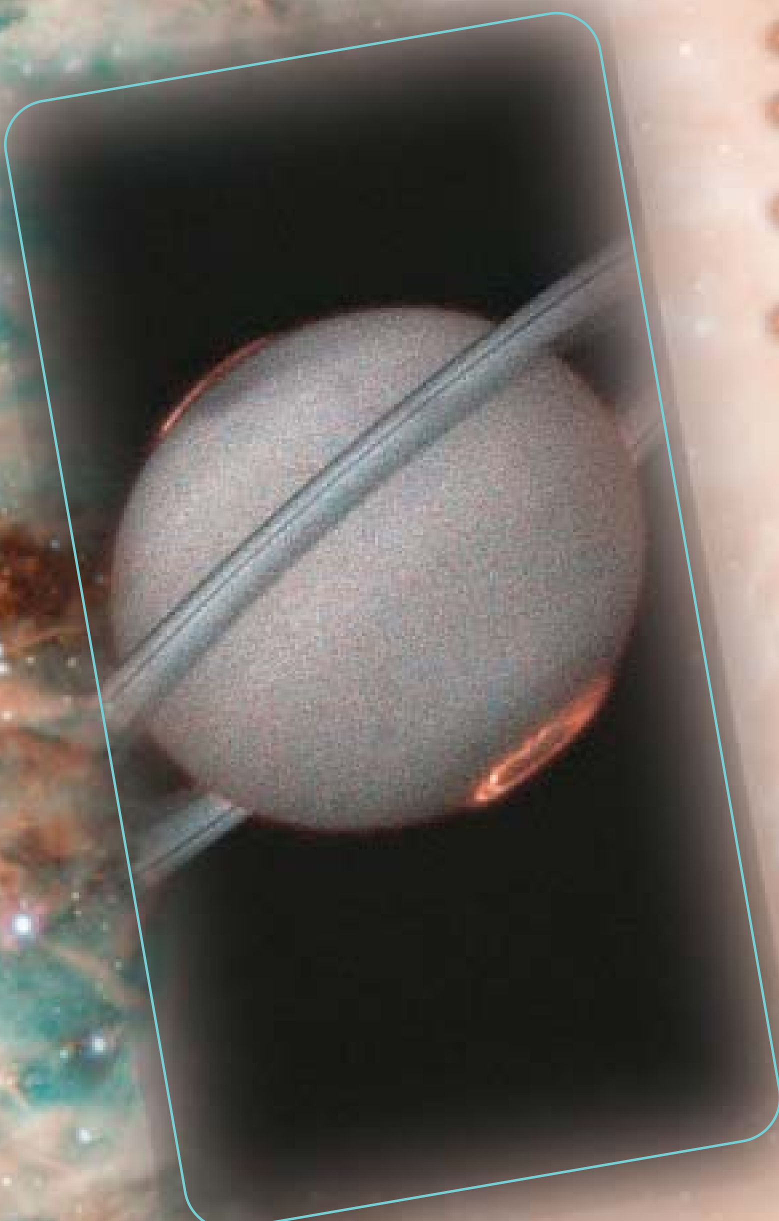
7 THE OUTER PLANETS

IN THIS CHAPTER YOU WILL DISCOVER

- Jupiter, an active, vibrant, multicolored world more massive than all the other planets combined
- Jupiter's diverse system of moons
- Saturn, with its spectacular system of thin, flat rings and numerous moons
- Uranus and Neptune: similar to each other but quite different from Jupiter and Saturn
- tiny Pluto and its moon, Charon, orbit each other in synchronous rotation



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Auroras on Saturn
Glowing auroras crown the poles of Saturn. This image of Saturn is entirely in the ultraviolet. These auroras are just one of the myriad features of the outer planets that we are now able to view with current, powerful telescopes and from spacecraft traveling into the realm of the planets.
(J. Trauger/JPL and NASA)

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WHAT DO YOU THINK?

1 Is Jupiter a "failed star" or almost a star?

2 What is Jupiter's Great Red Spot?

3 Does Jupiter have continents and oceans?

4 Is Saturn the only planet with rings?

5 Are the rings of Saturn solid ribbons?

It's easy to imagine a trip to Mars, exploring its vast canyons and icy polar regions. Even Venus and Mercury are best understood by carefully comparing them to the Earth and the Moon. However, we find few similarities between the Earth and the outer planets. Granted, the auroras, shown in the photograph of Saturn opening this chapter, are similar in shape and origin to Earth's auroras as seen from space (see Figure 5-10a). However, Jupiter, Saturn, Uranus, and Neptune are so much larger, are rotating so much faster, and have such different chemical compositions from our world that we will seem indeed to have left the Earth far behind. Pluto is so small that the tidal force of its moon, Charon, has set the planet into synchronous rotation—the same side of Pluto always faces Charon—unlike the Earth, which spins some 30 times faster than our Moon orbits us.

Nothing on Earth suggests the swirling red and brown clouds of Jupiter, the ever-changing ring system of Saturn or the blue-green clouds of Uranus and Neptune. (See the table "The Outer Planets: A Comparison.") We begin our exploration of the outer planets with Jupiter, an alien world of unsurpassed splendor.

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FIGURE 7-1 Jupiter as Seen from Earth Many features of Jupiter's clouds are visible from Earth, including multicolored parallel regions and several light and dark spots. The Great Red Spot appears in the lower, central region of the Jovian atmosphere. (S. Larson)

JUPITER

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Even viewed through a small telescope on Earth, Jupiter's appearance sets it apart from the terrestrial worlds (Figure 7-1). As seen from the *Voyager 1* and *Voyager 2* spacecraft, which flew by Jupiter within months of each other in 1979, from the *Galileo* spacecraft over the last few years, and from the Hubble Space Telescope today, Jupiter's multicolored bands create a world of breathtaking beauty. Figure 7-2 lists Jupiter's properties.

7-1 Jupiter's rotation helps create colorful, global weather patterns

1 More than 1300 Earths could be packed into the volume of Jupiter, the largest planet in the solar system. Using the orbital periods of its moons and Kepler's laws, astronomers have determined that Jupiter is 318 times more massive than Earth. Jupiter has more than $2\frac{1}{2}$ times as much mass as all the other planets combined. Nevertheless, it would have to be 75 times more massive still before it could generate energy as the Sun does and therefore be classified as a star.

What we see of Jupiter are the tops of clouds that permanently cover it (Figure 7-2). Because it rotates about once every 10 hours—the fastest of any planet—Jupiter's clouds are in perpetual motion and are confined to narrow bands. In contrast, winds on slower-rotating Earth wander over vast ranges of latitude (compare Figure 5-1).

Jupiter's cloud bands provide a backdrop for turbulent swirling cloud patterns, as well as for *white ovals* and *brown ovals*, which are rotating storms similar in structure to hurricanes on Earth (Figure 7-3). The white ovals are observed to be cool clouds higher than the average clouds in Jupiter's atmosphere. Conversely, the brown ovals are warmer and lower clouds. They are holes in the normal cloud layer. On Jupiter, the various oval features last from hours to centuries. In 1998, two 50-year-old storms on Jupiter were observed to merge into a single storm as large across as the Earth's diameter. Computers show us how the cloud features on Jupiter would look if the planet's atmosphere were unwrapped like a piece of paper (Figure 7-4). You can see ripples, plumes, and light-colored wisps in these images.

Jupiter's Vital Statistics

Mass	1.90×10^{27} kg (318 $M_{\oplus}$)
Equatorial radius	71,490 km (11.2 $R_{\oplus}$)
Average density	1330 kg/m^3 (0.241 Earth density)
Orbital eccentricity	0.048
Inclination of equator to plane of orbit	3.12°
Sidereal period of revolution (year)	11.88 Earth years
Average distance from Sun	7.78×10^8 km (5.20 AU)
Equatorial rotation period	9 h 50 min 28 s
Solar rotation period (day)	9 h 55 min 30 s
Albedo (average)	0.51

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WEB LINK 7.3 VIDEO 7.1

FIGURE 7-2 **Jupiter as Seen from a Spacecraft** This view was sent back from *Voyager 1* in 1979. Features as small as 600 km across can be seen in the turbulent cloudtops of this giant planet. The complex cloud motions surrounding the Great Red Spot are clearly visible. (NASA)

a R I V U X G

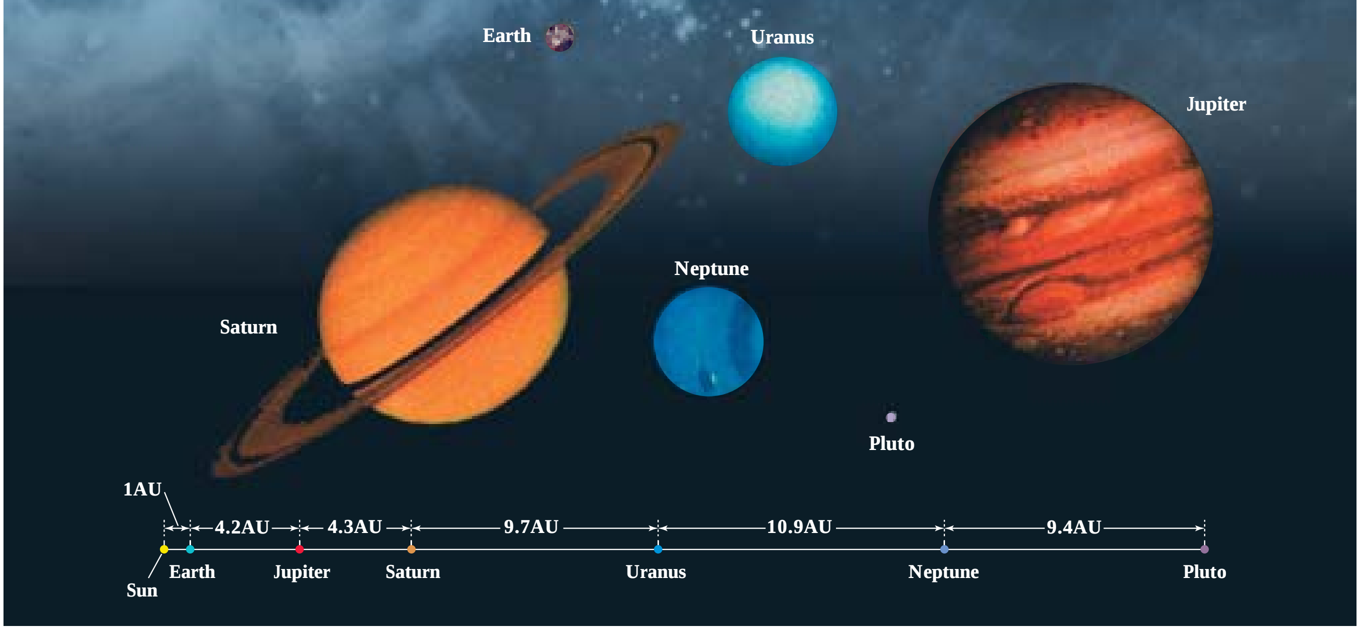
b R I V U X G

FIGURE 7-3 **Close-ups of Jupiter's Atmosphere** The dynamic winds, rapid rotation, internal heating, and complex chemical composition of Jupiter's atmosphere create this beautiful and complex banded pattern. (a) A *Voyager 2* southern hemisphere image showing a white oval that has existed for over 40 years. (b) A *Voyager 2* northern hemisphere image showing a brown oval. The white feature overlapping the oval is a high cloud. (a & b: NASA)

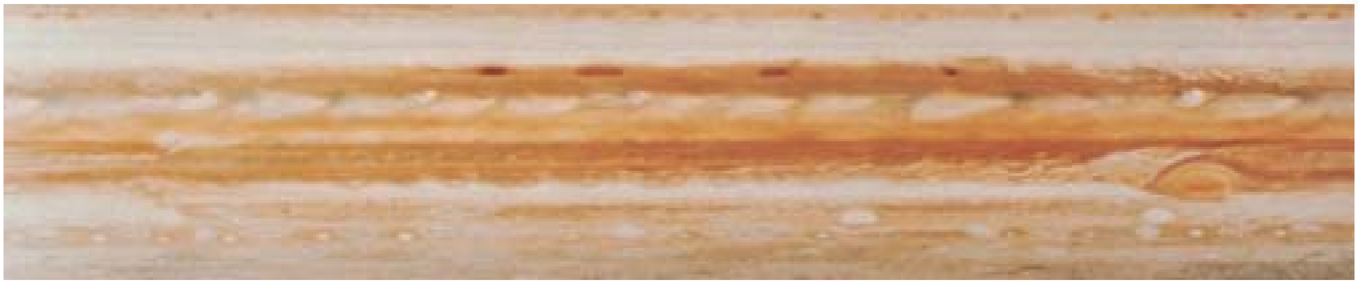
The Outer Planets: A Comparison

	Interior	Surface	Rings	Atmosphere	Magnetic Field
Jupiter	Terrestrial core, liquid metallic hydrogen shell, liquid hydrogen mantle	No solid surface, atmosphere gradually thickens to liquid state, belt and zone structure, hurricanelike features	Yes	Primarily H, He	19,000 × Earth's total field at its cloud layer, 14 × stronger than Earth's surface field
Saturn	Similar to Jupiter, with bigger terrestrial core and less metallic hydrogen	No solid surface, less distinct belt and zone structure than Jupiter	Yes	Primarily H, He	570 × Earth's total field at its cloud layer, ⅔ × Earth's surface field
Uranus	Terrestrial core, liquid water shell, liquid hydrogen and helium mantle	No solid surface, weak belt and zone system, hurricanelike features, color from methane absorption of red, orange, yellow	Yes	Primarily H, He, some CH_4	50 × Earth's total field at its cloud layer, 0.7 × Earth's surface field
Neptune	Similar to Uranus	Like Uranus	Yes	Primarily H, He, some CH_4	35 × Earth's total field at its cloud layer, 0.4 × Earth's surface field
Pluto	Unknown	Apparently rock and ice	No	Unknown	Unknown

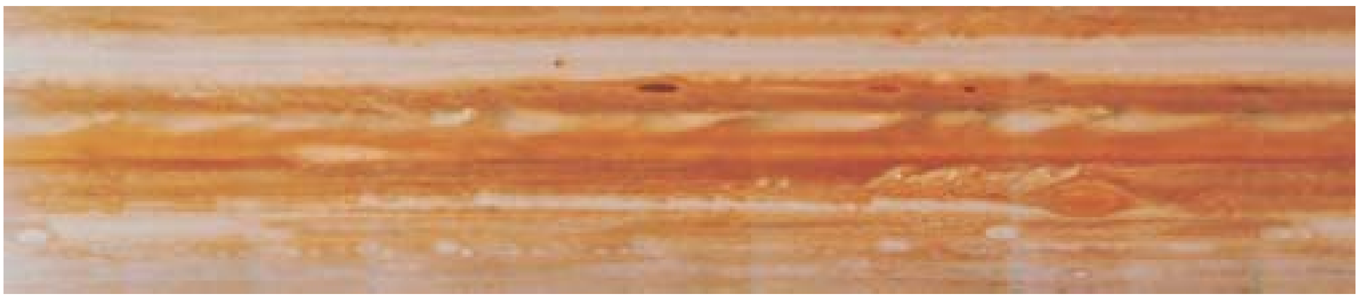
For detailed numerical comparisons between planets, see Appendix Tables A-1 and A-2.
*To see the orientations of these magnetic fields relative to the rotation axes of the planets, see Figure 7-31.



(Stephen P. Meszaros/NASA, M. Buie, K. Horne, and D. Tholen)



a *Voyager 1* view



b *Voyager 2* view

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FIGURE 7-4 Jupiter's Northern and Southern Hemispheres Computer processing shows the entire Jovian atmosphere from (a) *Voyager 1* and (b) *Voyager 2*. A computer was used to "unwrap" the planet's atmosphere. Notice in both views the dark ovals in the northern hemisphere and the white ovals in the southern hemisphere. The banded structure is absent near the poles. Notice, too, that the Great Red Spot moved westward while the white ovals moved eastward during the four months between the two *Voyager* flybys. (NASA)

One rust-colored oval feature called the **Great Red Spot**
2 (Figure 7-5) is so large that it can be seen through a small telescope. It changes dimensions, and at present it is about 25,000 km long by 12,000 km wide, large enough so that two Earths could easily fit side by side inside it. The Great Red Spot was first observed around 1665, either by English scientist Robert Hooke or Italian astronomer Giovanni Cassini. Because earlier telescopes were unlikely to have been able to see it, the Great Red Spot could well have formed long before that time. Heat welling upward from inside Jupiter has maintained this storm for more than three centuries. Consider what life would be like for us if the Earth sustained storms for such long periods.

In 1690, Cassini noticed that the speeds of Jupiter's clouds vary with latitude, an effect called **differential rotation.** Near the poles, the rotation period of Jupiter's atmosphere, 9 h 55 min 30 s, is 5 minutes longer than at the equator. Furthermore, clouds at different latitudes circulate in opposite directions—some eastward, some westward. At their boundaries the clouds rub against each other, creating beautiful swirling patterns (see Figure 7-3). The interactions of clouds at different latitudes also help provide stability for storms like the Great Red Spot.

Spectra from Earth-based telescopes and from the *Galileo* probe sent into Jupiter's upper atmosphere in 1995 give more detail about Jupiter's atmosphere. More than

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WEB LINK 7.4 VIDEO 7.2

FIGURE 7-5 The Great Red Spot This image of the Great Red Spot, taken by the *Galileo* spacecraft in 1996, has been color enhanced to show more details of the dynamic activity taking place in and around this giant storm. The counterclockwise circulation of gas in the Great Red Spot takes about six days to make one rotation. The clouds that encounter it are forced to pass around it, and when other oval features are near it, the entire system becomes particularly turbulent, like the batter in a two-bladed blender. (NASA/JPL)

86% of its atoms are hydrogen and 13% are helium. The remainder consist of molecular compounds such as methane (CH_4), ammonia (NH_3), and water vapor (H_2O). Keeping in mind that different elements have different masses, we can convert these percentages of atoms into the masses of various substances in Jupiter's atmosphere: 75% hydrogen, 24% helium, and 1% other substances. Because the interior contains more heavy elements than the surface, the overall mass distribution in Jupiter is calculated to be 71% hydrogen, 24% helium, and 5% all heavier elements.

The descent of the probe from the *Galileo* spacecraft into Jupiter's atmosphere revealed wind speeds of up to 600 km/h, higher-than-expected air density and temperature, and lower-than-expected concentrations of water, helium, neon, carbon, oxygen, and sulfur. This probably occurred because the probe descended into a particularly arid region of the atmosphere called a *hot spot,* akin to the air over a desert on Earth.

Observations from spacecraft visiting the Jovian system and the scientific model of Jupiter's atmosphere developed to explain these observations indicate that Jupiter has three major cloud layers (Figure 7-6). Apparently, because it descended through a hot spot, the *Galileo* probe failed to detect them.

The uppermost Jovian cloud layer is composed of crystals of frozen ammonia. Since these crystals and the frozen water in Jupiter's clouds are white, what chemicals create the subtle tones of brown, red, and orange? The answer is as yet unknown. Some scientists think that sulfur compounds, which can assume many different colors depending on their temperature, play an important role. Others think that phosphorus might be involved, especially in the Great Red Spot.

