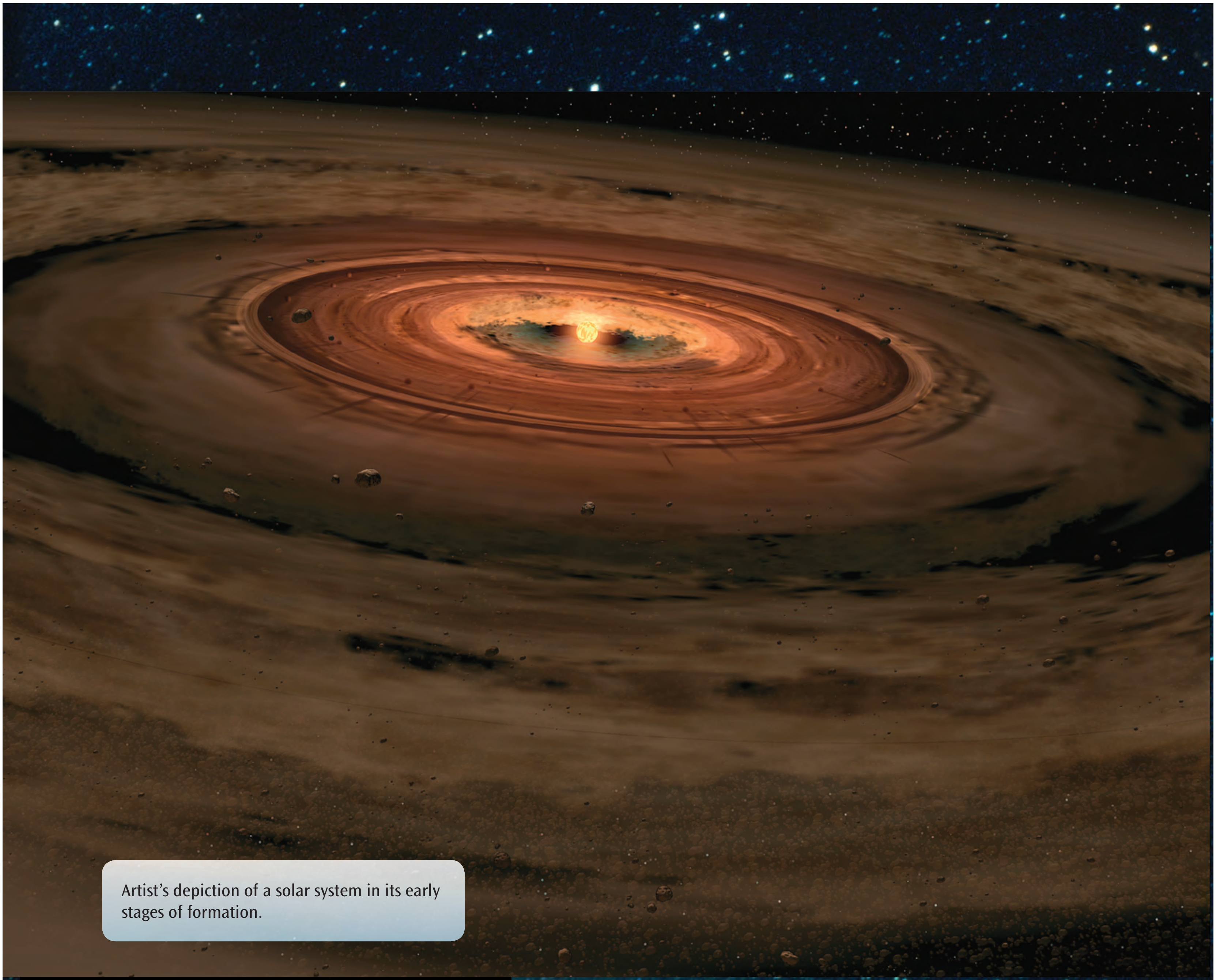


Artist's depiction of a solar system in its early stages of formation.

KEY CONCEPTS

- The Solar System consists of the Sun, the eight planets, their moons, and smaller objects (such as dwarf planets, asteroids, and comets).
- The planets orbit the Sun within a flat disk-shaped region, held there by the Sun's gravity.
- The planets form two families:
  - The four inner planets (Mercury, Venus, Earth, and Mars) are rocky with iron cores and are similar to the Earth in size.
  - The four outer planets (Jupiter, Saturn, Uranus, and Neptune) are much larger than the Earth and are balls of gas and liquid, rich in hydrogen and its compounds.
- Pluto, which fits into neither family, is now considered a dwarf planet. It and a number of similar small icy objects orbit beyond Neptune.
- The Solar System formed about 4.6 billion years ago from an interstellar gas cloud that collapsed and shrank under the force of its own gravity.
- Rotation of the cloud made it flatten into a disk.
- Within the disk, gravity drew dust and gas into clumps that became the planets.
- Hundreds of planets around other stars have been detected.
- The patterns of these other planetary systems look quite different from the Solar System, but the techniques used to find *exoplanets* are not yet sensitive enough to detect systems like the Solar System.
- Some giant exoplanets orbit so close to their stars that they must have "migrated" to these positions—a process now thought to have been important in the young Solar System.

