague detail can be seen only with the largest telescopes under the finest conditions.

Miscellaneous Basic Data and Terminology

Readers intending to pursue scientific careers would be well advised to memorize a few numerical facts about the planets. In spite of popular arguments against "memorizing mere facts," a small investment in memorization can produce large savings in time spent looking up trivia and allow quick checks of ideas that might otherwise turn out to be blind alleys. Table 2-2 lists some data that are used in a large number of simple calculations. The solar constant, listed in Table 2-2, is defined as the rate at which energy is received from the sun by a 1-m² surface facing the sun at the mean distance of the earth's orbit (Joules per meter squared per second). In other words, it is the mean flux* of sunlight at the top of Earth's atmosphere. Helpful facts to remember are that the sun's mass is about 1,000 times that of Jupiter. Also, the sun's radius is about 10 times that of Jupiter, which is about 10 times that of Earth, which in turn is about 10 times that of the largest asteroid.

Figure 2-36 illustrates a number of terms common to planetary astronomy. Most of the terms in the diagram are self-explanatory. The term apparition refers to the period of several months when a planet is best visible—for example, an apparition of Mars (when it was on our side of the sun). Elongations (inner planets only) can be either eastern (appearing east of the sun in the evening sky) or western (west in the morning). A mnemonic device is the e in east and evening.

As shown in Figure 2-36, an eclipse occurs when one body enters the shadow of another (not necessarily when one appears to pass behind another, which is called an occultation). The shadow of any object (a planet or your hand) has two parts: the umbra, or dense inner region in which the light source is completely covered, and the penumbra, or lighter outer region in which the light source is only partly covered. An eclipse can be either umbral or penumbral, depending on which part of the shadow is occupied by the eclipsed body. Figure 2-37 shows a penumbral eclipse of the Viking 1 landing site on Mars by the Mars satellite Phobos (Phobos is not big enough to cover the sun totally, as seen from Mars).

Certain dynamical terms should be noted—for instance, the prefixes peri- (designating the point when a smaller body is closest to the primary body) and ap- or apo- (designating the farthest point). If one wants to speak in general terms, without specifying a particular primary body, one uses the suffix -apsis; thus, periapsis and apoapsis can be used to designate points in orbits around any planet or satellite. For referring to specific bodies, one uses specific suffixes (usually Greek), such as -gee for Earth (perigee and apogee), or -helion for the sun (perihelion and aphelion).

Certain other terms are of very general use. The ecliptic is the plane of Earth's orbit. Inclination is the angle between the plane of a planet's or satellite's orbit and the Earth's orbit. Earth's orbit, or the ecliptic plane, was chosen long ago as the standard of reference. Celestial mechanicians sometimes refer to the invariable plane, which is defined by the total angular momentum of the entire solar system. The distinction is small, because Jupiter's inclination is only 1.3°. The planets with the greatest inclinations are Pluto (17°) and Mercury (7°). Sometimes the "inclinations" given for satellite orbits are the angles between their orbit and the planet's equatorial plane, not the plane of the solar system. Thus, a listing under "inclinations" for Uranus's

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*Flux is a general technical term for amount passing through unit area per second.
Figure 2-35. Appearance of the planets to a visually experienced observer using a moderate-sized telescope.
### Useful Facts to Memorize