Astronomers first determined Jupiter's overall chemical composition from its average density—only 1330 kg/m^3— 3
which implies that Jupiter is composed primarily of lightweight elements such as hydrogen and helium surrounding a relatively small core of metal and rock. (Recall the discussion of Jupiter's formation in Essentials II.) Jupiter's surface and mantle are entirely liquid. Because the vast majority of Jupiter's mass is composed of hydrogen, we cannot easily distinguish the planet's atmosphere from its "surface." However, at a distance of 150 km below the cloudtops, the pressure (about 10 atm) is enough to liquefy hydrogen. It was just at this distance below the cloudtops that the *Galileo* probe failed, presumably crushed by the high pressure of the atmosphere.

In introducing the solar system, we also noted that a young planet heats up as it coalesces. After it forms, radioactive elements continue to heat its interior. On Earth, this heat leaks out of the surface through volcanoes and other vents. Jupiter loses heat everywhere on its surface, because, unlike the Earth, it has no landmasses to block the heat loss.

As the heat from within Jupiter warms its liquid mantle, blobs of heated hydrogen and helium move upward. When these blobs reach the cloudtops, they give off their heat and descend back into the interior. (The same process, *convection,* drives the motion of the Earth's mantle and its tectonic plates, as well as soup simmering on a stove.) Jupiter's rapid, differential rotation draws the convecting gases into bands

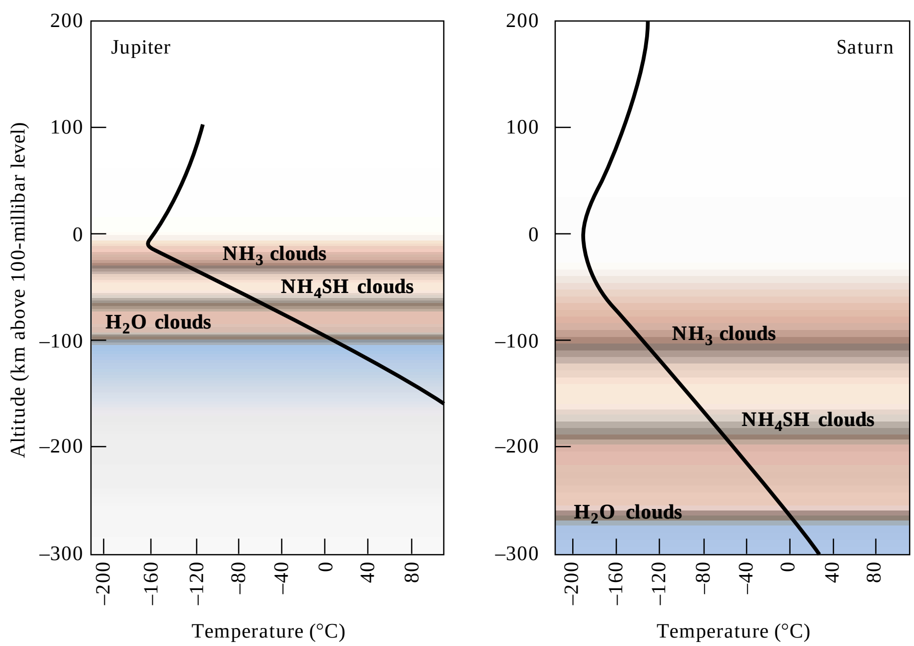

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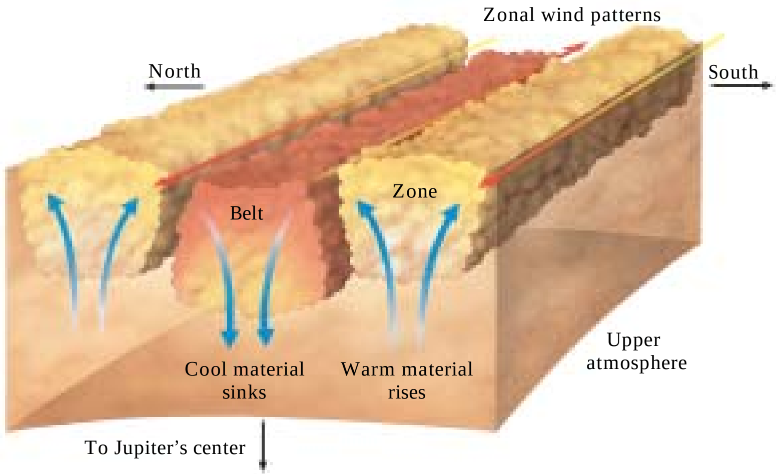
FIGURE 7-6 Jupiter's and Saturn's Upper Layers These graphs display temperature and pressure profiles of Jupiter's and Saturn's upper regions, as deduced from measurements at radio and infrared wavelengths. Three major cloud layers are shown in each, along with the colors that predominate at various depths. Data from the *Galileo* spacecraft indicate that Jupiter's cloud layers are not found at all locations around the planet; there are some relatively clear, cloud-free areas.



VIDEO 7.3

FIGURE 7-7 Why Jupiter Has Belts and Zones The light-colored zones and dark-colored belts in Jupiter's atmosphere are regions of rising and descending gases, respectively. In the zones, gases warmed by heat from Jupiter's interior rise upward and cool, forming high-altitude clouds. In the belts, cooled gases descend and undergo an increase in temperature; the cloud layers seen there are at lower altitudes than in the zones. Jupiter's rapid differential rotation shapes these regions of rising and descending gas into bands parallel to the planet's equator. Differential rotation also causes the wind velocities at the boundaries between belts and zones to be predominantly to the east or west.

around the planet. Even through a small telescope, you can see on Jupiter dark, reddish bands called **belts** alternating with light-colored bands called **zones.** Jupiter's belts and zones result from the combined actions of the planet's convection and rapid rotation. The light zones are regions of hotter, rising gas, while the dark belts are regions of cooler, descending gas (Figure 7-7).

7-2 Jupiter's interior has four distinct regions

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Because Jupiter is mostly hydrogen and helium, its average density is less than one-quarter that of the Earth. Yet the gravitational force created by its enormous bulk compresses and heats its interior so much that 20,000 km below the cloudtops the pressure is 3 million atmospheres. Below this depth, the pressure is high enough to transform hydrogen into **liquid metallic hydrogen.** Under such conditions hydrogen is a metal, meaning that it is an excellent conductor of electricity, like the copper wiring in a house. Electric currents running through this rotating, metallic region of Jupiter generate a powerful planetary magnetic field. At the cloud level of Jupiter, this field is 14 times stronger than Earth's field is at our planet's surface.

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For Earth-based astronomers, the only evidence of Jupiter's magnetosphere is a faint hiss of radio static, which varies cyclically over a period of 9 h 55 min 30 s, the planet's internal rotation rate. The two *Pioneer* and two *Voyager* spacecraft that journeyed past Jupiter in the 1970s revealed the awesome dimensions of Jupiter's magnetosphere. The volume it engulfs is nearly 30 million kilometers across. It envelops the orbits of many of its moons. If Jupiter's magnetosphere were visible from Earth, it would cover an area in the sky 16 times larger than the full Moon.

Despite its preponderance of hydrogen and helium, Jupiter formed around a terrestrial (rock and metal) protoplanet. This core is only 4% of Jupiter's mass, which amounts to nearly 13 times the mass of the entire Earth. As discussed in Essentials II, this core formed early in Jupiter's life. Along with the rock and metal, there were almost certainly quantities of frozen water, carbon dioxide, methane, and ammonia. When astronomers talk about "ice," they generically refer to any or all of these compounds.

The tremendous crushing weight of the bulk of Jupiter above the core—equal to the mass of 305 Earths—compresses the terrestrial core down to a sphere only 20,000 km in diameter. By comparison, Earth's diameter is 12,756 km. At the same time, the pressure forced the lighter ices out of the rock and metal, thereby forming a shell of these "ices" between the solid core and the liquid metallic hydrogen layer. Calculations reveal that the temperature and pressure inside Jupiter should make these "ices" liquid there! The pressure at Jupiter's very center is calculated to be about 70 million atmospheres, and the temperature there is about 25,000 K, nearly 4 times hotter than the surface of the Sun.

7-3 Cometary fragments were observed to strike Jupiter

On July 7, 1992, a comet passed so close to Jupiter that the planet's gravitational tidal force ripped it into at least 21 pieces. The debris from this comet was first observed in March 1993 by comet hunters Gene and Carolyn Shoemaker and David Levy. (Because it was the ninth comet they had found together, it was named Shoemaker-Levy 9 in their honor.) Shoemaker-Levy 9 was an unusual comet that

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WEB LINK 7.8

FIGURE 7-8 Comet Shoemaker-Levy 9 Debris Approaching Jupiter The comet was torn apart by Jupiter's gravitational force on July 7, 1992, fracturing into at least 21 pieces. Returning debris, shown here in May 1994, struck Jupiter between July 16 and July 22, 1994. (H. A. Weaver, T. E. Smith, STScI and NASA)

actually orbited Jupiter, rather than just orbiting the Sun. Calculations of the comet's orbit showed that the pieces would return to strike Jupiter between July 16 and July 22, 1994 (Figure 7-8).

Recall from Essentials II that impacts were extremely common in the first 800 million years of the solar system's existence. From more recent times, two chains of impact craters have been discovered on Earth, consistent with pieces of comets having hit our planet within the past 300 million years. However, it is very uncommon for pieces of space debris as large as several kilometers in diameter to collide with planets today. Therefore, the discovery that Shoemaker-Levy 9 would hit Jupiter created great excitement in the astronomical community. Seeing how a planet and a comet respond to such an impact would allow astronomers to deduce information about the planet's atmosphere and interior and also about the striking body's properties.

The impacts occurred as predicted, with most of Earth's major telescopes—as well as those on several spacecraft—watching closely (Figure 7-9). At least 20 fragments from Shoemaker-Levy 9 struck Jupiter, and 15 of them had detectable impact sites. The impacts resulted in fireballs some 10 km in diameter with temperatures of 7500 K, which is hotter than the surface of the Sun. Indeed, the largest fragment gave off as much energy as 600 million megatons of TNT, far more than the energy that could be released by all the nuclear weapons remaining on Earth, combined. Impacts were followed by crescent-shaped ejecta containing a variety of chemical compounds. Ripples or waves spread out from the impact sites through Jupiter's clouds in splotches that lasted for months.

The observations suggest that the pieces of comet did not penetrate very far into Jupiter's upper cloud layer. This fact, in turn, suggests that the pieces were not much larger than a kilometer in diameter. The ejecta from each impact included a dark plume that rose high into Jupiter's atmosphere. The darkness was apparently due to carbon compounds vaporized from the comet bodies. Also detected

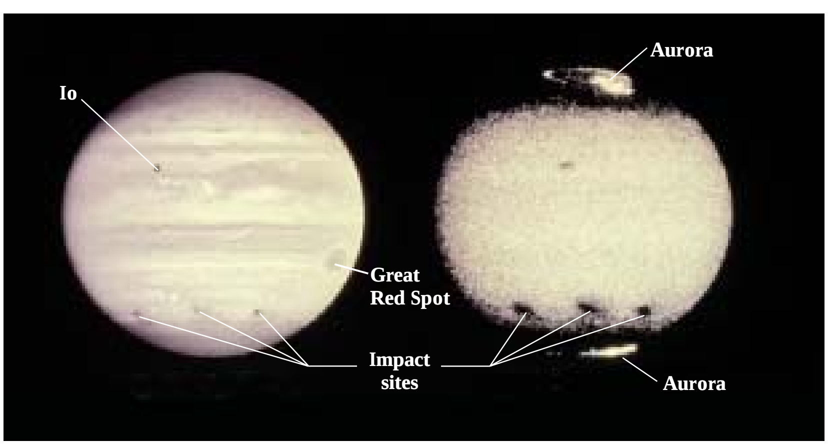

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FIGURE 7-9 Three Impact Sites of Comet Shoemaker-Levy 9 on Jupiter Shown here are visible (left) and ultraviolet (right) images of Jupiter taken by the Hubble Space Telescope after three pieces of Comet Shoemaker-Levy 9 struck the planet. The astronomers had expected white remnants (the color of condensing ammonia or water vapor); the darkness of the impact sites may have come from carbon compounds in the comet debris. Note the auroras in the ultraviolet image. Auroras and lightning are common on Jupiter, due in part to the planet's strong magnetic fields and dynamic cloud motions. (NASA) from the comet were water, sulfur compounds, silicon, magnesium, and iron. By watching how rapidly the impact debris traveled above the clouds, astronomers were able to determine that the winds some 250 km above the cloud layer move at speeds of 3600 km/h (more than 2200 mph).

JUPITER'S MOONS AND RINGS

Jupiter hosts at least 28 moons. Galileo was the first person to observe the four largest moons, in 1610, seen through his meager telescope as pinpoints of light. He called them the "Medicean stars" to attract the attention of the Medicis, rulers of Florence and wealthy patrons of the arts and sciences. To Galileo, the moons provided evidence supporting the then-controversial Copernican cosmology; at that time, Western theologians asserted that all cosmic bodies orbited the Earth. The fact that the Medicean stars orbited Jupiter raised grave concerns in some circles.

ANIMATION 7.1 To the modern astronomer, these moons are four extraordinary worlds, different both from the rocky terrestrial planets and from hydrogen-rich Jupiter. Now called collectively the **Galilean moons** or **Galilean satellites,** they are named after the mythical lovers and companions of the Greek god Zeus (called Jupiter by the early Romans). From the closest moon outward, they are Io, Europa, Ganymede, and Callisto.

These four worlds were photographed extensively by the *Voyager 1* and *Voyager 2* flybys and by the *Galileo* spacecraft (Figure 7-10). The two inner Galilean satellites, Io and Europa, are approximately the same size as our Moon. The two outer satellites, Ganymede and Callisto, are comparable in size to Mercury. Figure 7-10 presents comparative information about these six bodies.

7-4 Io's surface is sculpted by volcanic activity

Sulfury Io is among the most exotic moons in our solar system (Figure 7-11). With a density of 3570 kg/m^3, it is neither terrestrial nor "Jovian" in chemical composition. Its density is similar to that of Earth's surface, suggesting that most of Io is rock, rather than denser metals or lighter water. It zooms through its orbit of Jupiter once every 1.8 days. Like our Moon, Io is in synchronous rotation with its planet. Like the Earth, Io has a sizable iron core—it extends halfway out from the moon's center.

Images of Io reveal giant plumes rich in sulfur dioxide emitted by geysers, similar to Old Faithful on Earth, such as the two labeled in Figure 7-11a. Most of this ejected material falls back onto Io's surface; the rest is moving fast enough to escape into space. Although they are geysers, the plumes are actually emitted through volcanoes (Figure 7-11b), which also emit basaltic lava flows rich in magnesium and iron. Io's volcanoes are named after gods and goddesses associated with fire in Greek, Norse, Hawaiian, and other mythologies. Io also has numerous black "dots" on its surface, which apparently are dormant volcanic vents. Old lava flows radiate from many of these locations, which are typically 10 to 50 km in diameter and cover 5% of Io's surface. Observations suggest that Io has about 300 active volcanoes emitting 10 trillion tons of matter each year in plumes up to 500 km high. That is enough material to resurface Io to a depth of 1 meter each century.

Insight into Science **What's in a Name?** Following up on the preconceptions that common words create (see the Insight into Science "Imagine the Moon" in Chapter 6), objects with familiar names often have different characteristics than we expect. We tend to envision moons as inert, airless, lifeless, dry places similar to our Moon. As we will see throughout this chapter, starting with Io, some moons have active volcanoes, atmospheres, and probably vast, underground, liquid water oceans.

Just before their discovery, the existence of active volcanoes on Io was predicted from analysis of the gravitational forces to which that moon is subjected. As it rapidly orbits Jupiter, Io repeatedly passes between Jupiter and one or another of the other Galilean satellites. These moons pull Io farther from Jupiter, changing the tidal forces acting on it from the planet. As the distance between Io and Jupiter varies, the resulting tidal stresses alternately squeeze and flex the moon. In turn, this constant tidal stressing heats Io's interior through friction, generating as much energy inside Io as the detonation of 2400 tons of TNT every second. Gas and molten rock eventually make their way to the moon's surface, where they are ejected.

Satellite instruments have identified sulfur and sulfur dioxide in the material erupting from Io's volcanoes. Sulfur is normally bright yellow. If heated and suddenly cooled, however, it forms molecules that assume a range of colors, from orange and red to black, which accounts for Io's tremendous range of colors (see Figure 7-11). Sulfur dioxide (SO_2) is an acrid gas commonly discharged from volcanic vents here on Earth and, apparently, on Venus. When eruptions on Io release this gas into the cold vacuum of space, it crystallizes into white flakes, which fall onto the surface and account for the moon's whitish deposits.

The *Galileo* spacecraft detected an atmosphere around Io. Composed of oxygen, sulfur, and sulfur dioxide, it is only one-billionth as dense as the air we breathe. Io's atmosphere can sometimes be seen to glow blue, red, or green, depending on the gases involved. Gases ejected from Io's volcanoes have also been observed extending out into space and forming a doughnut-shaped region around Jupiter called the *Io torus,* about which we will say more shortly.