8

Survey of Solar Systems

CONCEPTS AND SKILLS TO REVIEW

- Law of gravity (3.4)
- Density (6.1)
- Modified form of Kepler's third law (3.6)

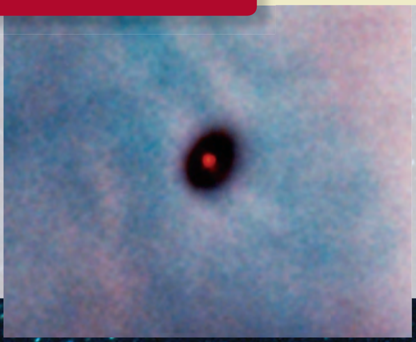
The Solar System consists of the Sun and the bodies in its gravitational domain: the eight planets, dozens of dwarf planets, and swarms of moons, asteroids and comets. Although earthlings have not walked on any objects except the Earth and Moon, we have detailed pictures sent to us from spacecraft of most of the planets and their satellites. Some are naked spheres of rock; others are mostly ice. Some have thin, frigid atmospheres so cold that ordinary gases crystallize as snow on their cratered surfaces; others have thick atmospheres the consistency of wet cement and no solid surface at all. Despite such diversity, the Solar System possesses an underlying order, an order from which astronomers attempt to read the story of how our Solar System came to be.

The Solar System formed in the extremely remote past, about 4.6 billion years ago. Astronomers hypothesize that the Sun and planets formed from the collapse of a huge, slowly spinning cloud of gas and dust. Most of the cloud's material fell inward and ended up in the Sun, but in response to rotation, some settled into a swirling disk around it. Then, within that disk, dust particles coagulated—perhaps aided by electrostatic effects such as those that make lint cling to your clothes—to form pebble-size chunks of material, which in turn collided and sometimes stuck together, growing ever larger to become the planets we see today. The objects that formed in the disk retained the motion of the original gas and dust, and so we see them today, moving in a flattened system, all orbiting the Sun in the same direction.

Seeing planets around other stars is much more challenging—something like trying to see a mosquito flying around a light bulb hundreds of miles away. However, astronomers have developed an array of techniques that have revealed hundreds of planets around other stars. Astronomers can even observe other "solar systems" in their first stages of formation. The other systems detected so far look very different from our own, challenging astronomers' understanding of how solar systems form.

In this chapter, we will survey the general properties of our Solar System and others. In later chapters we will explore the components of our Solar System in much more detail.

Q: WHAT IS THIS? See end of chapter for the answer



8.1 Components of the Solar System

The Sun

The Sun is a star, a ball of incandescent gas (fig. 8.1) whose light and heat are generated by nuclear reactions in its core. It is by far the largest body in the Solar System—more than 700 times the mass of all the other bodies put together—and its gravitational force holds the planets and other bodies in the system in their orbital patterns about it. This gravitational domination of the planets by the Sun justifies our calling the Sun's family the **Solar System.**

The Sun is mostly hydrogen (about 71%) and helium (about 27%), but it also contains very small proportions of nearly all the other chemical elements (carbon, iron, uranium, and so forth) in vaporized form, as we can tell from the spectrum of the light it emits.

The Orbits and Spins of the Planets

The planets are much smaller than the Sun and orbit about it. They emit no visible light of their own but shine by reflected sunlight. In order of increasing distance from the Sun, they are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. The planets move around the Sun in approximately circular* orbits all lying in nearly the same plane, as shown in the view from above in figure 8.2 and the side view in figure 8.3. Thus, the Solar System is like a spinning pancake, with the planets traveling around the Sun in the same direction: counterclockwise, as seen from above the Earth's

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*The circularity of the orbits is only approximate, because we know from Kepler's laws that in reality the orbits are ellipses. However, the amount of ellipticity is, in general, very small.