<table>
<thead>
<tr>
<th>Body</th>
<th>Important satellite</th>
<th>Mass (kg)</th>
<th>Radius (m)</th>
<th>No. known satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>Jupiter</td>
<td>$2 \times 10^{30}$</td>
<td>$7 \times 10^{11}$</td>
<td>thousands</td>
</tr>
<tr>
<td>Mercury</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0</td>
</tr>
<tr>
<td>Venus</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0</td>
</tr>
<tr>
<td>Earth</td>
<td>Moon</td>
<td>$6.0 \times 10^{24}$</td>
<td>$6.4 \times 10^{6}$</td>
<td>1</td>
</tr>
<tr>
<td>Mars</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Phobos</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Deimos</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Asteroids</td>
<td>—</td>
<td>$\leq 10^{19}$</td>
<td>$\leq 5 \times 10^5$</td>
<td>?</td>
</tr>
<tr>
<td>Jupiter</td>
<td>—</td>
<td>$2 \times 10^{27}$</td>
<td>$7 \times 10^7$</td>
<td>$\geq 28$</td>
</tr>
<tr>
<td></td>
<td>Io</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Europa</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Ganymede</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Callisto</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Saturn</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>$\geq 30$</td>
</tr>
<tr>
<td></td>
<td>Titan</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Uranus</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>$\geq 21$</td>
</tr>
<tr>
<td>Neptune</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>$\geq 8$</td>
</tr>
<tr>
<td>Pluto</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>Comets</td>
<td>—</td>
<td>$10^{13} - 10^{16}$</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gravitational constant</th>
<th>$G = 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astronomical unit</td>
<td>1 AU $= 1.49 \times 10^{11} \text{ m} (-50 \text{ million km})$</td>
</tr>
<tr>
<td>Boltzmann constant</td>
<td>$k = 1.38 \times 10^{-23} \text{ J} / \text{deg}$</td>
</tr>
<tr>
<td>Stefan–Boltzmann constant</td>
<td>$\sigma = 5.67 \times 10^{-8} \text{ J} / \text{m}^2 \cdot \text{deg}^4 \cdot \text{s}$</td>
</tr>
<tr>
<td>Velocity of light</td>
<td>$c = 3.00 \times 10^8 \text{ m/s}$</td>
</tr>
<tr>
<td>Mass of H atom</td>
<td>$M_h = 1.67 \times 10^{-27} \text{ kg}$</td>
</tr>
<tr>
<td>Planck's constant</td>
<td>$h = 6.63 \times 10^{-34} \text{ J} \cdot \text{s}$</td>
</tr>
<tr>
<td>Mass of sun</td>
<td>$M_\odot = 2.00 \times 10^{30} \text{ kg}$</td>
</tr>
<tr>
<td>Luminosity of sun</td>
<td>$L_\odot = 4 \times 10^{26} \text{ J/s}$</td>
</tr>
<tr>
<td>Solar constant</td>
<td>$f_\odot = 1.36 \times 10^7 \text{ J/m}^2 \cdot \text{s} = 1.36 \text{ kW/m}^2$</td>
</tr>
</tbody>
</table>

*Note that one joule/second (J/s) is equal to one watt (W).*

satellites might be given as about 1° or as 98°, and one must be careful to determine which definition is being used.

As shown in Figure 2-38, revolution is the motion of one body around a second body, whereas rotation is the spinning motion of a body around an axis within itself. Rotation and revolution are commonly confused, especially in everyday speech (to be entirely proper we should speak of rotating doors and rotators).

**Obliquity** is the tilt angle between a planet's axis of rotation and the pole of the orbit. For Earth, it has the familiar value 23½°. Most other planets have similar low values, except Venus (which has a value near 180°), Uranus (with the unusual value, 98°), and Pluto (122°). The biggest planet, Jupiter, has the smallest obliquity, 3°, which may prove significant to theories of planetary origin. Obliquity is sometimes incorrectly labeled inclination. Obliquity is responsible for seasons on the planets, because it causes one hemisphere to be tipped toward the sun at a given point in a planet's orbit. As with inclinations, retrograde rotation is indicated by quoting an obliquity greater than 90°.

**Albedo** is a measure of the reflectivity of a surface—that is, the percentage of sunlight the surface reflects. An albedo can be calculated for each color, or an average albedo can be given for all the colors of sunlight (that is
<table>
<thead>
<tr>
<th>Configuration (plane of solar system, viewed from north-ecliptic pole)</th>
<th>Appearance in sky</th>
</tr>
</thead>
</table>
| **Elongation**  
Greatest elongation is illustrated (pertains only to inner planets). | ![Elongation](image1)  
greatest elongation  
horizon  
planet's orbit  
sun |
| **Opposition**  
(Pertains only to outer planets.) | ![Opposition](image2)  
planet seen against background stars in midnight sky |
| **Conjunction**  
Two or more planets close together in the sky. | ![Conjunction](image3) |
| **Occultation**  
Small body passes behind larger body. | ![Occultation](image4)  
moon in front of sun |
| **Eclipse**  
One body passes into the shadow of another. | ![Eclipse](image5) |
| **Transit**  
Small body passes in front of larger body. | ![Transit](image6) |

Examples from Jupiter satellite system:

A Satellite and its shadow (A')
B Not visible (occulted)
C Not visible (eclipsed)
D Just out of eclipse
E In transit

Figure 2-36. Terms used in planetary astronomy. (See the text for discussion.)

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averaged over the wavelength range of sunlight), which is the more common practice.

A complication arises because of phase effects. Phase is defined as the angle between the sun and the observer as seen from the planet. The Bond albedo, the most commonly used definition of albedo, refers to the total percentage of sunlight reflected in all directions. To determine the Bond albedo, we have to observe a planet over a wide range of phases to determine how the amount of light reflected depends on direction, a dependence called the phase function. Different surface particles, such as fine dust, rocks, or cloud droplets, have different phase functions. For this reason the Bond albedo (A) is broken into two factors, p and q (A = pq). The factor q is known as the phase integral and can be either observed or theoretically calculated. The factor p, known as the geometric albedo, gives the percentage of light reflected at zero phase angle.