Vital Statistics of the Galilean Moons, Mercury, and the Moon

	Mean distance from Jupiter (km)	Sidereal period (d)	Diameter (km)	Mass (kg)	Mass (Moon = 1)	Mean density (kg/m^3)
Io	421,600	1.77	3630	8.94×10^{22}	1.22	3570
Europa	670,900	3.55	3138	4.80×10^{22}	0.65	2970
Ganymede	1,070,000	7.16	5262	1.48×10^{23}	2.01	1940
Callisto	1,883,000	16.69	4800	1.08×10^{23}	1.47	1860
Mercury	—	—	4878	3.30×10^{23}	4.49	5430
Moon	—	—	3476	7.35×10^{22}	1.00	3340

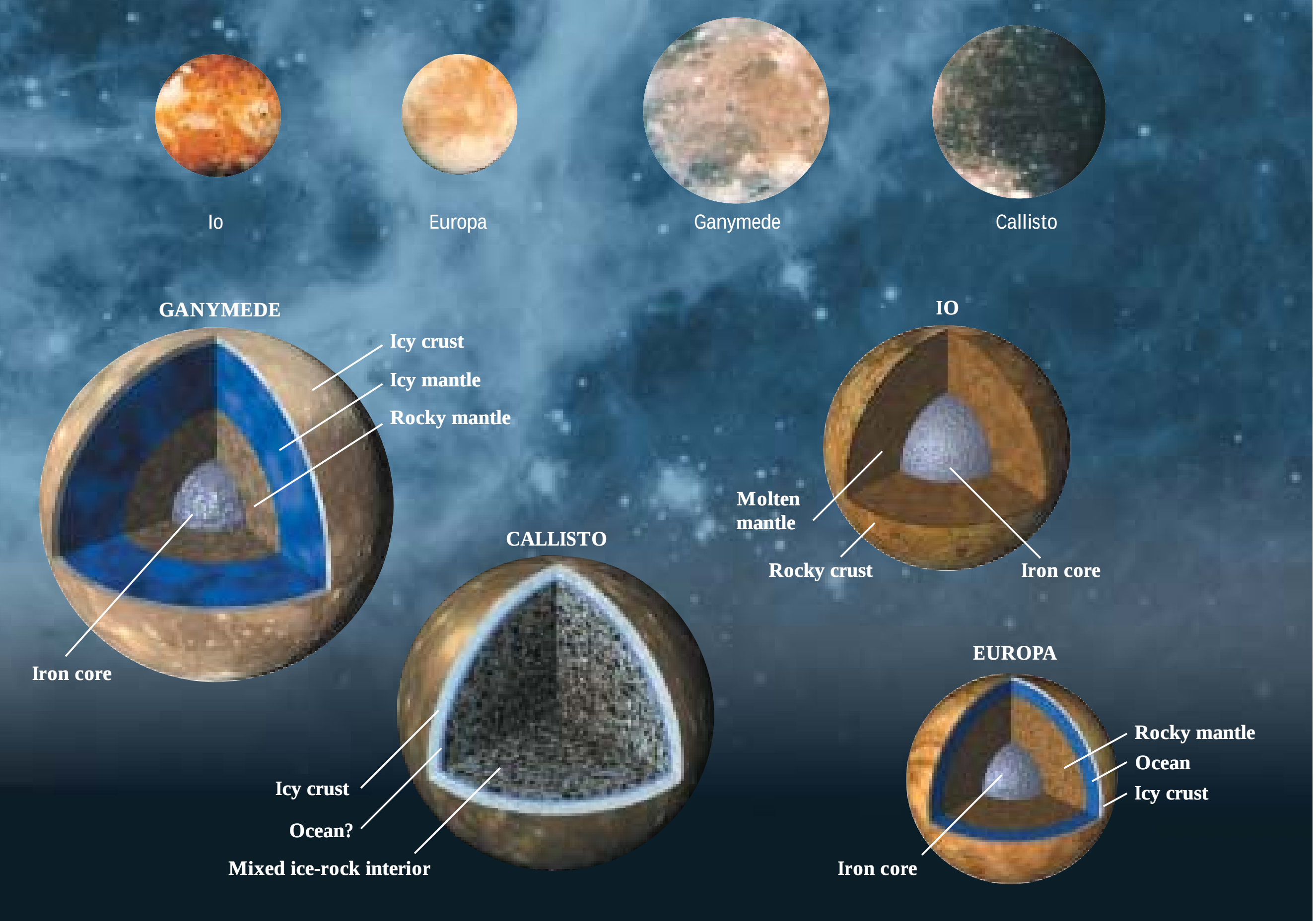

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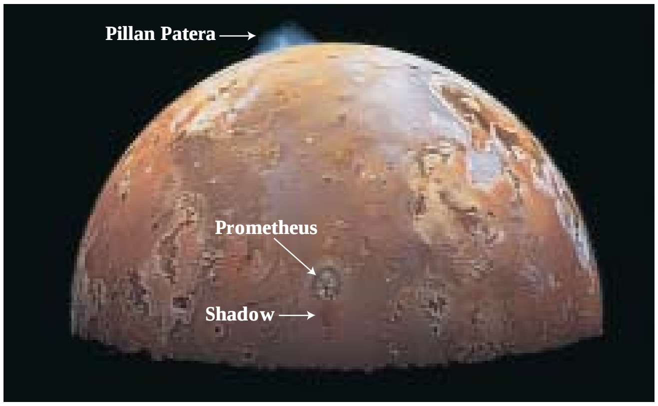
FIGURE 7-10 The Galilean Satellites The four Galilean satellites are shown here to the same scale. Io and Europa have diameters and densities comparable to our Moon and are composed primarily of rocky material. Ganymede and Callisto are roughly as big as Mercury, but their low average densities indicate that each contains a thick layer of water and ice. The cross-sectional diagrams of the interiors of the four Galilean moons show the probable internal structures of the moons based on their average densities and on information from the *Galileo* mission. (NASA and NASA/JPL)



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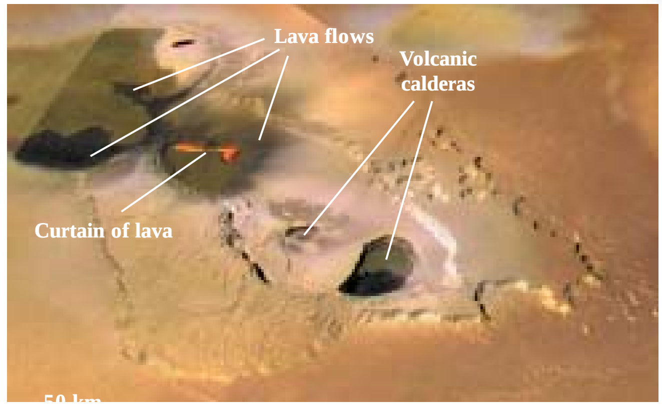

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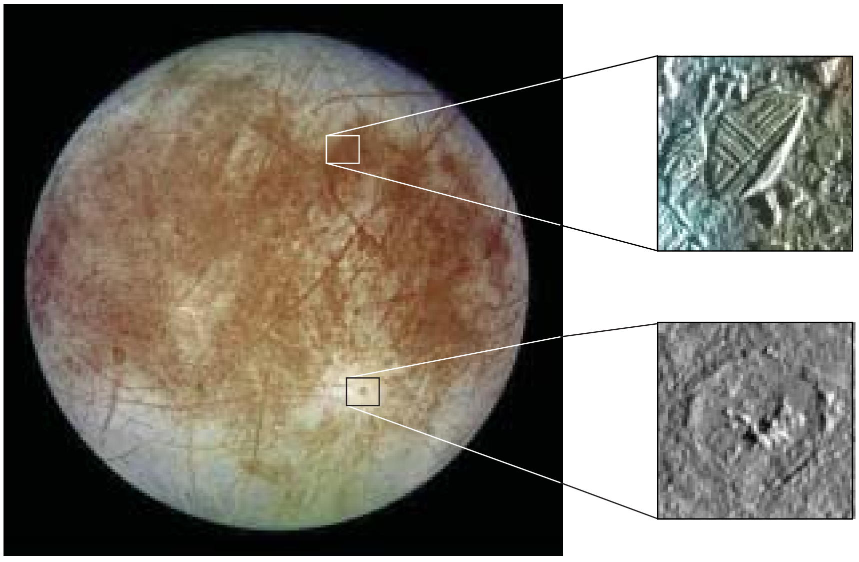
WEB LINK 7.10 VIDEO 7.4 **FIGURE 7-11** Io (a) This close-up view was taken by the *Galileo* spacecraft in 1997. Scientists believe that the range of colors results from surface deposits of sulfur ejected from Io's numerous volcanoes. The plume on the top, from the active Pillan Patera volcano, rises more than 190 km above the moon's surface. The plume from the volcano Prometheus rises up 100 km, casting a visible shadow. Prometheus has been active in every image taken of Io since the *Voyager* flybys of 1979. (b) Photographed in 1999 and then 2000 (shown here), the ongoing lava flow from this volcanic eruption at Tvashtar Catena has considerably altered this region of Io's surface. (a: NASA/JPL; b: University of Arizona/JPL/NASA)

7-5 Europa apparently harbors liquid water below its surface

Images of Europa's ice and rock surface from *Voyager 2* and the *Galileo* spacecraft suggest that Jupiter's second-closest Galilean moon contains liquid water (Figure 7-12). Europa orbits Jupiter every $3^1/_2$ days and, like Io, is in synchronous rotation. The changing gravitational tug of Io creates stress inside Europa similar to the magma-generating distortion that Io undergoes. The stress may create enough heat inside Europa to keep the water just a few kilometers below the moon's ice and rock surface in a liquid state.

Strong evidence for liquid water inside Europa comes from the ice floes seen in Figure 7-12. The surface features are similar to those seen in the Arctic region on Earth. The movement of the surface features creating the floes, along with swirls, strips, and ridges, appears to be driven by circulating water underneath the moon's surface, creating tectonic plate motion and tidal flexing. Also indicative of water is the moon's reddish color. The coloring may be due to salt deposits left after liquid water rose to the surface and evaporated.

Galileo spacecraft images suggest that some of Europa's features have moved within the past few million years, and



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WEB LINK 7.11 **FIGURE 7-12** Europa Imaged by the *Galileo* spacecraft, Europa's ice surface is covered by numerous streaks and cracks that give the satellite a fractured appearance. The streaks are typically 20 to 40 km wide. The upper inset shows the thin, disturbed icy crust of Europa, colored by dust from the impact crater Pwyll. The grooves and ridges in this image are typically 100 m across. The lower inset shows details of Pwyll Crater, 50 km in diameter. (Jet Propulsion Laboratory/NASA; upper inset: Planetary Image Research Laboratory/University of Arizona/JPL/NASA; lower inset: NASA)

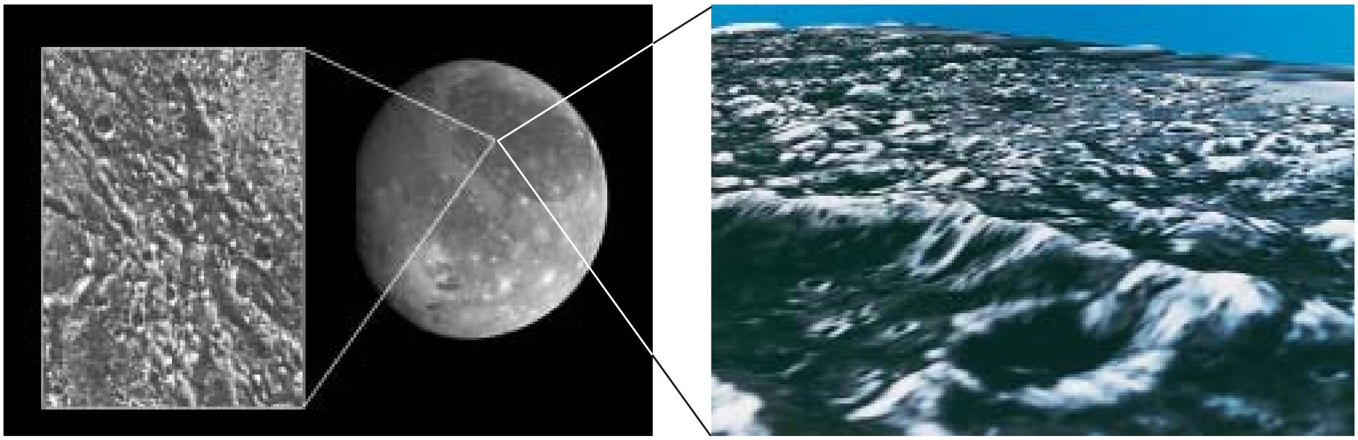

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FIGURE 7-13 Ganymede This side of Ganymede is dominated by a huge, dark, circular region called Galileo Regio, which is the largest remnant of Ganymede's ancient crust. Darker areas of the moon are older; lighter areas are younger, tectonically deformed regions. The white areas in and around some craters indicate the presence of water ice. Inset (a) is about 46 × 64 km (29 × 38 mi). Note in this *Galileo* spacecraft image the deep furrows in the moon's icy crust that probably resulted from crustal movement due to impacts and tectonic plate motion. The perspective in inset (b) was created by combining information from two *Galileo* images. (NASA/JPL)

perhaps are still in motion. Indeed, the chaotic surface revealed by *Galileo* is interpreted as having formed as a result of volcanism on Europa, strengthening the belief that this moon still has a liquid water layer. Replenishment of the surface by tectonic plate motion would explain why only a few small impact craters, such as the crater Pwyll (see Figure 7-12), have survived.

Europa's average density of 2970 kg/m^3 is slightly less than Io's. A quarter of its mass may be water. It also has a metallic core of much higher density. In 1995 astronomers discovered an extremely thin atmosphere containing molecular oxygen surrounding Europa. The density of this gas is about 10^{-11} times the density of the air we breathe. The oxygen may come from water molecules broken up on the moon's surface by ultraviolet radiation from the Sun.

7-6 Ganymede is larger than Mercury

Ganymede is the largest satellite in the solar system (Figure 7-13). Its diameter is larger than Mercury's, although its density of 1940 kg/m^3 is much less than that of Mercury. It also has a permanent magnetic field that is twice as strong as Mercury's field. Ganymede orbits Jupiter in synchronous rotation once every 7.2 days. Like its neighbor Europa, Ganymede has an iron-rich core, a rocky mantle, a liquid water ocean, a thin atmosphere, and a covering of dirty ice.

The existence of the ocean is implied by the discovery of a second, changing magnetic field around Ganymede that is generated by Jupiter's magnetic field. As Ganymede orbits Jupiter, the planet's powerful magnetic field creates an electrical current inside the moon, which in turn creates Ganymede's varying magnetic field. (The same effect is used to create electrical currents in electrical power stations here on Earth.) The best explanation of why the current flows inside Ganymede is that liquid salt water exists there; salt water is a good conductor of electricity. This implies, of course, the presence of a liquid ocean. Furthermore, salts have been observed on Ganymede's surface. They were apparently carried upward and deposited there as water leaked out and froze.

Like our Moon, Ganymede has two very different kinds of terrain. Dark, polygon-shaped regions are its oldest surface features, as judged by their numerous craters. Light-colored, heavily grooved terrain is found between the dark, angular islands. These lighter regions are much less cratered and therefore younger. Ganymede's grooved terrain consists of parallel mountain ridges up to 1 km high and spaced 10 to 15 km apart. These features suggest that the process of plate tectonics may have dominated Ganymede's early history. But unlike Europa, where tectonic activity still occurs today, tectonics on Ganymede bogged down 3 billion years ago as the satellite's crust froze solid.

Another mechanism that may have created Ganymede's large-scale features is a bizarre property of water. Unlike most liquids, which shrink upon solidifying, water expands when it freezes. Seeping up through cracks in Ganymede's original crust, water thus forced apart fragments of that crust. This process could have produced jagged, dark islands of old crust separated by bands of younger, light-colored, heavily grooved ice. Topping off Ganymede's varied features is the discovery that auroras occur there.

7-7 Callisto bears the scars of a huge asteroid impact

Callisto is Jupiter's outermost Galilean moon. It orbits Jupiter in 16.7 days, and, like the other Galilean moons, Callisto's rotation is synchronous. Callisto is 91% as big and 96% as dense as Ganymede. It has a thin atmosphere of hydrogen and carbon dioxide. Like Ganymede, Callisto apparently harbors a substantial liquid water ocean. Its presence is again inferred by Callisto's changing magnetic field. The heat that keeps the ocean liquid apparently comes from energy released by radioactive decay inside the moon.

While numerous large impact craters are scattered over Callisto's dark, ancient, icy crust, it has very few craters smaller than 100 m across (Figure 7-14). Astronomers speculate that the smaller craters have disintegrated. Unlike Ganymede and Europa, Callisto has no younger, grooved terrain. The absence of grooved terrain suggests that tectonic activity never began there: The satellite simply froze too rapidly. It is bitterly cold on Callisto's surface. *Voyager* instruments measured a noontime temperature of 155 K (–180°F), and the nighttime temperature plunges to 80 K (–315°F).

Callisto carries the cold, hard evidence of what happens when one astronomical body strikes another. *Voyager 1* photographed the huge impact basin, Valhalla, on Callisto (see Figure 7-14). An asteroid-sized object produced Valhalla Basin, which is located on Callisto's Jupiter-facing hemisphere. Like throwing a rock into a calm lake, ripples ran out from the impact site along Callisto's surface, cracking the surface and freezing into place for eternity. The largest remnant rings surrounding the impact crater have diameters of 3000 km. In 2001, the *Galileo* spacecraft revealed spires 80–100 m high on Callisto. These are also believed to have been created by an impact, perhaps the same one. The probable interiors of the Galilean moons are shown in Figure 7-10.

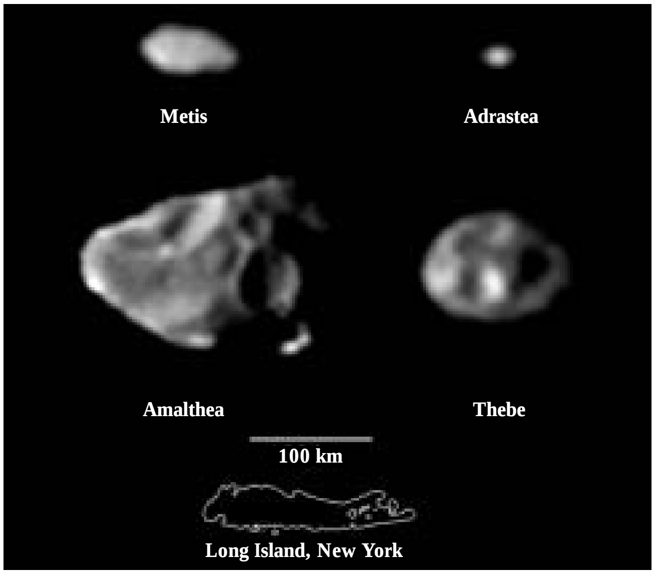

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FIGURE 7-15 Irregularly Shaped Inner Moons The four known inner moons of Jupiter are significantly different than the Galilean satellites. They are roughly oval-shaped bodies. While craters have not yet been resolved on Adrastea and Metis, their irregular shapes strongly suggest that they are cratered. All four moons are named for characters in mythology relating to Jupiter (in Greek mythology, Zeus). (NASA/JPL, Cornell University)

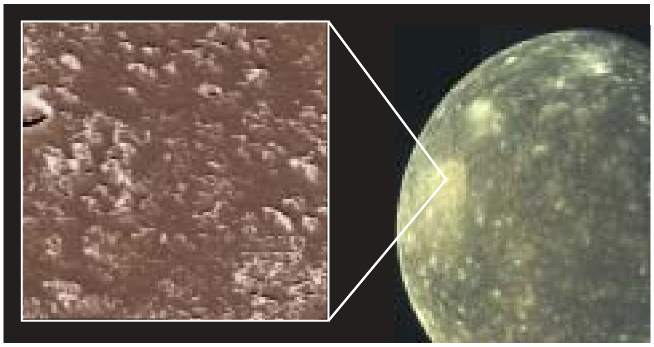

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FIGURE 7-14 Callisto The outermost Galilean satellite is almost exactly the same size as Mercury. Numerous craters pockmark Callisto's icy surface. Note the series of faint, concentric rings that cover the left third of the image. These rings outline a huge impact basin called Valhalla, which dominates the Jupiter-facing hemisphere of this frozen, geologically inactive world. The inset, a high resolution *Galileo* image, shows a portion of Valhalla. Most of the very smallest craters in this close-up view have been completely obliterated, and the terrain between the craters has been blanketed by dark dusty material. The area shown is about 11 km (7 mi) across. (Left: Arizona State University/JPL/NASA; right: JPL/NASA)

7-8 Other debris orbits Jupiter as smaller moons and ringlets

Besides the four Galilean moons, Jupiter has at least 24 other moons, a set of tenuous ringlets, and the doughnut-shaped Io torus of electrically charged gas particles. The non-Galilean moons are all irregular in shape and smaller than 150 km in diameter. Four of these moons are inside Io's orbit (Figure 7-15); all the other confirmed and suspected moons are outside Callisto's orbit. The Galilean moons along with the smaller moons closer to Jupiter and six of the outer moons orbit in the same direction that Jupiter rotates (**prograde orbits**). The remaining outer moons revolve in the opposite direction (**retrograde orbits**). The outer ones appear to be

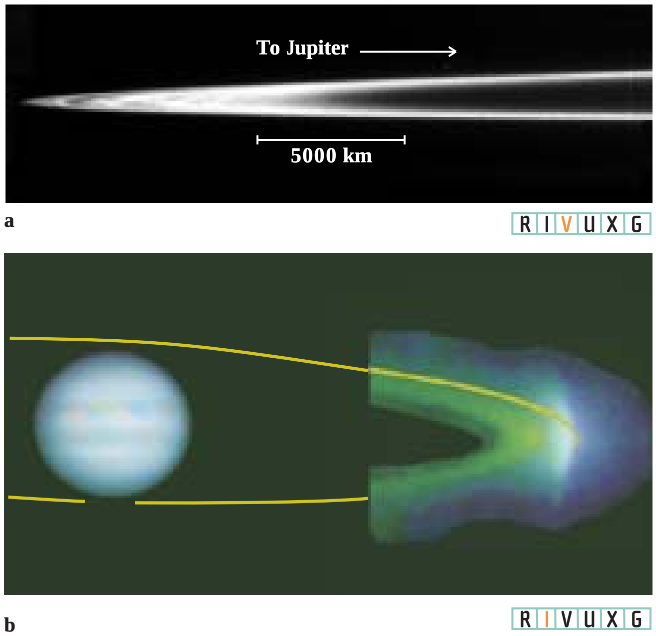

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FIGURE 7-16 Jupiter's Ring and Torus (a) A portion of Jupiter's faint ring system, photographed by *Voyager 2.* The ring is probably composed of tiny rock fragments. The brightest portion of the ring is about 6000 km wide. The outer edge of the ring is sharply defined, but the inner edge is somewhat fuzzy. A tenuous sheet of material extends from the ring's inner edge all the way down to the planet's cloudtops. (b) Io's torus (also called Io's plasma torus because the gas particles in it are charged—a plasma). This infrared image was obtained from an Earth-based telescope. The colors indicate temperature: Purple shows emission from hot sulfur ions; green shows emission from cooler sulfur ions. These ions were ejected from Io's volcanoes. An artist has added the line showing the full range of the Io torus, which fills a doughnut-shaped volume around Jupiter. (a: NASA/JPL, Cornell University; b: Courtesy of J. Trauger)

captured asteroids, while the inner ones are probably smaller pieces broken off a larger body.

As astronomers predicted, the cameras aboard *Voyager 1*
4 discovered ringlets around Jupiter. There are three, the brightest of which is seen in Figure 7-16a, a *Voyager 2* image. They are the darkest, simplest set of rings in the solar system. They consist of very fine dust particles that are continuously kicked out of orbit by radiation from Jupiter and the Sun. Therefore, these rings are being replenished by material from Io and the other moons that has been knocked free by impacts from tiny pieces of interplanetary space debris. As we will see, Jupiter is only the first of four planets with rings.

A doughnut-shaped region of electrically charged gas particles, a *plasma,* orbits Jupiter in the same orbit as Io (Figure 7-16b). Called the Io torus, it consists of sulfur and oxygen ions (charged atoms) along with free electrons. These particles were ejected by Io's geysers and they are held in orbit by Jupiter's strong magnetic field. Guided by the field, some of this matter spirals toward Jupiter, thereby creating the aurora seen there (see Figure 7-9).

SATURN

Saturn, with its ethereal rings, presents the most spectacular image of all the planets (Figure 7-17). Giant Saturn has 95 times as much mass as the Earth, making it second in mass and size to Jupiter. Like Jupiter, Saturn has a thick, active atmosphere composed predominantly of hydrogen. It also has a strong magnetic field. Ultraviolet images from the Hubble Space Telescope reveal auroras around Saturn (see Chapter 7 opener) like those seen around Jupiter (see Figure 7-9). Saturn's vital statistics are listed in Figure 7-17.

7-9 Saturn's surface and interior are similar to those of Jupiter

Partly obscured by the thick, hazy atmosphere above them, Saturn's clouds lack the colorful contrast visible on Jupiter. Nevertheless, photographs do show faint stripes in Saturn's atmosphere similar to Jupiter's belts and zones (Figure 7-18). Changing features there show that Saturn's atmosphere, too, has differential rotation—ranging from 10 hours and 14 minutes at the equator to 10 hours and 40 minutes at high latitudes. As on Jupiter, some of the belts and zones move eastward, while others move westward. Although Saturn lacks a long-lived spot like Jupiter's Great Red Spot, it does have storms, including a major new one discovered by the Hubble Space Telescope in November 1994 (Figure 7-19).

Saturn's atmosphere is composed of the same basic gases as Jupiter. However, because its mass is lower than Jupiter's, Saturn's gravitational force on its atmosphere is less. Therefore, Saturn's atmosphere is more spread out than that of its larger neighbor (see Figure 7-6). Astronomers infer that Saturn's interior structure resembles Jupiter's. A layer of molecular hydrogen just below the clouds surrounds a mantle of liquid metallic hydrogen, liquid "ices," and a solid, terrestrial core (Figure 7-20).

Because of its smaller mass, Saturn's interior is also less compressed than Jupiter's. Saturn's rocky core is larger, and the pressure there is insufficient to convert as much hydrogen into a liquid metal. Saturn's rocky core is about 32,000 km in diameter, while its layer of liquid metallic hydrogen is 12,000 km thick (see Figure 7-20). To alchemists, Saturn was associated with the extremely dense element lead. This is wonderfully ironic in that at 690 kg/m^3, Saturn is the least dense body in the entire solar system.

Saturn's Vital Statistics

Mass	5.69×10^{26} kg (95.2 $M_{\oplus}$)
Equatorial radius	60,270 km (9.45 $R_{\oplus}$)
Average density	690 kg/m^3 (0.125 Earth density)
Orbital eccentricity	0.056
Inclination of equator to plane of orbit	26.7°
Sidereal period of revolution (year)	29.5 Earth years
Average distance from Sun	1.43×10^9 km (9.53 AU)
Equatorial rotation period	10 h 13 min 59 s
Internal sidereal rotation period	10 h 39 min 25 s
Albedo (average)	0.50

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WEB LINK 7.16

FIGURE 7-17 Saturn *Voyager 2* sent back this image when the spacecraft was 34 million kilometers from Saturn. Note that you can see the planet through the gaps in the rings. This creates the illusion that the gaps are empty. (NASA)

R I V U X G

FIGURE 7-18 Belts and Zones on Saturn *Voyager 1* took this view of Saturn's cloudtops at a distance of 1.8 million kilometers. Note that there is little swirling structure and substantially less contrast between belts and zones on Saturn than there is on Jupiter. (NASA)

R I V U X G

WEB LINK 7.17 VIDEO 7.6

FIGURE 7-19 A New Storm on Saturn An arrowhead-shaped storm was discovered on Saturn in July 1994. Located near Saturn's equator, it stretches 12,700 km across, making its diameter roughly the same as that of the Earth. (Reta Beebe, New Mexico State University/ D. Gilmore and L. Bergeron, STScI/NASA)

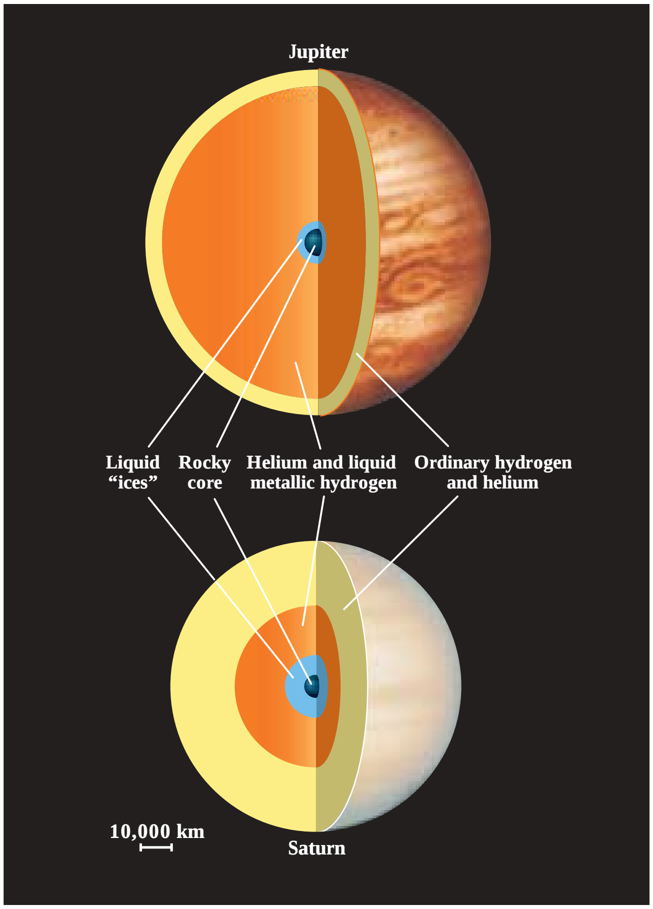

FIGURE 7-20 Cutaways of the Interiors of Jupiter and Saturn The interiors of both Jupiter and Saturn are believed to have four regions: a terrestrial core, a liquid "ice" shell, a metallic hydrogen shell, and a normal liquid hydrogen mantle. Their atmospheres are thin layers above the normal hydrogen, which boils upward, creating the belts and zones.

7-10 Saturn's spectacular rings are composed of fragments of ice and ice-coated rock

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Even when viewed through a telescope from the vicinity of the Earth, Saturn's magnificent rings are among the most spectacular objects in the solar system. They are tilted 27° from Saturn's plane of orbit, so sometimes they are nearly edge-on to us, making them virtually impossible to see (Figure 7-21). Even when the rings are at their maximum tilt from our perspective, Saturn is so far away that our best Earth-mounted telescopes can reveal only their largest features. But even these have turned out to hold surprises. In 1675, Giovanni Cassini discovered one remarkable feature—a dark division in the rings. This 5000-km-wide gap, called the **Cassini division,** separates the dimmer **A ring** from the brighter **B ring,** which lies closer to the planet. By the mid-1800s, astronomers using improved telescopes detected a faint **C ring** just inside the B ring and barely visible in Figure 7-19 (see Figure 7.22a for more detail). The Cassini division exists because the gravitational force from Saturn's moon Mimas combines with the gravitational force from the planet to keep the region clear of debris. Whenever matter drifts into the Cassini division, Mimas (orbiting at a different rate than the matter in the Cassini division) periodically exerts a force on this matter, thereby forcing it out of the division. This effect is called a **resonance** and is similar to what happens when you push someone on a swing at the right time and so enable them to go higher and higher.

A second gap exists in the outer portion of the A ring (again, barely visible in Figure 7-19), named the **Encke division** (Figure 7-22a), after the German astronomer Johann Franz Encke, who allegedly saw it in 1838. (Many astronomers have argued that Encke's report was erroneous, because his telescope was inadequate to resolve such a narrow gap.) The first undisputed observation of the 270-km-wide division was made by the American astronomer James Keeler in the late 1880s, with the newly constructed 36-in. refractor at the Lick Observatory in California. Unlike the Cassini division, the Encke division is kept clear because a small moon, Pan, orbits within it.

Pictures from the *Voyager* spacecraft show that Saturn's rings are remarkably thin—less than 2 km thick according to recent estimates. This is amazing when you consider that the total ring system has a width (from inner edge to outer edge) of more than 89,000 km.

Because Saturn's rings are very bright (albedo = 0.80), the particles that form them must be highly reflective. Astronomers had long suspected that the rings consist of ice and ice-coated rocks. Spectra taken by Earth-based observatories and by the *Voyager* spacecraft have confirmed this suspicion. Because the temperature of the rings ranges from 93 K (–290°F) in the sunshine to less than 73 K (–330°F) in Saturn's shadow, frozen water is in no danger of melting or evaporating from the rings.

Saturn's rings are slightly salmon-colored. This coloring suggests that they contain traces of organic molecules, which often have similar hues. It appears that the rings have gained this material by being bombarded with debris from the outer solar system.

To determine the size of the particles in Saturn's rings, *Voyager* scientists measured the brightness of different rings 5
from many angles as the spacecraft flew past the planet. They also measured changes in radio signals received from the spacecraft as it passed behind the rings. The largest particles in Saturn's rings are roughly 10 m across, although snowball-sized particles about 10 cm in diameter are more abundant than larger pieces. High-resolution images from *Voyager* revealed that the ring structure seen from Earth

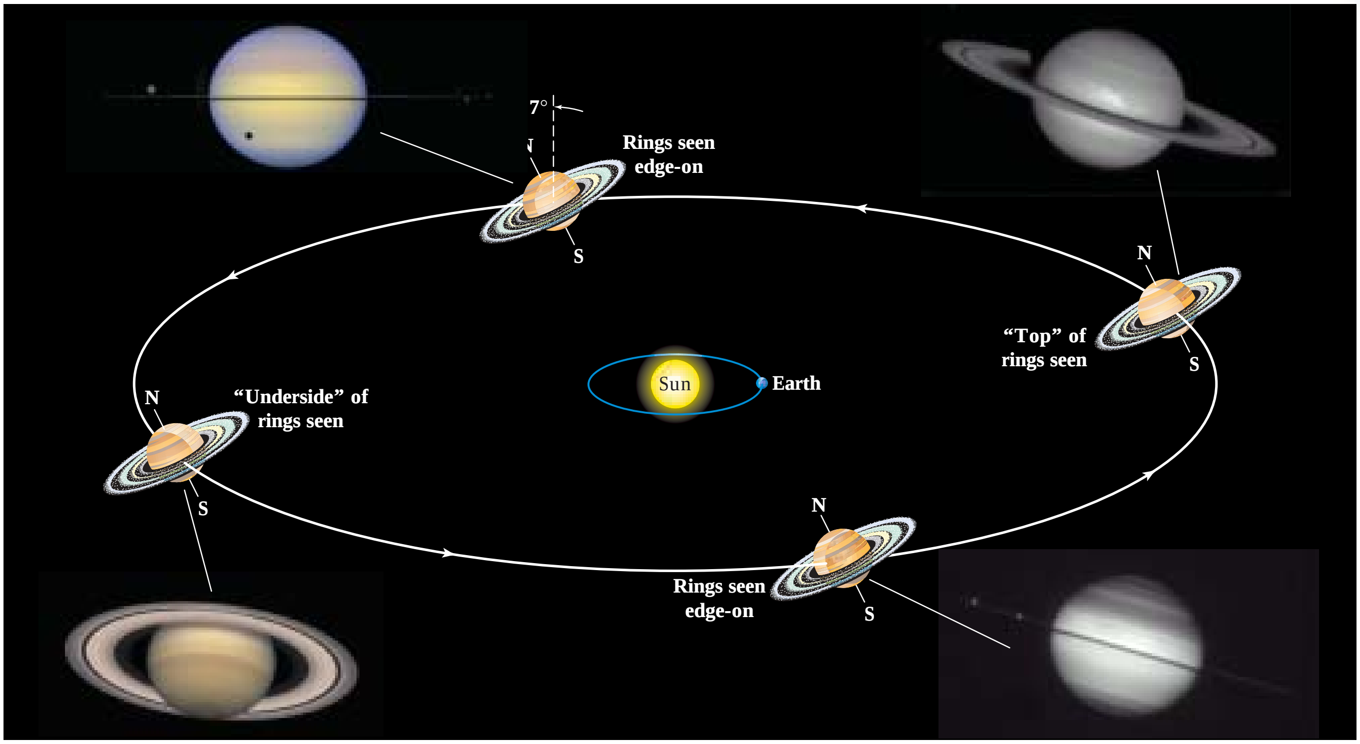
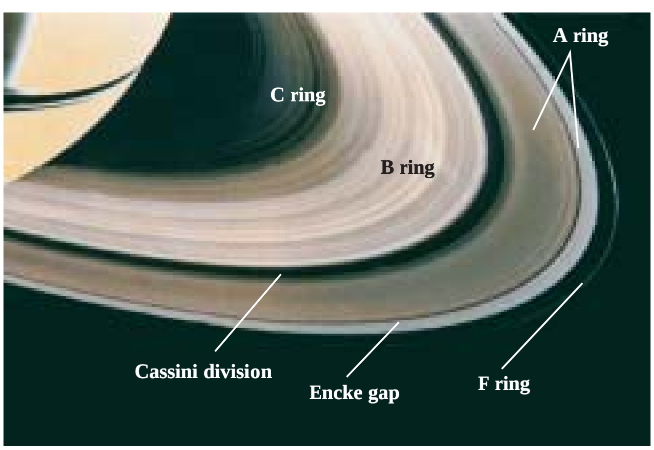
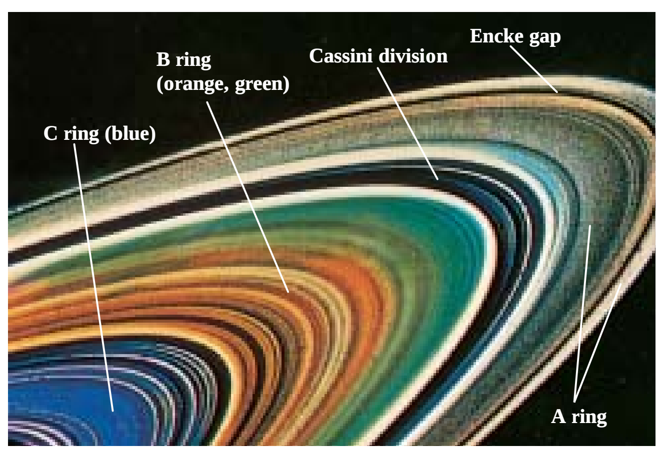


FIGURE 7-21 Saturn from the Earth Saturn's rings are aligned with its equator, which is tilted 27° from the plane of Saturn's orbit around the Sun. Therefore, Earth-based observers see the rings at various angles as Saturn moves around its orbit. The plane of Saturn's rings and equator keeps the same orientation in space as the planet goes around its orbit, just as the Earth does as it orbits the Sun. The accompanying Earth-based photographs show how the rings seem to disappear entirely about every 15 years. (Top left: E. Karkoschka/U. of Arizona Lunar and Planetary Lab and NASA; bottom left: AURA/STScI/NASA; bottom right and top right: A. Bosh/Lowell Obs. and NASA)





VIDEO 7.7 VIDEO 7.8

FIGURE 7-22 Numerous Thin Ringlets Constitute Saturn's Rings (a) This *Voyager 1* image hints that Saturn's rings contain numerous ringlets. Note the shadow of the rings on the planet and the gap in the shadow from Cassini's division. (b) Details of Saturn's rings are visible in this photograph sent back by *Voyager 2*. It shows that the rings are actually composed of thousands of closely spaced ringlets. The colors are exaggerated by computer processing to show the different ringlets more clearly. (NASA/JPL) actually consists of hundreds upon hundreds of closely spaced thin bands, or **ringlets,** of particles (Figure 7-22b). Furthermore, myriad dust-sized particles fill the Cassini and Encke divisions.