In general, all these albedos are about 2% to 10% for dark rocks, 10% to 23% for lighter rocks, and about 40% to 70% for clouds and frosts. Albedos are thus indicators of surface and atmospheric properties. Venus, because of its nearly white clouds, has a Bond albedo of 76%. Earth has an intermediate value of about 36% (averaging over clouds, oceans, and land). The moon and Mercury have low values, in the range of 6% to 10%, depending on the region. Certain asteroids and most comets, whose surface soils are rich in carbon minerals, have albedos of only 2% to 5%.

The ages of the planets and older surface features are measured in units of 10⁹ y, or billions of years (abbreviated “b.y.”). To avoid problems of different abbreviations in different languages, the International System of Units (SI or System International) has been adopted throughout science. The SI system employs the following prefixes to indicate various multiples of 10⁹:

- **giga**-means 10⁹ (abbreviated G)
- **mega**-means 10⁶ (abbreviated M)
- **kilo**-means 10³ (abbreviated k)
- **milli**-means 10⁻³ (abbreviated m)
- **micro**-means 10⁻⁶ (abbreviated μ)

One may thus encounter 1 billion years = 1 b.y. = 1 Gy = 10⁹ y. Similarly, 1 million years may be written 1 m.y. = 1 My = 10⁶ y.

### SUMMARY

Dynamical properties (such as orbit and size) and surface and atmospheric properties (such as composition and temperature) are now known to the first order for all principal planets and many satellites. The frontier of the solar system visited by spacecraft is now beyond Neptune. Earth has turned out to be unique, apparently being the only body in the solar system with substantial amounts of liquid surface water, a temperate climate, a breathable atmosphere, and probably life. The moon, Mercury, and most satellites present airless, or nearly airless, cratered landscapes with various degrees of tectonic or volcanic modification. Titan has a cold, dense atmosphere. Venus has a very hot surface with a high-pressure CO₂ atmosphere. Mars has the most earthlike surface, with a thin CO₂ atmosphere, blowing dust, temperatures occasionally above freezing, ice caps, seasonal
change, and perhaps had some running water during ancient times. Io has active volcanoes. Europa is an icy billiard ball with a probable liquid water ocean beneath a thin ice crust. Ganymede (Jupiter), Enceladus (Saturn), and Miranda (Uranus) are notable for fractures and swaths of tectonically modified surface. Moons and planets have remarkably varied and eccentric “geologic personalities.”

1. Why is the term planet difficult to define in a scientifically useful way?

2. How many “planetary bodies” are known in the universe if one defines them as (a) principal planets, (b) nonstellar bodies occupying nonoverlapping zones of the solar system (such as described by Bode’s rule), (c) nonstellar bodies larger than 5,000-km diameter?

3. Why is Bode’s rule not a “law of nature” with the same status as, for example, Newton’s law of gravitation?
4. Why is Venus the planet most commonly associated with the phrase the “evening star”? Explain by referring to its distance, size, albedo, and angular distance from the sun as seen from earth. What planet would make the most prominent evening star as seen from Mars?

5. Explain why the “canals of Mars” were the most widely discussed Martian surface features at the turn of the century but are not discussed at all now.

6. What satellites have been photographed at a range close enough to reveal surface features, and how do these features compare with those of our moon?

7. Which planet, Earth or Pluto, is usually closer to Uranus?

8. Which planet, Earth or Saturn, comes closest to Jupiter?

9. Briefly describe the appearance or properties of each planet and of the satellite systems.

10. If Venus, Earth, Mars, and Jupiter are in a straight line on the same side of the sun, what phenomena does an observer on Earth see? What ones would an observer on Mars see?

**PROJECTS**

1. Observe as many planets as possible with the largest telescope available. Make sketches showing the appearance and any surface features seen (a disk 5 cm in diameter is often considered standard for sketching planetary images). Observe each planet for at least three nights if possible and observe changes from night to night. (Even experienced observers may need at least three nights before they can see substantial detail on the planetary disks, which usually seem disappointingly small to the inexperienced observer.)

2. By using an almanac, an astronomical guide such as the *American Ephemeris and Nautical Almanac*, or monthly listings in magazines such as *Sky and Telescope* and *Astronomy*, determine which planets will be reaching their best positions (oppositions and elongations) for observing in the next few months and plan observing programs similar to that in project 1 above for a week or two at those times.

3. If the Great Red Spot or other cloud details can be seen on Jupiter, monitor their position for an hour or so until you detect the planet's rotation. Monitor Jupiter's satellites for an hour or so until you detect their revolution.