The *Voyager* cameras also sent back the first high-quality pictures of the **F ring,** a thin set of ringlets just beyond the outer edge of the A ring. Two tiny satellites following orbits on either side of the F ring serve to keep the ring intact (Figure 7-23). The outer of the two satellites orbits Saturn at a slower speed than do the ice particles in the ring. As the ring particles pass near it, they receive a tiny, backward gravitational tug, which slows them down, causing them to fall into orbits a bit closer to Saturn. Meanwhile, the inner satellite orbits the planet faster than the F ring particles. Its gravitational force pulls them forward and nudges the particles into a higher orbit. The combined effect of these two satellites is to focus the icy particles into a well-defined, narrow band about 100 km wide.

Because of their confining influence, these two moons, Prometheus and Pandora, are called **shepherd satellites** or **shepherd moons.** Among the most curious features of the F ring is that the ringlets are sometimes braided (Figure 7-24) and sometimes separate.

Saturn's shell of liquid metallic hydrogen produces a planetwide magnetic field that apparently affects its rings. Saturn's slower rotation and much smaller volume of liquid metallic hydrogen produce a surface magnetic field only about 2/3 as strong as Earth's surface field. Data from spacecraft show that Saturn's magnetosphere contains radiation belts similar to those of Earth. Furthermore, dark **spokes** move around Saturn's rings (Figure 7-25); these are believed to be created by the magnetic field, which lifts charged particles out of the plane in which the rings orbit. Spreading the particles out decreases the light scattered from them and therefore makes the rings appear darker.

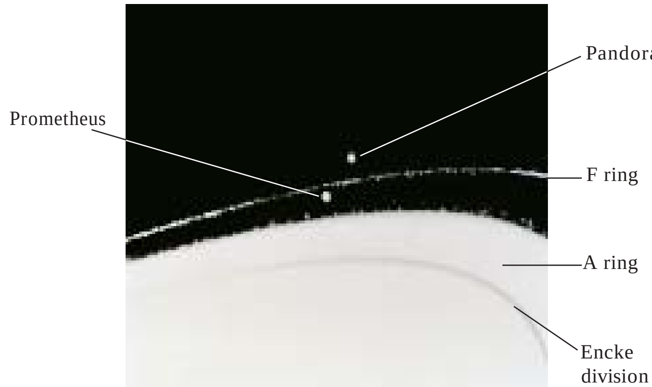


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FIGURE 7-23 The F Ring and Its Two Shepherds Two tiny satellites, Prometheus and Pandora, each measuring about 50 km across, orbit Saturn on either side of the F ring. The gravitational effects of these two shepherd satellites confine the particles in the F ring to a band about 100 km wide. (NASA)

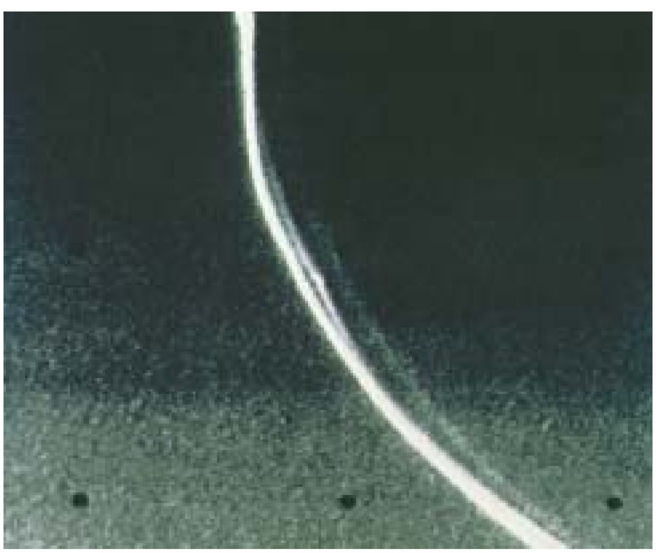

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FIGURE 7-24 Braided F Ring This photograph from *Voyager 1* shows several strands, each measuring roughly 10 km across, that comprise the F ring. The total width of the F ring is about 100 km. (NASA)

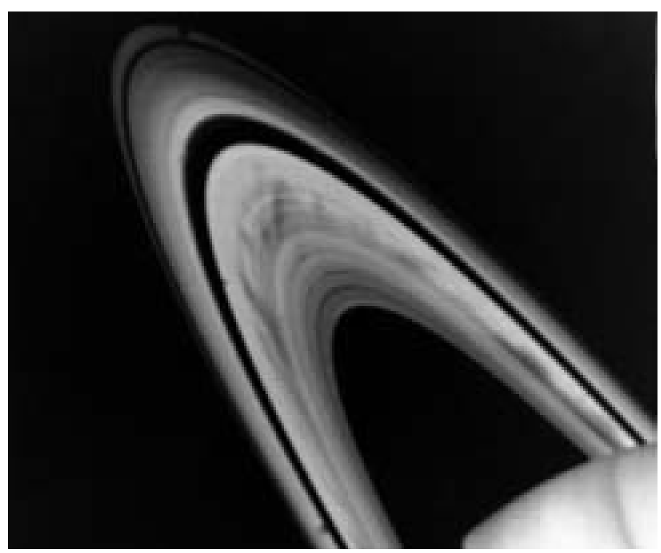

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FIGURE 7-25 Spokes in Saturn's Rings Believed to be caused by Saturn's magnetic field temporarily lifting particles out of the ring plane, these dark regions move around the rings like the spokes on a rotating wheel. (NASA)

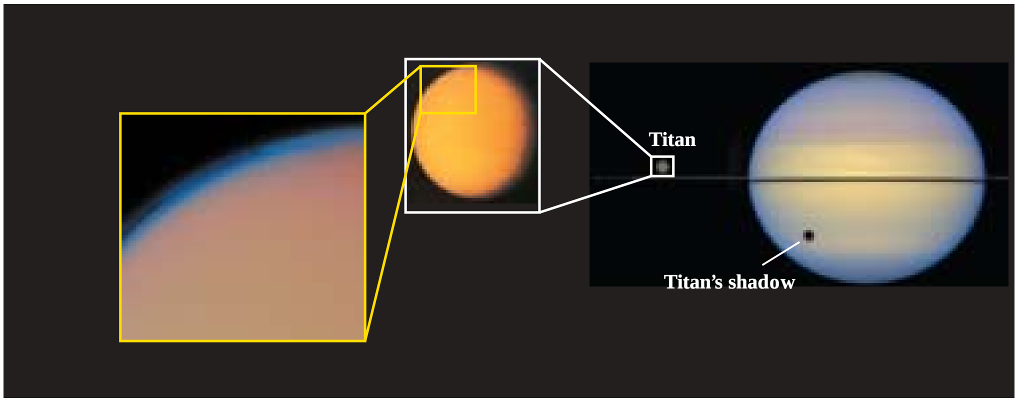

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FIGURE 7-26 **Titan** These views of Titan were taken by *Voyager 2.* Very few features are visible in the thick, unbroken haze that surrounds this large satellite. The main haze layer is located nearly 300 km above Titan's surface. (Left: JPL/NASA; center: NASA; right: Erich Karkoschka, LPL/STScI/NASA)

7-11 Titan has a thick, opaque atmosphere rich in nitrogen, methane, and other hydrocarbons

Only 7 of Saturn's 30 known moons are spherical. The rest are oblong, suggesting that they are captured asteroids. The 12 moons discovered in 2001 move in clumps, indicating that they may be pieces of a larger moon that was broken up by impacts. Saturn's largest moon, Titan, is second in size to Ganymede among the moons of the solar system, and the only moon to have a dense atmosphere. About 10 times more gas lies above each square meter of Titan's surface than lies above each square meter of the Earth.

Christiaan Huygens discovered Titan in 1655, the same year he proposed that Saturn has rings. By the early 1900s, several scientists had begun to suspect that Titan might have an atmosphere, because it is cool enough and massive enough to retain heavy gases.

Because of its atmosphere, Titan was a primary target for the *Voyager* missions. To everyone's disappointment, the *Voyagers* spent hour after precious hour sending back featureless images (Figure 7-26). Unexpectedly, Titan's thick cloud cover completely blocked any view of its surface. The same dense haze allows little sunlight to penetrate—that moon's surface must be a dark, gloomy place.

Voyager data indicated that roughly 90% of Titan's atmosphere is nitrogen. Most of this nitrogen probably formed from the breakdown of ammonia (NH_3) by the Sun's ultraviolet radiation into hydrogen and nitrogen atoms. Because Titan's gravity is too weak to retain hydrogen, this gas has escaped into space, leaving behind ample nitrogen. The unbreathable atmosphere is about 4 times as dense as Earth's.

The second most abundant gas on Titan is methane, a major component of natural gas. Sunlight interacting with methane induces chemical reactions that produce a variety of other carbon-hydrogen compounds, or **hydrocarbons.** For example, spacecraft have detected small amounts of ethane (C_2H_6), acetylene (C_2H_2), ethylene (C_2H_4), and propane (C_3H_8) in Titan's atmosphere.

Ethane, the most abundant of these compounds, condenses into droplets as it is produced and falls to Titan's surface to form a liquid. Enough ethane may exist to create rivers, lakes, and even oceans on Titan (Figure 7-27). Nitrogen combines with these hydrocarbons to produce other compounds. Although one of these compounds, hydrogen cyanide (HCN), is a poison, some of the others are the building blocks of life's organic molecules.

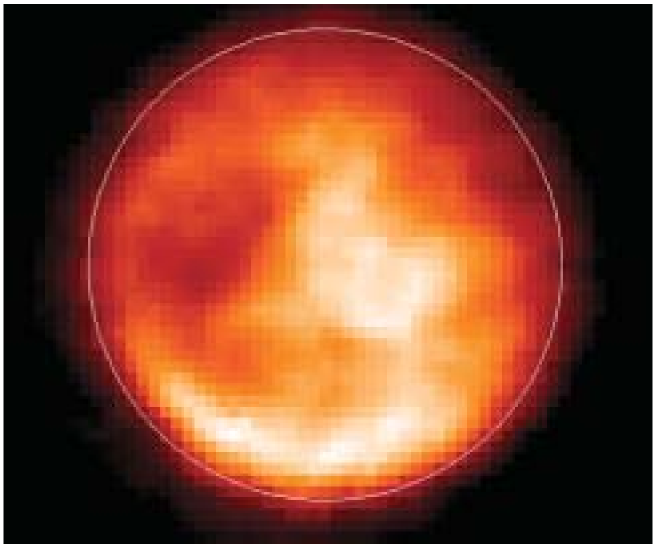

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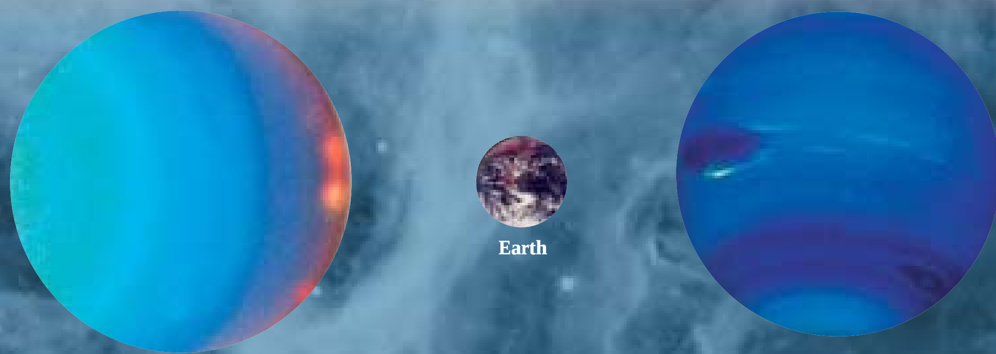
FIGURE 7-27 **Surface Features on Titan** The Keck I Telescope, using an infrared camera, was able to peer through Titan's haze (see Figure 7-26). The dark region, emitting little infrared, may be a sea of liquid methane or more complex hydrocarbons, while the brighter regions may be rock and water ice. The white circle indicates Titan's circumference. (Lawrence Livermore National Laboratory)

Uranus's Vital Statistics

Neptune's Vital Statistics



Uranus's Vital Statistics

Mass	8.68×10^{25} kg (14.5 $M_\oplus$)
Equatorial radius	25,559 km (4.01 $R_\oplus$)
Average density	1290 kg/m^3 (0.234 Earth density)
Orbital eccentricity	0.047
Sidereal period of revolution (year)	84.0 Earth years
Average distance from Sun	2.87×10^9 km (19.2 AU)
Equatorial rotation period	16 h 30 min (retrograde)
Interior sidereal rotation period	17 h 14 min (retrograde)
Albedo (average)	0.66

Neptune's Vital Statistics

Mass	1.02×10^{26} kg (17.1$M_\oplus$)
Equatorial radius	24,764 km (3.88 $R_\oplus$)
Average density	1640 kg/m^3 (0.297 Earth density)
Orbital eccentricity	0.009
Sidereal period of revolution (year)	164.8 Earth years
Average distance from Sun	4.50×10^9 km (30.1 AU)
Equatorial rotation period	19 h 6 min
Interior sidereal rotation period	16 h 7 min
Albedo (average)	0.62

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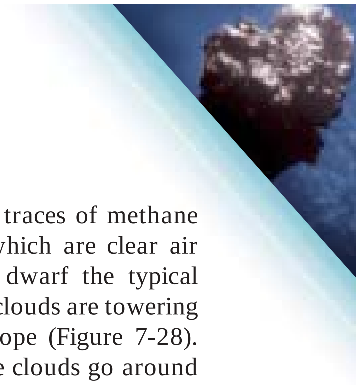
FIGURE 7-28 **Uranus, Earth, and Neptune** These images of Uranus, the Earth, and Neptune are to the same scale. Uranus and Neptune are quite similar in mass, size, and chemical composition. Both planets are surrounded by thin, dark rings, quite unlike Saturn's, which are broad and bright. The clouds on the right of Uranus are each the size of Europe. (NASA)

Some molecules can join together in long, repeating molecular chains to form substances called **polymers,** of which plastics are the best known example. Many of the hydrocarbons and carbon-nitrogen compounds in Titan's atmosphere can form such polymers. Scientists hypothesize that droplets of lighter polymers remain suspended in Titan's atmosphere to form a mist, while heavier polymer particles settle down onto Titan's surface. Using the Keck I telescope in 1999, astronomers observed infrared emissions from Titan's surface. The bright areas in Figure 7-27 are inferred to be islands or continents of rock and ice, while the dark areas are believed to be ethane oceans.

We have little reason to suspect that life exists on Titan, however; its surface temperature of 95 K (–288°F) is prohibitively cold. Nevertheless, a more detailed study of the chemistry of Titan may shed light on the origins of life on Earth.

Just as we have recently revisited Jupiter, we are sending back a spacecraft to Saturn. Launched in October 1997, spacecraft *Cassini* is scheduled to go into orbit in July 2004



on a four-year mission to study the ringed planet and the bodies that orbit it. Like *Galileo* at Jupiter, *Cassini* will deploy a probe, named *Huygens*, that will descend into Saturn's atmosphere.

URANUS

Uranus and its largest moons are so far from the Sun (19.2 AU) that from Earth they appear to be a small cluster of stars. No wonder they seem fixed in the heavens: A Uranian year equals 84 Earth years. Since its discovery in 1781, Uranus has only orbited the Sun just over $2^1/_2$ times.

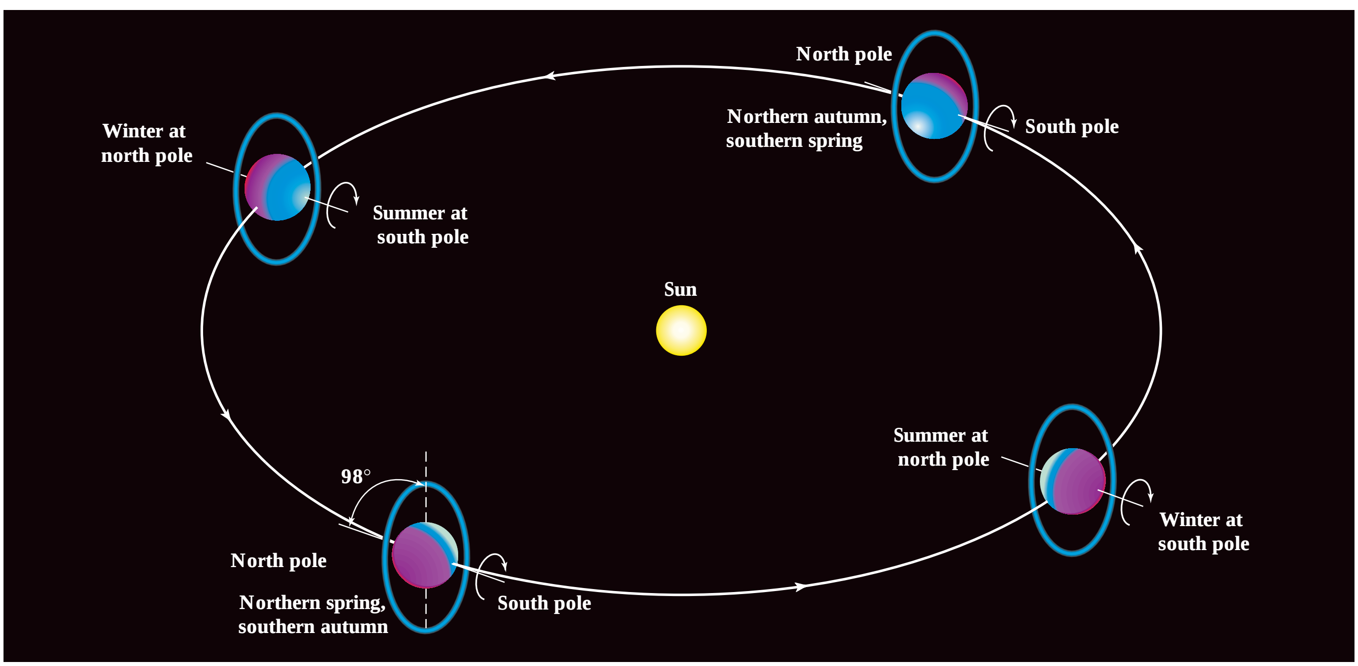
7-12 Uranus sports a hazy atmosphere and clouds

WEB LINK 7.21

Until early 1996, observations of Uranus, the fourth most massive planet in our solar system, revealed few notable features in the visible part of the spectrum. Even the 1986 visit of *Voyager 2* to Uranus showed a remarkably featureless world. It took the Hubble Space Telescope's infrared camera to find what *Voyager*'s visible light camera could not: Uranus has a system of belts and zones. Its hydrogen atmosphere has traces of methane along with a high-altitude haze under which are clear air and ever-changing methane clouds that dwarf the typical cumulus clouds we see on Earth. Uranus's clouds are towering and huge, each typically as large as Europe (Figure 7-28). Along with the rest of the atmosphere, the clouds go around the planet once every $16^1/_2$ hours.

Uranus contains $14^1/_2$ times as much mass as the Earth and is 4 times bigger in diameter (see Figure 7-28). Its outer layers are composed predominantly of gaseous hydrogen and helium. The temperature in the upper atmosphere of the planet is so low (about 73 K, or –330°F) that the methane and water there condense to form clouds of ice crystals. Because methane freezes at a lower temperature than water, methane forms higher clouds over Uranus. Methane efficiently absorbs red light, giving Uranus its blue-green color.

Earth-based observations show that Uranus rotates once every 17 hours 14 minutes on an axis of rotation that lies very nearly in the plane of the planet's orbit. Uranus's rotation axis is inclined 98° from a line perpendicular to its plane of orbit. Therefore, it is one of only three planets with retrograde rotation (Venus and Pluto are the other two). As Uranus orbits the Sun, its north and south poles alternately point almost directly toward or directly away from the Sun, producing exaggerated seasons (Figure 7-29). In the



ANIMATION 7.2

FIGURE 7-29 Exaggerated Seasons on Uranus Uranus's axis of rotation is tilted so steeply that it lies nearly in the plane of its orbit. Seasonal changes on Uranus are thus greatly exaggerated. For example, during midsummer at Uranus's south pole, the Sun appears nearly overhead for many Earth years, while the planet's northern regions are subjected to a long, continuous winter night. Half an orbit later, the seasons are reversed.

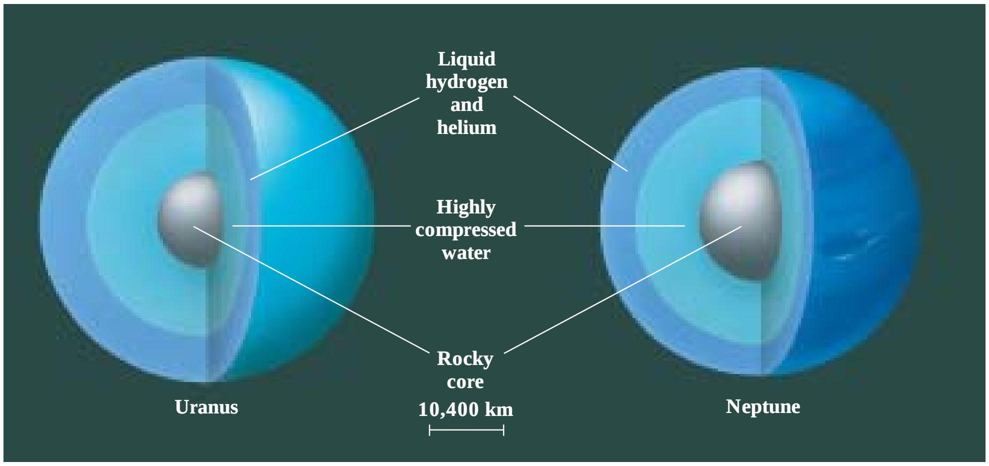


FIGURE 7-30 Cutaways of the Interiors of Uranus and Neptune The interiors of both Uranus and Neptune are believed to have three regions: a terrestrial core surrounded by a liquid water mantle, which is surrounded in turn by liquid hydrogen and helium. Their atmospheres are thin layers at the top of their hydrogen and helium layers.

summertime, near Uranus's north pole, the Sun is almost directly overhead for many Earth years, at which time southern latitudes are subjected to a continuous, frigid winter night. Forty-two Earth years later, the situation is reversed. For more on this, see the essay "What If … Earth's Axis Lay on the Ecliptic?" on page 42.

From *Voyager* photographs, planetary scientists have concluded that each of the five largest Uranian moons has probably had at least one shattering impact. A catastrophic collision with an Earth-sized object may also have knocked Uranus on its side, as we see it today.

From its mass and density (1290 kg/m^3), astronomers conclude that Uranus's interior has three layers. The outer 30% of the planet is liquid hydrogen and helium, the next 40% inward is highly compressed liquid water (with some methane and ammonia), and the inner 30% is a rocky core (Figure 7-30). Indirect evidence for the water layer comes from the apparent deficiency of ammonia on Uranus. This gas dissolves easily in water, so an ocean would explain the scarcity of ammonia in the planet's atmosphere.

Voyager 2 passed through the magnetosphere of Uranus, revealing that the planet's surface magnetic field is about $^3/_4$ that of the Earth. That strength is reasonable, considering the planet's mass and rotation rate, but everything else about the magnetic field is extraordinary. It is remarkably tilted—59% from its axis of rotation—and does not even pass through the center of the planet (Figure 7-31).

Because of the large angle between the magnetic field of Uranus and its rotation axis, the magnetosphere of Uranus wobbles considerably as the planet rotates. Such a rapidly changing magnetic field will help us in explaining pulsars, a type of star we will study in Chapter 12.

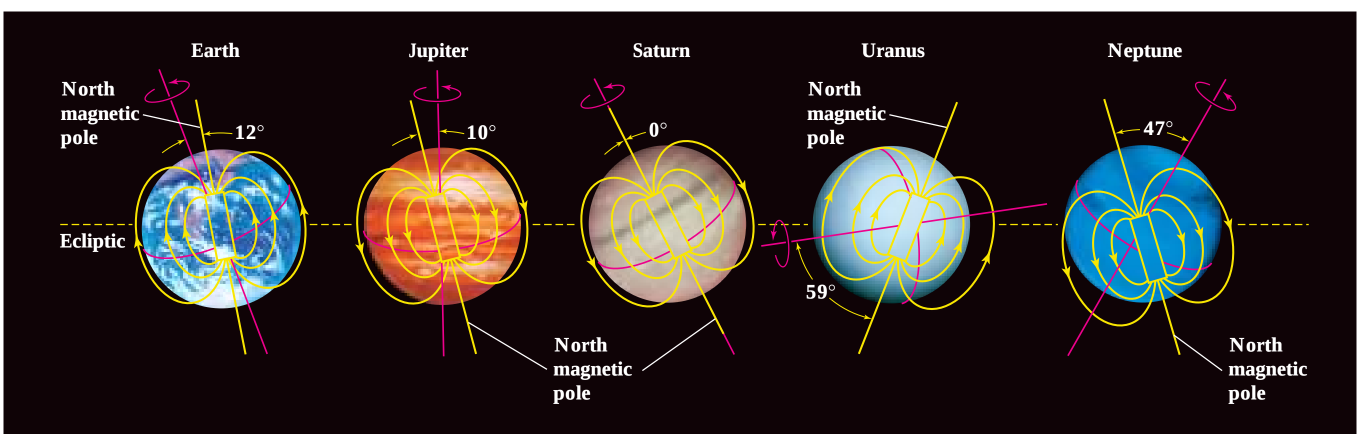
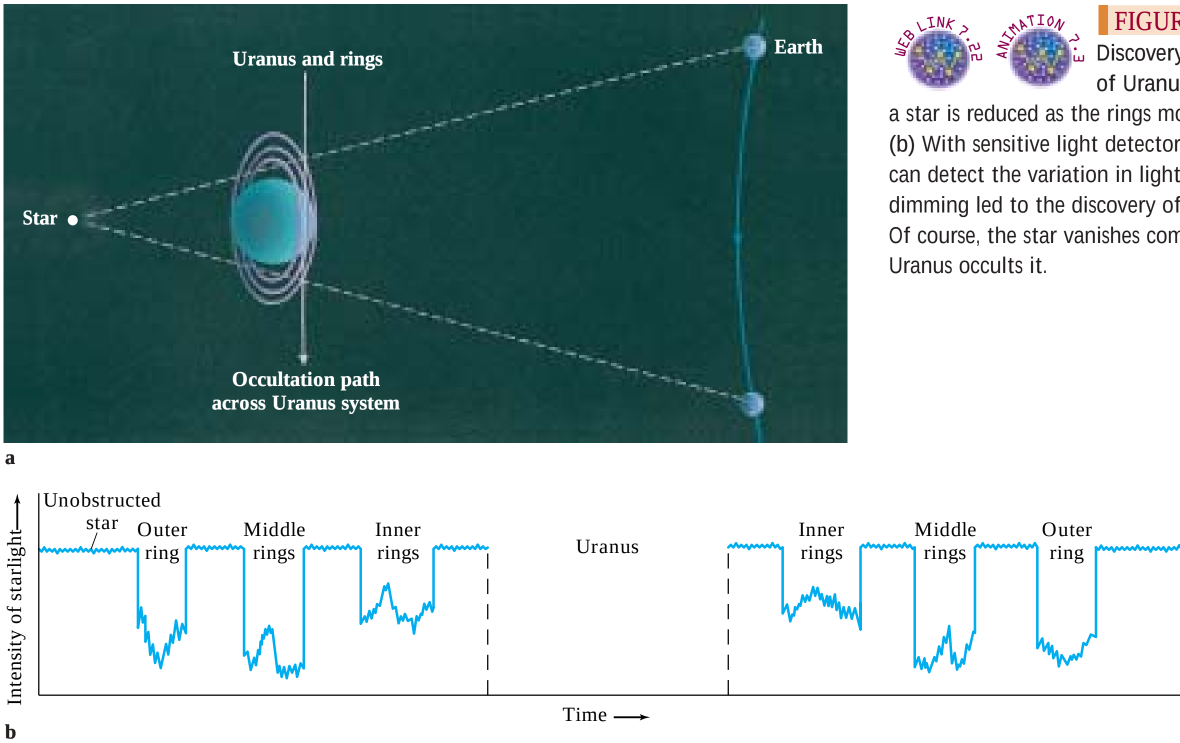


FIGURE 7-31 The Magnetic Fields of Five Planets This drawing shows how the magnetic fields of Earth, Jupiter, Saturn, Uranus, and Neptune are tilted relative to their rotation axes. Note that the magnetic fields of Uranus and Neptune are offset from the centers of the planets and steeply inclined to their rotation axes. Jupiter, Saturn, and Neptune have north magnetic poles on the hemisphere where Earth has its south magnetic pole.



WEB LINK 7.22 ANIMATION 7.3

FIGURE 7-32 Discovery of the Rings of Uranus (a) Light from a star is reduced as the rings move in front of it. (b) With sensitive light detectors, astronomers can detect the variation in light intensity. Such dimming led to the discovery of Uranus's rings. Of course, the star vanishes completely when Uranus occults it.

7-13 A system of rings and satellites revolves around Uranus

Nine of Uranus's thin, dark rings were discovered accidentally in 1977 when Uranus passed in front of a star. The star's light was momentarily blocked by each ring, thereby revealing their existence to astronomers (Figure 7-32). Blocking the light of a more distant object, such as the star here, by something between it and us, such as Uranus's rings, is called an **occultation.** A picture taken while *Voyager* was in Uranus's shadow revealed more thin rings (Figure 7-33).

Most of Uranus's moons, like its rings, orbit in the plane of the planet's equator. Five of these satellites, ranging in diameter from 480 to nearly 1600 km, were known before

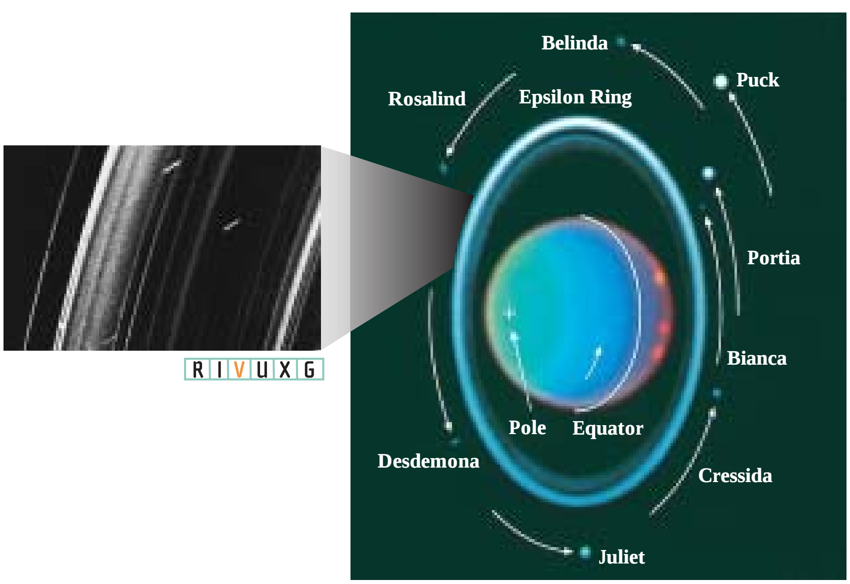


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FIGURE 7-33 The Rings and Moons of Uranus This image of Uranus, its rings, and eight of its moons was taken by the Hubble Space Telescope. Inset: Close-up of part of the ring system taken by *Voyager 2* when the spacecraft was in Uranus's shadow looks back toward the Sun. Numerous fine dust particles between the main rings gleam in the sunlight. Uranus's rings are much darker than Saturn's, and this long exposure revealed many very thin rings and dust lanes. The short streaks are star images blurred because of the spacecraft's motion during the exposure. (Inset: NASA)

VIDEO 7.9

FIGURE 7-34 Miranda The patchwork appearance of Miranda in this mosaic of *Voyager 2* images suggests that this satellite consists of huge chunks of rock and ice that came back together after an ancient, shattering impact by an asteroid or a neighboring Uranian moon. The curious banded features that cover much of Miranda are parallel valleys and ridges that may have formed as dense, rocky material sank toward the satellite's core. At the very bottom of the image—where a "bite" seems to have been taken out of the satellite—is a range of enormous cliffs that jut upward as high as 20 km, twice the height of Mount Everest. (NASA)

the *Voyager* mission. However, *Voyager*'s cameras discovered ten additional satellites, each fewer than 50 km across. Still others have since been observed from Earth. Several of these tiny, irregularly shaped moons are shepherd satellites whose gravitational pull confines the particles within the thin rings that circle Uranus.

The smallest of Uranus's five main satellites, Miranda, is the most fascinating and bizarre of its 21 known moons. Unusual wrinkled and banded features cover Miranda's surface (Figure 7-34). Its highly varied terrain suggests that it was once seriously disturbed. Perhaps a shattering impact temporarily broke it into several pieces that then recoalesced, or perhaps severe tidal heating, as we saw on Io, moved large pieces of its surface.

Miranda's core originally consisted of dense rock, while its outer layers were mostly ice. If a powerful impact did occur, blocks of debris broken off from Miranda drifted back together through mutual gravitational attraction. Recolliding with that moon, they formed a chaotic mix of rock and ice. In this scenario, the landscape we see today on Miranda is the result of huge, dense rocks trying to settle toward the satellite's center, forcing blocks of less dense ice upward toward the surface.

NEPTUNE

Neptune is physically similar to Uranus (review Figures 7-28 and 7-30). Neptune has 17.1 times the Earth's mass, 3.88 times Earth's diameter, and a density of 1640 kg/m^3. Unlike Uranus, however, cloud features can readily be discerned on Neptune. Its whitish, cirruslike clouds consist of methane ice crystals. The methane absorbs red light, leaving the planet's belts and zones with a banded, bluish appearance (Figure 7-35). Like Jupiter, the atmosphere of Neptune also experiences differential rotation. The winds on Neptune blow as fast as 2000 km/h—among the fastest in the solar system.

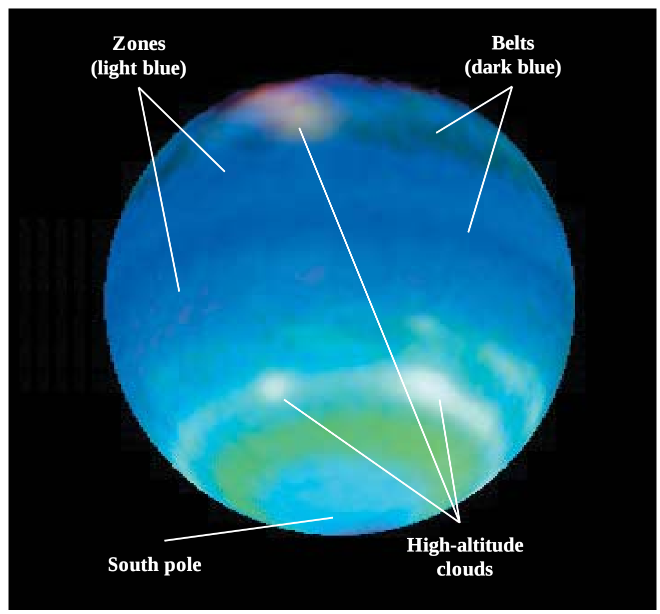

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FIGURE 7-35 Neptune's Banded Structure. Several Hubble Space Telescope images at different wavelengths were combined to create this enhanced-color view of Neptune. The dark blue and light blue areas are the belts and zones, respectively. The dark belt running across the middle of the image lies just south of Neptune's equator. White areas are high-altitude clouds, presumably of methane ice. The very highest clouds are shown in yellow-red, as seen at the very top of the image. The green belt near the south pole is a region where the atmosphere absorbs blue light, perhaps indicating some differences in chemical composition. (Lawrence Sromovsky, University of Wisconsin-Madison and STScI/NASA)

7-14 Neptune was discovered because it had to be there

Neptune's discovery is storied because it illustrates a scientific prediction leading to an expected discovery. In 1781 the British astronomer William Herschel discovered Uranus. Its position was carefully plotted, and by the 1840s, it was clear that even considering the gravitational effects of all the known bodies in the solar system, Uranus was not following the path predicted by Newton's and Kepler's laws. Either the theories behind these laws were wrong, or there had to be another, yet-to-be-discovered body in the solar system pulling on Uranus.

Independent, nearly simultaneous calculations by an English mathematician, John Adams, and a French astronomer, Urbain Leverrier, predicted the same location for the alleged planet. That planet, Neptune, was located in 1846 by the German astronomer Johann Galle, within a degree or two of where it had to be to have the observed influence on Uranus.

In August 1989, nearly 150 years after its discovery, *Voyager 2* arrived at Neptune to cap one of NASA's most ambitious and successful space missions. Scientists were overjoyed at the detailed, close-up pictures and wealth of data about Neptune sent back to Earth by the spacecraft.

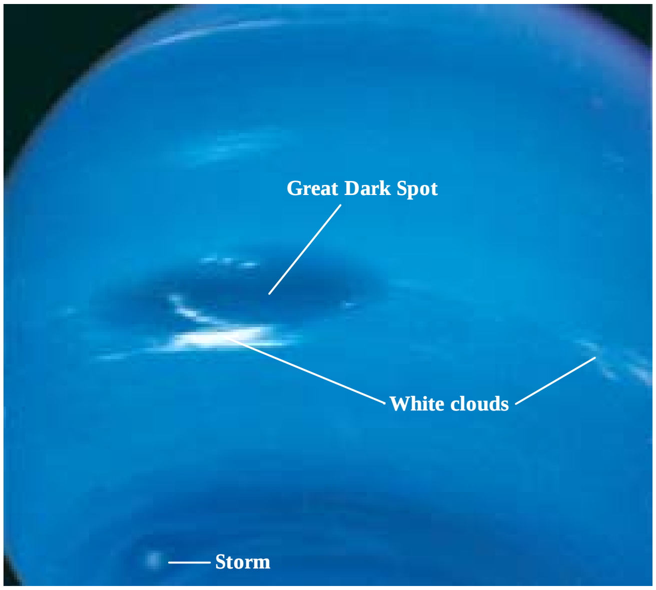


FIGURE 7-36 Neptune This view from *Voyager 2* looks down on the southern hemisphere of Neptune. The Great Dark Spot, whose diameter at the time was about the same size as the Earth's diameter, is near the center of this picture. It has since vanished. Note the white, wispy methane clouds. (NASA/JPL)

VIDEO 7.10

Insight into Science **Process and Progress** Scientific theories make testable predictions (see Chapter 1). Based on the details of Uranus's orbit around the Sun, Newton's law of gravitation predicted that Uranus's orbit was being affected by the gravitational attraction of another planet. The law also predicted where that planet was located, leading to the discovery of Neptune.

At the time *Voyager 2* passed it, a giant storm raged in Neptune's atmosphere. Called the **Great Dark Spot,** it was about half as large as Jupiter's Great Red Spot. The Great Dark Spot (Figure 7-36) was located at about the same latitude on Neptune and occupied a similar proportion of Neptune's surface as the Great Red Spot does on Jupiter. Although these similarities suggested that similar mechanisms created the spots, the Hubble Space Telescope in 1994 showed that the Great Dark Spot had disappeared. Then, in April 1995, another storm developed in the opposite hemisphere.

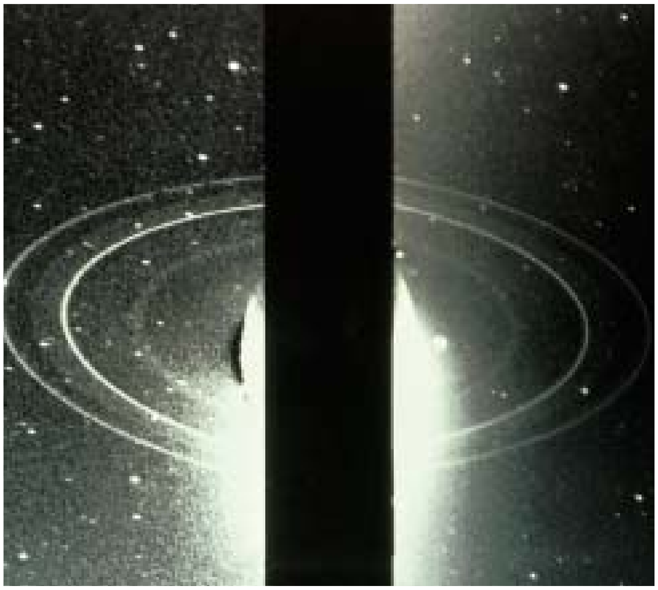
Neptune's interior is believed to be very similar in composition and structure to that of Uranus: a rocky core surrounded by ammonia- and methane-laden water (see Figure 7-30). Neptune's surface magnetic field is about 40 percent that of the Earth. Also, as with Uranus, Neptune's magnetic axis, the line connecting its north and south magnetic poles, is tilted sharply from its rotation axis. In this case, the tilt is 47%. Again like Uranus, Neptune's magnetic axis does not pass through the center of the planet (see Figure 7-31).

We saw in section 7-2 that the magnetic fields of Jupiter and Saturn are believed to be generated by the motions of their liquid metallic hydrogen. However, Uranus and Neptune lack this material, and their magnetic fields have a different origin. These fields are believed to exist because molecules such as ammonia dissolved in their water layers lose electrons (become ionized). These ions, moving with the planets' rotating, fluid interiors, create the same dynamo effect that produces the magnetic field.

7-15 Neptune has rings and has captured most of its moons

Like Uranus, Neptune is surrounded by a system of thin, dark rings (Figure 7-37). It is so cold at these distances from the Sun that both planets' ring particles retain methane ice. Scientists speculate that eons of radiation damage have converted this methane ice into darkish carbon compounds, thus accounting for the low reflectivity of the rings.

Neptune has eight known moons. Seven have irregular shapes and highly elliptical orbits, which suggest that Neptune captured them. Triton, discovered in 1846, is spherical and was quickly observed to have a nearly circular, retrograde orbit around Neptune. It is difficult to imagine how a



R I V U X G

WEB LINK 7.25 VIDEO 7.11 **FIGURE 7-37** Neptune's Rings Two main rings are easily seen in this view alongside over-exposed edges of Neptune. Careful examination also reveals a faint inner ring. A fainter-still sheet of particles, whose outer edge is located between the two main rings, extends inward toward the planet. (NASA)

satellite and planet could form together but rotate in opposite directions. Indeed, only a few of the small outer satellites of Jupiter and Saturn have retrograde orbits, and these bodies are probably captured asteroids. Some scientists have therefore suggested that Triton may have been captured 3 or 4 billion years ago by Neptune's gravity.

Upon being captured, Triton was most likely in a highly elliptical orbit. However, the tidal force the moon creates on Neptune's liquid surface would have made Triton's orbit more circular. Conversely, the tidal force created on Triton by Neptune due to the moon's changing distance to Neptune would have caused the moon to stretch and flex, providing enough energy to melt much of the satellite's interior and obliterate Triton's original surface features, including craters. Triton's south polar region is shown in Figure 7-38. Note that very few craters are visible. Calculations based on these observations indicate that Triton's present surface is about 100 million years old.

Triton does exhibit some surface features seen on other icy worlds, such as long cracks resembling those on Europa and Ganymede. Other features unique to Triton are quite puzzling. For example, the top half of Figure 7-38 reveals a wrinkled terrain that resembles the skin of a cantaloupe. Triton also has a few frozen lakes like the one shown in Figure 7-39. Some scientists have speculated that these lake-like features are the calderas of extinct ice volcanoes. A mixture of methane, ammonia, and water, which can have a melting point far below that of pure water, could have formed a kind of cold lava on Triton.

Voyager instruments measured a surface temperature of 36 K (–395ºF), making Triton the coldest world that our probes have ever visited. Nevertheless, *Voyager* cameras did glimpse two towering plumes of gas extending up to 8 km above the satellite's surface. These are apparently plumes of nitrogen gas warmed by interior radioactive decay and escaping through vents or fissures.

In the same way that our Moon raises tides on Earth, Triton raises tides on Neptune. Whereas the tides on Earth cause our Moon to spiral outward, the tides on Neptune cause Triton (in its retrograde orbit) to spiral inward. Within the next quarter of a billion years, Triton will reach the **Roche limit,** the distance at which a planet creates tides on its moon's solid surface high enough to pull its moon apart. Pieces of Triton will then literally float into space until the entire moon is demolished! By destroying Triton, Neptune

R I V U X G

VIDEO 7.12 VIDEO 7.13 **FIGURE 7-38** Triton's South Polar Cap Approximately a dozen high-resolution *Voyager 2* images were combined to produce this view of Triton's southern hemisphere. The pinkish polar cap is probably made of nitrogen frost. A notable scarcity of craters suggests that Triton's surface was either melted or flooded by icy lava after the era of bombardment that characterized the early history of the solar system. (NASA)

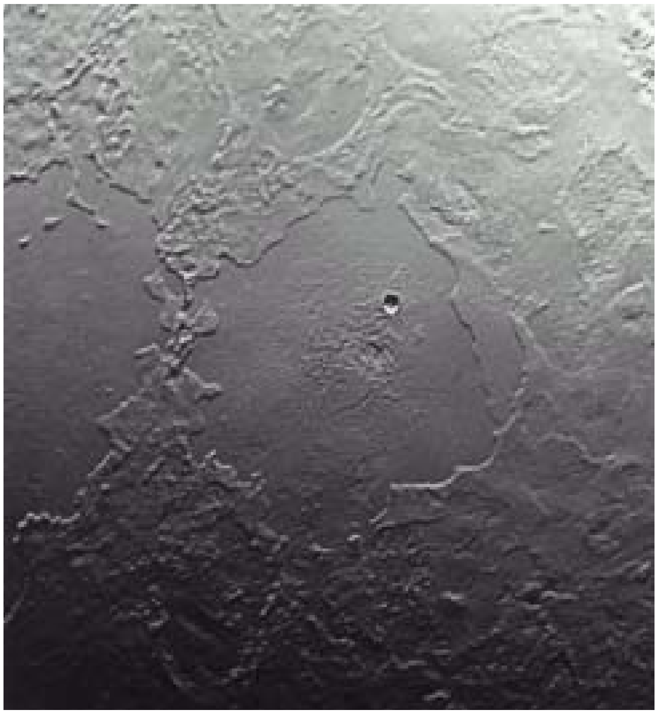


FIGURE 7-39 A Frozen Lake on Triton Scientists believe that the feature in the center of this image is a basin filled with water ice. The flooded basin is about 200 km across. (NASA)

will create a new ring system that will be much more substantial than its present one.

MORE TO KNOW 7.1 Roche Limit

PLUTO AND BEYOND

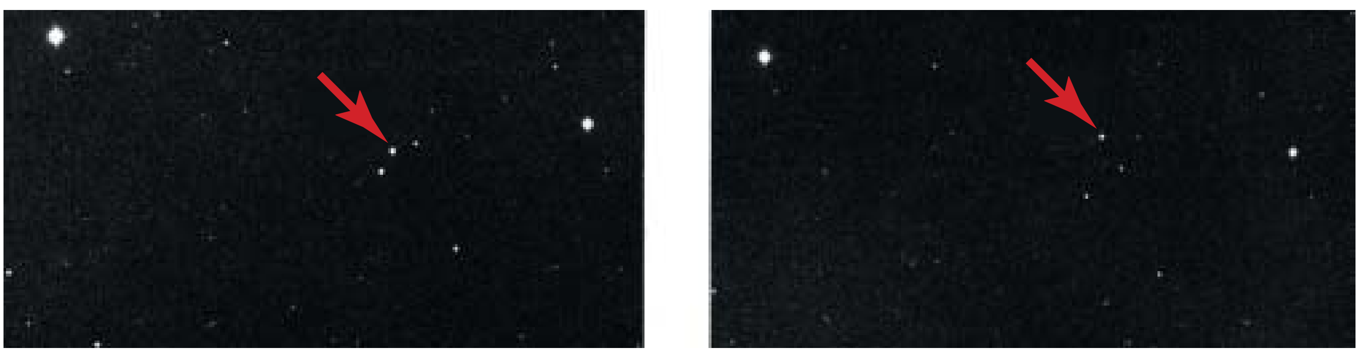
In 1930, the astronomer Clyde W. Tombaugh was searching for a giant planet that was allegedly affecting Neptune's orbit. Instead, Tombaugh discovered tiny Pluto (Figure 7-40), a planet far too small to have a noticeable gravitational effect on Neptune. Figure 7-41 lists Pluto's data. Refined observations show that Neptune's orbit is not being affected by another giant planet. No such planet has ever been found.

Tombaugh recognized Pluto as a planet because it moved among the background stars from night to night, but he had no idea how strange its orbit is compared with those of the other planets. As discussed in Essentials II (see Figure II-8), Pluto's orbit is so elliptical that it is sometimes closer to the Sun than Neptune, as it was from 1979 to 1999. It is now farther away from the Sun than Neptune and will continue to be so for about the next 230 years. Pluto's orbit is tilted with respect to the plane of the ecliptic more than any other planet.

7-16 Pluto and its moon Charon are about the same size

Pluto was little understood for half a century until astronomers noticed that its image sometimes appears oblong (Figure 7-42). This observation led to the discovery in 1978 of Pluto's only known moon, Charon (pronounced KAR-en, after the mythical boatman who ferried souls across the River Styx to Hades, the domain ruled by Pluto). From 1985 through 1990, the orbit of Charon was oriented so that Earth-based observers could watch it eclipse Pluto. Astronomers used observations of these eclipses to determine that Pluto is only twice as broad as its satellite: its diameter is 2380 km and Charon's is 1190 km.

The average distance between Charon and Pluto is less than $^{1}/_{20}$ the distance between the Earth and our Moon.

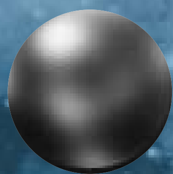


R I V U X G

WEB LINK 7.2b

FIGURE 7-40 Discovery of Pluto Pluto was discovered in 1930 by searching for a dim, starlike object that slowly moves against the background stars. These two photographs were taken one day apart. (Lick Observatory)

Pluto's Vital Statistics

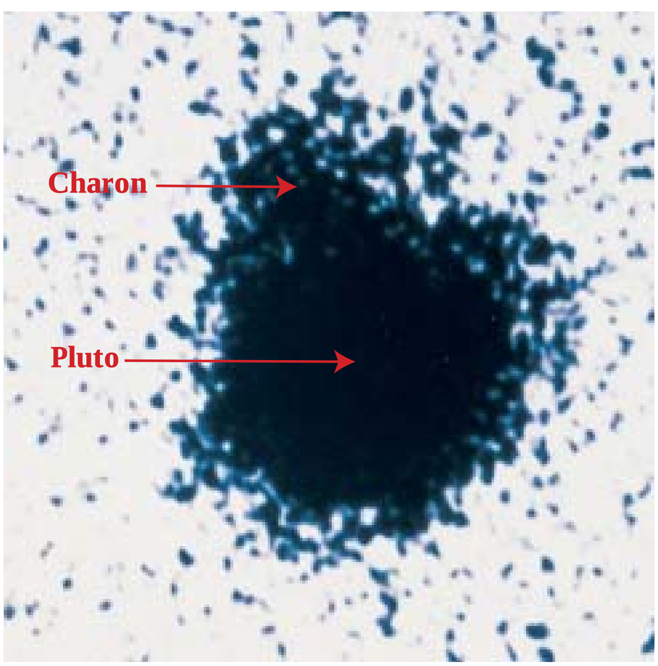


Mass	1.30×10^{22} kg ($0.002\ M_{\oplus}$)
Radius	1190 km ($0.19\ R_{\oplus}$)
Average density	1800 kg/m^3 (0.326 Earth density)
Orbital eccentricity	0.249
Inclination of equator to plane of orbit	118°
Sidereal period of revolution (year)	248.6 Earth years
Average distance from Sun	5.91×10^9 km (39.5 AU)
Sidereal rotation period	6.39 Earth days (retrograde)
Albedo (average)	0.50

R I V U X G

WEB LINK 7.27

FIGURE 7-41 Pluto and Its Vital Statistics This Hubble Space Telescope image of Pluto shows little detail but indicates that the major features of Pluto's surface each cover large amounts of its surface area. (Alan Stern, Southwest Research Institute, Marc Buie, Lowell Observatory, NASA/ESA)



R I V U X G

VIDEO 7.14

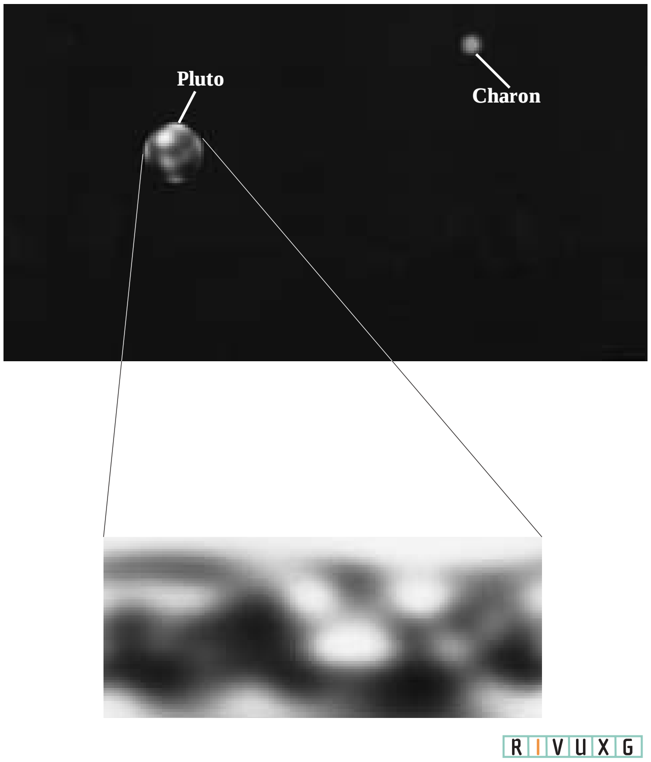
FIGURE 7-42 Discovery of Charon Long ignored as just a defect in the photographic emulsion, the bump on the upper left side of this image of Pluto led astronomer James Christy to discover the moon Charon. (U.S. Naval Observatory)

Furthermore, Pluto always keeps the same side facing Charon. This is the only case in which a moon and a planet both have synchronous rotation with respect to each other. As seen from the satellite-facing side of Pluto, Charon neither rises nor sets, but instead hovers in the sky, perpetually suspended above the horizon.

The exceptional similarities between Pluto and Charon suggest that this binary system may have formed when Pluto collided with a body of similar size. Perhaps chunks of matter were stripped from this second body, leaving behind a mass, now called Charon, that was vulnerable to capture by Pluto's gravity. Alternatively, perhaps Pluto's gravity captured Charon into orbit during a close encounter between the two worlds.

Both of these are unlikely scenarios. For either to be feasible, many Pluto-sized objects must have existed in the outer regions of the young solar system. One astronomer estimates that there must have been at least a thousand Pluto-sized bodies in order for a collision or close encounter between two of them to have occurred at least once since the solar system formed 4.6 billion years ago.

The best pictures of Pluto and Charon were taken by the Hubble Space Telescope (Figure 7-43). Like Neptune's moon Triton, these worlds are probably composed of nearly equal amounts of rock and ice. The surface of Pluto shows more large-scale features than any object in the solar system other than the Earth. Examination of Hubble Space Tele-



VIDEO 7.15 **FIGURE 7-43** **Pluto and Charon** This picture of Pluto and its moon, Charon, is a composite of Hubble Space Telescope images. It shows the greatest detail we have of Pluto's surface. Pluto and Charon are separated here by only 19,700 km. **Inset:** A map covering 85% of Pluto's surface. The contrast between dark and light strongly suggests regions covered with ice and regions covered with rocky material. (Pluto: Alan Stern/SwRI, Mar Cuie/Lowell Observatory, NASA, & ESA; Charon: R. Albrecht, ESA/ESO Space Telescope European Coordinating Facility, and NASA; inset: A. Stern/SwRI, M. Buie/Lowell Observatories, NASA, and ESA)

scope images has revealed some 12 distinct regions, and studies of Pluto's surface temperature show that different regions vary by up to 25 K from each other.

Pluto's spectrum shows that its surface contains frozen nitrogen, methane, and carbon monoxide. The planet is also observed to have a very thin atmosphere of nitrogen and carbon monoxide when it is closest to the Sun. In contrast, Charon's surface appears to be covered predominantly with water ice.

Ever since Pluto was discovered, astronomers have searched for other objects in our solar system. Neptune's captured moons support the idea of other bodies at the outskirts of the solar system, and astronomers have begun discovering them by the hundreds. These distant masses of ice and rock, which we will discuss further in Chapter 8, lie in a region now called the Kuiper belt, which is believed to extend out 500 AU from the Sun.

Insight into Science **Paradigm Shift** Usually it takes overwhelming evidence contradicting established beliefs before scientists begin looking at old ideas in completely new ways. Such changes in fundamental beliefs are sometimes called *paradigm shifts.* The acceptance of tectonic plate motion is one such change. Until the past few years, astronomers took it for granted that Pluto is a planet. Perhaps another paradigm shift in the near future will reclassify tiny Pluto as the largest object in the Kuiper belt.

7-17 Frontiers yet to be discovered

The outer planets hold countless new insights into the formation and evolution of the solar system. Considering that virtually all present extrasolar planets are Jupiter-like gas giants, our outer planets all have a lot to tell us about planets throughout our Galaxy. Why did the *Galileo* probe fail to detect the atmospheric structures believed to exist on Jupiter? How has the Great Red Spot persisted for so long? Is there life in the oceans of the outer Galilean moons? What, exactly, do the ring particles around each of the planets look like? How long ago did Saturn's ring system form? How long will it last? Are the spokes in Saturn's rings really caused by its magnetic field, and, if so, why do the spokes appear as they do? What caused Miranda's surface to become so profoundly disturbed? How did the Pluto-Charon system form? These are but a few of the questions about the outer planets that will be answered during this century.

Further Reading on These Topics

WHAT DID YOU KNOW?

1 *Is Jupiter a "failed star" or almost a star?* No. Jupiter has 75 times too little mass to shine as a star.

2 *What is Jupiter's Great Red Spot?* The Great Red Spot is a long-lived, oval cloud circulation similar to a hurricane on Earth.

3 *Does Jupiter have continents and oceans?* No. Jupiter is surrounded by a thick atmosphere primarily of hydrogen and helium that becomes liquid as one moves inward. The only solid matter in Jupiter is its core.

4 *Is Saturn the only planet with rings?* No. Four planets (Jupiter, Saturn, Uranus, and Neptune) have rings.

5 *Are the rings of Saturn solid ribbons?* Saturn's rings are all composed of thin, closely spaced ringlets consisting of particles of ice and ice-coated rocks. If they were solid ribbons, Saturn's gravitational tidal force would tear them apart.

KEY WORDS

A ring, 204
B ring, 204
belt, 195
C ring, 204
Cassini division, 204
differential rotation, 193
Encke division, 204
F ring, 206
Galilean moon (satellite), 197
Great Dark Spot, 213
Great Red Spot, 193
hydrocarbon, 207
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spoke, 206
zone, 195

KEY IDEAS

Jupiter and Saturn

• Jupiter is by far the largest and most massive planet in the solar system.

• Jupiter and Saturn probably have rocky cores surrounded by a thick layer of liquid metallic hydrogen and an outer layer of ordinary liquid hydrogen. Both planets have an overall chemical composition very similar to that of the Sun.

• The visible features of Jupiter exist in the outermost 100 km of its atmosphere. Saturn has similar features, but they are much fainter. Three cloud layers exist in the upper atmospheres of both Jupiter and Saturn. Because Saturn's cloud layers extend through a greater range of altitudes, the colors of the Saturnian atmosphere appear muted.

• The colored ovals visible in the Jovian atmosphere represent gigantic storms, some of which (such as the Great Red Spot) are stable and persist for years or even centuries.

• Jupiter and Saturn have strong magnetic fields created by electric currents in the metallic hydrogen layer.

• Four large satellites orbit Jupiter. The two inner Galilean moons, Io and Europa, are roughly the same size as our Moon. The two outer moons, Ganymede and Callisto, are approximately the size of Mercury.

• Io is covered with a colorful layer of sulfur compounds deposited by frequent explosive eruptions from volcanic vents. Europa is covered with a smooth layer of frozen water crisscrossed by an intricate pattern of long cracks.

• The heavily cratered surface of Ganymede is composed of frozen water with large polygons of dark, ancient crust separated by regions of heavily grooved, lighter-colored, younger terrain. Callisto has a heavily cratered ancient crust of frozen water.

• Saturn is circled by a system of thin, broad rings lying in the plane of the planet's equator. Each major ring is composed of a great many narrow ringlets consisting of numerous fragments of ice and ice-coated rock. Jupiter has a much less substantial ring system.

Uranus and Neptune

• Uranus and Neptune are quite similar in appearance, mass, size, and chemical composition. Each has a rocky core probably surrounded by a dense, watery mantle; the axes of their magnetic fields are steeply inclined to their axes of rotation; and both planets are surrounded by systems of thin, dark rings.

• Uranus is unique in that its axis of rotation lies nearly in the plane of its orbit, producing greatly exaggerated seasons on the planet.

• Uranus has five moderate-sized satellites, the most bizarre of which is Miranda.

• The largest satellite of Neptune, Triton, is an icy world with a tenuous nitrogen atmosphere. Triton moves in a retrograde orbit that suggests it was captured into orbit by Neptune's gravity, and its orbit is spiraling down toward Neptune.

Pluto and Beyond

• Pluto, the smallest planet in the solar system, and its satellite, Charon, are icy worlds that may well resemble Triton.

• Other objects orbit the Sun beyond the orbit of Pluto. Hundreds of these Kuiper belt objects have been observed.

REVIEW QUESTIONS

1 Describe the appearance of Jupiter's atmosphere. Which features are long-lived and which are fleeting?

INTERACTIVE EXERCISE 7.1

2 To test your knowledge of Jupiter's belt and zone structure, do Interactive Exercise 7-1 on the CD-ROM or Web. You can print out your results, if required.

3 What causes the belts and zones in Jupiter's atmosphere?

INTERACTIVE EXERCISE 7.2

4 To test your knowledge of Jupiter's internal structure, do Interactive Exercise 7-2 on the CD-ROM or Web. You can print out your results, if required.

5 What is liquid metallic hydrogen? Which planets appear to contain this substance? What produces this form of hydrogen?

6 Compare and contrast the surface features of the four Galilean satellites, discussing their geologic activity and their evolution.

INTERACTIVE EXERCISE 7.3

7 To test your knowledge of the Galilean Moons, do Interactive Exercise 7-3 on the CD-ROM or Web. You can print out your results, if required.

8 What energy source powers Io's volcanoes?

9 Why are numerous impact craters found on Ganymede and Callisto but not on Io or Europa?

10 Describe the structure of Saturn's rings. What are they made of?

INTERACTIVE EXERCISE 7.4

11 To test your knowledge of Saturn's rings, do Interactive Exercise 7-4 on the CD-ROM or Web. You can print out your results, if required.

12 Why do features in Saturn's atmosphere appear to be much fainter and "washed out" compared with features in Jupiter's atmosphere?

13 Explain how shepherd satellites operate. Is "shepherd satellite" an appropriate term for these objects? Explain.

14 Describe Titan's atmosphere. What effect has sunlight presumably had on Titan's atmosphere?

15 Describe the seasons on Uranus. Why are the Uranian seasons different from those on any other planet?

16 Briefly describe the evidence supporting the idea that Uranus was struck by a large planetlike object several billion years ago.

17 Why are Uranus and Neptune distinctly bluer than Jupiter and Saturn?

18 Compare the ring systems of Saturn and Uranus. Why were Uranus's rings unnoticed until the 1970s?

19 How do the orientations of Uranus's and Neptune's magnetic axes differ from those of the other planets?

INTERACTIVE EXERCISE 7.5

20 To test your knowledge of planetary magnetic fields, do Interactive Exercise 7-5 on the CD-ROM or Web. You can print out your results, if required.

21 Suppose you were standing on Pluto. Describe the motions of Charon relative to the horizon. Under what circumstances would you never see Charon?

22 Describe the circumstantial evidence supporting the idea that Pluto is one of a thousand similar icy worlds that once occupied the outer regions of the solar system.

23 Explain why Triton will never collide with Neptune, even though Triton is spiraling toward that planet.

24 The discovery of Pluto's moon, Charon, could have been made decades before it actually was. What caused the delay?

ADVANCED QUESTIONS

25 Consult the Internet or such magazines as *Sky & Telescope* or *Astronomy* to determine what space missions are now under way. What data and pictures have they sent back that update information presented in this chapter?

26 Long before the *Voyager* flybys, Earth-based astronomers reported that Io appeared brighter than usual for a few hours after emerging from Jupiter's shadow. From what we know about the material ejected from Io's volcanoes, explain this brief brightening of Io.

27 Compare and contrast Valhalla on Callisto with the Caloris Basin on Mercury.

28 Can we infer from naked-eye observations that Saturn is the most distant of the planets visible without a telescope? Explain.

29 As seen by Earth-based observers, the intervals between successive edge-on presentations of Saturn's rings alternate between 13 years 9 months and 15 years 9 months. Why are these two intervals not equal?

30 Compare and contrast the internal structures of Jupiter and Saturn with the internal structures of Uranus and Neptune. Can you propose an explanation for why the differences between these two pairs of planets occurred?

31 Neptune has the third largest mass of all the planets, but Uranus has the third largest diameter. Reconcile these two facts.

DISCUSSION QUESTIONS

32 Suppose that you were planning a mission to Jupiter employing an airplanelike vehicle that would spend many days, even months, flying through the Jovian clouds. What observations, measurements, and analyses should this aircraft make? What dangers might it encounter, and what design problems would you have to overcome?

33 Discuss the possibility that Europa, Ganymede, or Callisto might harbor some sort of marine life.

34 Suppose you were planning separate missions to each of Jupiter's Galilean moons. What questions would you want these missions to answer, and what kinds of data would you want your spacecraft to send back? Given the different environments on the four satellites, how would the designs of the four spacecraft differ?

35 NASA and the Jet Propulsion Laboratory have tentative plans to place spacecraft in orbit about Uranus and Neptune in this century. What kinds of data should be collected and what questions would you like to see answered by these missions?

36 Would you expect the surfaces of Pluto and Charon to be heavily cratered? Explain.

WHAT IF ...

37 Jupiter, at its present location, were a star? What would Earth be like? *Hint:* Recall that to be a star, Jupiter would have to have 75 times more mass than it has today.

38 Jupiter had formed at one-third its present distance of 5.2 AU from the Sun? What would Earth be like?

39 Io were struck by another object of similar size? *Hint:* You can create a variety of different scenarios by imagining the impacting body striking from different directions and with different speeds and at different angles.

40 Jupiter were orbiting in the opposite direction that it actually is? What effects might this have on the other planets? Would this change affect Earth? If so, how?

WEB/CD-ROM QUESTIONS

VIDEO 7.2

41 **Moving Weather Systems on Jupiter** Access and view the video "The Great Red Spot" in Chapter 7 of the *Discovering the Universe* Web site or CD-ROM. (a) Near the bottom of the video window you will see a white oval moving from left to right. By stepping through the video one frame at a time, estimate how long it takes this oval to move a distance equal to its horizontal dimension. (*Hint:* You can keep track of time by noticing how many frames it takes a feature in the Great Red Spot, at the center of the video window, to move in a complete circle around the center of the spot. The actual time for this feature to complete a circle is about six days.) (b) The horizontal dimension of the white oval is about 4000 km. At what approximate speed (in km/hr) does the white oval move? (Speed = distance/time).

42 Search the Web, especially the Web sites at NASA's Jet Propulsion Laboratory and the European Space Agency, for information about the current status of the *Cassini* mission. When will *Cassini* arrive at Saturn? What are the current plans for its tour of Saturn's satellites? What ideas are being considered for the *Cassini* extended mission, to begin in 2008?

43 In 2000, astronomers reported the discovery of several new moons of Saturn. Search the Web for information about these. How did astronomers discover them? Have the observations been confirmed? How large are these moons? What sort of orbits do they follow?

44 **The Rotation Rate of Saturn** Access and view the video "Saturn from the Hubble Space Telescope" in Chapter 7 of the *Discovering the Universe* Web site or CD-ROM. The total time that actually elapses in this video is 42.6 hours. Using this information, identify and follow an atmospheric feature and determine the rotation period of Saturn.

45 The discovery of Charon, Figure 7-42, was made by an astronomer at the U.S. Naval Observatory. Search the Web to find out why the U.S. Navy carries out work in astronomy.

OBSERVING PROJECTS

46 Consult such magazines as *Sky & Telescope* and *Astronomy* or your *Starry Night Backyard*™ software to determine whether Jupiter is currently visible in the night sky. If so, make arrangements to view the planet through a telescope. What magnifying power seems to give you the best view? Draw a picture of what you see. Can you see any belts and zones? How many? Can you see the Great Red Spot?

47 Make arrangements to view Jupiter's Great Red Spot through a telescope. Consult the *Sky & Telescope* Web site, which lists the times when the center of the Great Red Spot passes across Jupiter's central region, as seen from Earth. The Great Red Spot is well placed for viewing for 50 minutes before and after this time. You will need a refractor with an objective lens of at least 15 cm (6 in.) diameter or a reflector with an objective of at least 20 cm (8 in.) diameter. Using a pale blue or green filter can increase the color contrast and make the spot more visible. For other useful hints, see the article, "Tracking Jupiter's Great Red Spot" by Alan MacRobert (*Sky & Telescope*, September 1997). Sketch Jupiter based on your observations.

48 If it is visible at night, observe Jupiter through a pair of binoculars or telescope. Can you see all four Galilean moons? Make a drawing of what you observe. To identify the moons, use *Starry Night Backyard*™. Start by going to Atlas mode (*Go/Atlas*). Then locate Jupiter (*Edit/Find/Jupiter*). Zoom out to 30' angle. You should be able to see all the moons labeled in their present positions (be sure that the time is *not* changing). Compare the locations of the moons on the screen with your observations to determine which ones you are seeing.

49 Use *Starry Night Backyard*™ to observe the motion of the Galilean moons of Jupiter. First go to Atlas mode (*Go/Atlas*). Lock on Jupiter (*Edit/Find/Jupiter*) and zoom out to 30' angle. Set the timestep to 1 hour and click the ▶ button. You will see the four Galilean moons orbiting Jupiter. (a) Are all four moons ever on the same side of Jupiter? (b) Observe the moons passing in front of and behind Jupiter (zoom in as needed). Explain how your observations tell you that all four satellites orbit Jupiter in the same direction.

50 Consult such magazines as *Sky & Telescope* and *Astronomy* or your *Starry Night Backyard*™ software to determine whether Saturn is currently visible in the night sky. If so, view Saturn through a small telescope. Make a sketch of what you see. Estimate the angle at which the rings are tilted to your line of sight. Can you see the Cassini division? Can you see any belts or zones in Saturn's clouds? Do you observe a faint, starlike object near Saturn that might be Titan? What observations could you perform to test whether the starlike object is a Saturnian satellite?

51 Use the *Starry Night Backyard*™ program to observe the changing appearance of Saturn. First go to Atlas mode (*Go/Atlas*) and then find Saturn (*Edit/Find/Saturn*). Zoom in until Saturn nearly fills the screen. Set the timestep to 1 year. Use the single-step time control buttons to observe the changing aspect or orientation of the rings. During which of the next 30 years will we see the rings edge-on?

52 Determine whether Uranus or Neptune is currently visible in the night sky. If so, make arrangements to view them through a telescope. To help you find these planets, use your *Starry Night Backyard*™ software or the star chart published each January in *Sky & Telescope* showing the paths of Uranus and Neptune against the background stars. For more detailed images than you can get through a telescope, locate these planets with your *Starry Night Backyard*™ software and zoom to high resolution. Also, locate Triton with the software.

53 Use the *Starry Night Backyard*™ program to observe Pluto and Charon. First go to Atlas mode (*Go/Atlas*) and find Pluto (*Edit/Find/Pluto*). Zoom in as close as possible. Select Planet List in the Window menu and click on the triangle to the left of the name Pluto. Then, in the "Orbit" column on the right-hand side of the Planet List, click to the right of the name Charon. A mark will appear in this column and Charon's orbit will appear in the main window. In the Control Panel, set the timestep to 3 hours. (a) Use the single-step time button to step through enough time to determine the period of Charon's orbit. How does your answer compare with Pluto's sidereal rotation period given in Figure 7-41? Explain. (b) What is the apparent shape of Charon's orbit around Pluto? How can you reconcile this with the fact that Charon's actual orbit is nearly a perfect circle?

WHAT IF . . .

WE LIVED ON A METAL-POOR EARTH?

Earth provides a wealth of building blocks necessary for the development and evolution of complex life-forms. More than 80 elements on or near Earth's surface combine in countless ways essential for its diversity of flora and fauna. Especially important for life on Earth are metals such as iron. The human body typically contains more than 3 grams of iron, mostly in the form of hemoglobin that helps transport oxygen through the bloodstream. A slight iron imbalance leads to anemia or toxicity. And without abundant metals, most of our technologies would never have developed.

But what if the solar system formed from an interstellar gas cloud containing fewer metals and high-mass elements, that is, a solar system with less iron, nickel, copper, and other metals crucial for life as we know it?

Metal-Rich versus Metal-Poor Earth formed with almost 6×10^{21} metric tons of star matter, almost one-third of it iron. If the solar system formed from interstellar gas containing relatively few heavy elements, Earth would contain a much lower fraction of such elements as uranium, lead, iron, and nickel. The Earth would be comprised of a correspondingly higher fraction of lower-mass elements, such as carbon, nitrogen, oxygen, silicon, and aluminum. That version of Earth—let's call it Lithia—would be profoundly different from our planet.

The Environment of Lithia Without heavy elements like iron, Lithia's density, gravity, and magnetic fields are much lower than Earth's. Let's assume that the density of Lithia is similar to that of the Moon. (We'll assume that the Moon doesn't change in its characteristics or its distance from Lithia.)

If Lithia has the same radius as Earth, the force of gravity on Lithia's surface is only 60% that on Earth. That is, you would weigh 40% less on Lithia. Mobile life-forms that evolve on the metal-poor planet require much less muscle strength to get about and less bone density to resist the planet's gravity.

With few radioactive elements to provide heat, the core of Lithia cooled off quickly compared with the core of Earth. As a result, Lithia has much less heat flowing upward through its mantle and crust, so there most likely is no plate tectonic activity. Lithia also has less volcanic activity. But without plate motion to spread the lava flows, volcanoes will grow to higher elevations than on Earth. The lack of crustal motions also means that pockets of high-density material will not rise from below, forming the metal ores mined on Earth.

The Moon's orbit and the tides it induces are different, too. With Lithia having 60% of Earth's mass, the Moon at its present distance orbits once every 36 days instead of once every 29.5 days. Thus, the cycle of lunar phases is longer, but the cycle of lunar-induced tides is slightly shorter. Surprisingly, the tides have roughly the same height, because the tidal effects depend only on the Moon's gravity and not Earth's, and the distance between Earth and Lithia and their satellite is the same.

Life on Lithia The low abundance of iron and the resulting lack of a planetary magnetic field might preclude the development of complex life-forms on Lithia. And yet, the incredible diversity of life we find on Earth suggests that evolution on Lithia might well occur. If advanced life-forms evolve on Lithia before the Sun uses up its nuclear fuel and becomes a red giant, the chemical differences between Lithia and Earth dictate that they will differ profoundly from the complex life we find on Earth.

Without the heat of radioactive elements to keep Lithia's core molten for billions of years and with fewer metals, Lithia will have a much weaker magnetic field—if any at all—than Earth. Inhabitants can expect auroras to grace the night sky continuously. On the other hand, high-energy particles and the radiation they create in the atmosphere will bombard any life-forms on the surface continuously and will also adversely affect the ozone layer. A larger amount of the Sun's harmful ultraviolet radiation will reach the surface. Without more protection, life as we know it could not survive.

A Barren Landscape With a thin atmosphere and an abundance of lighter elements such as silicon (silicon dioxide is sand), Lithia might resemble a barren desert here on Earth. (Photri)