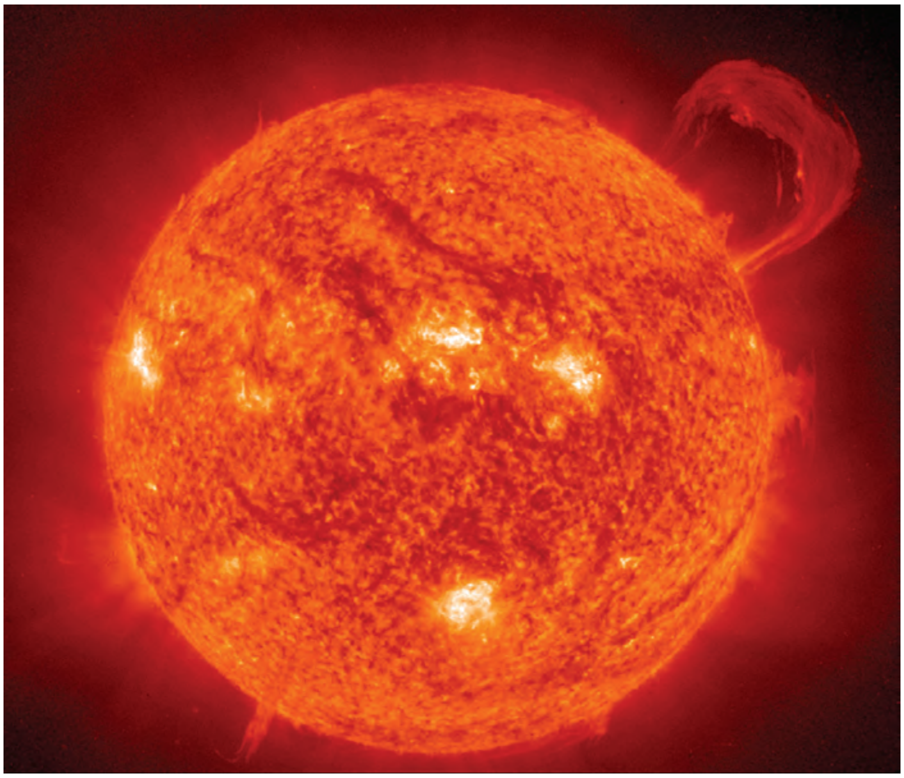

FIGURE 8.1
Image of the Sun made with an ultraviolet telescope that reveals high-temperature gases in the Sun's atmosphere.

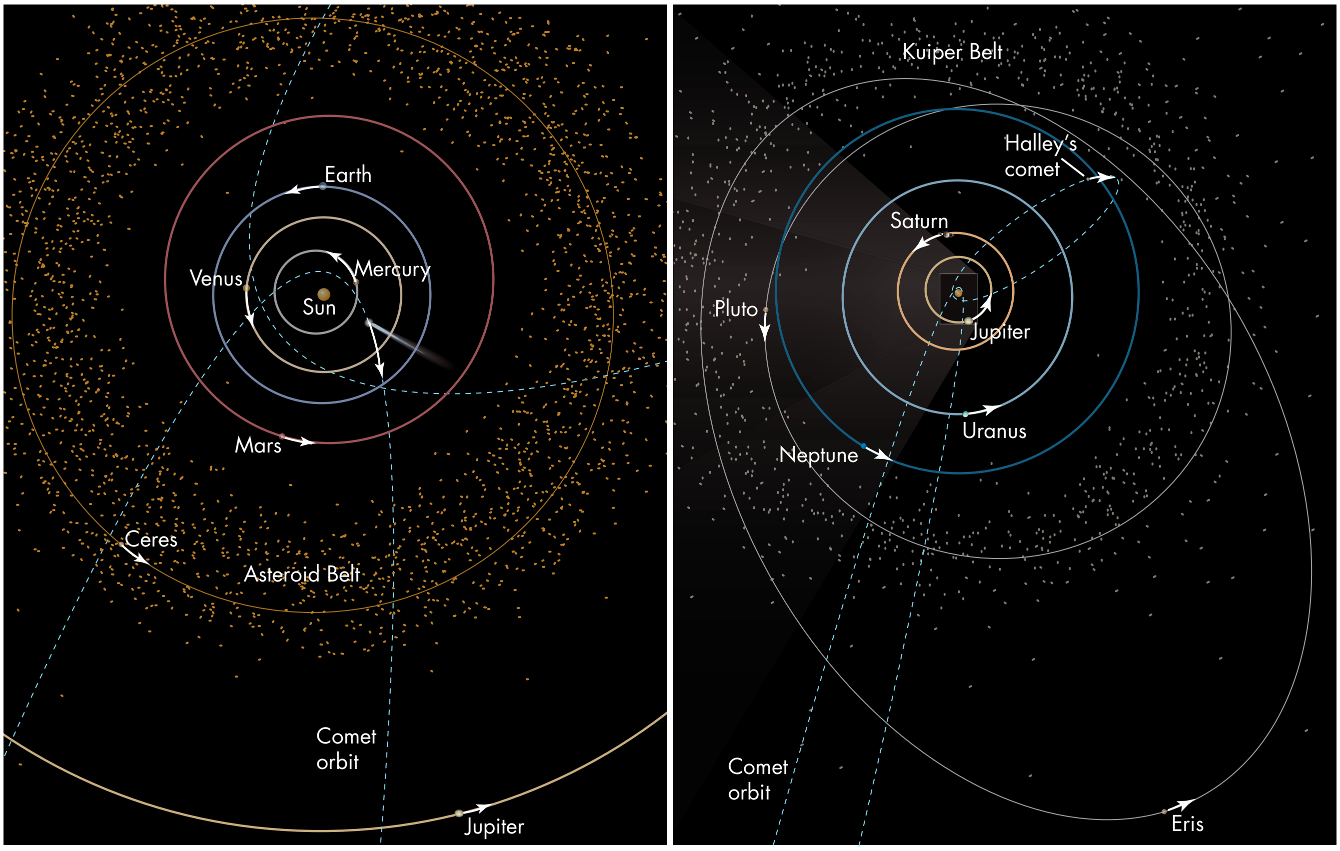

FIGURE 8.2
Diagrams of the Solar System from above. The orbits are shown in the correct relative scale in the two drawings. Because of the great difference in scale, the inner and outer Solar System are displayed separately.

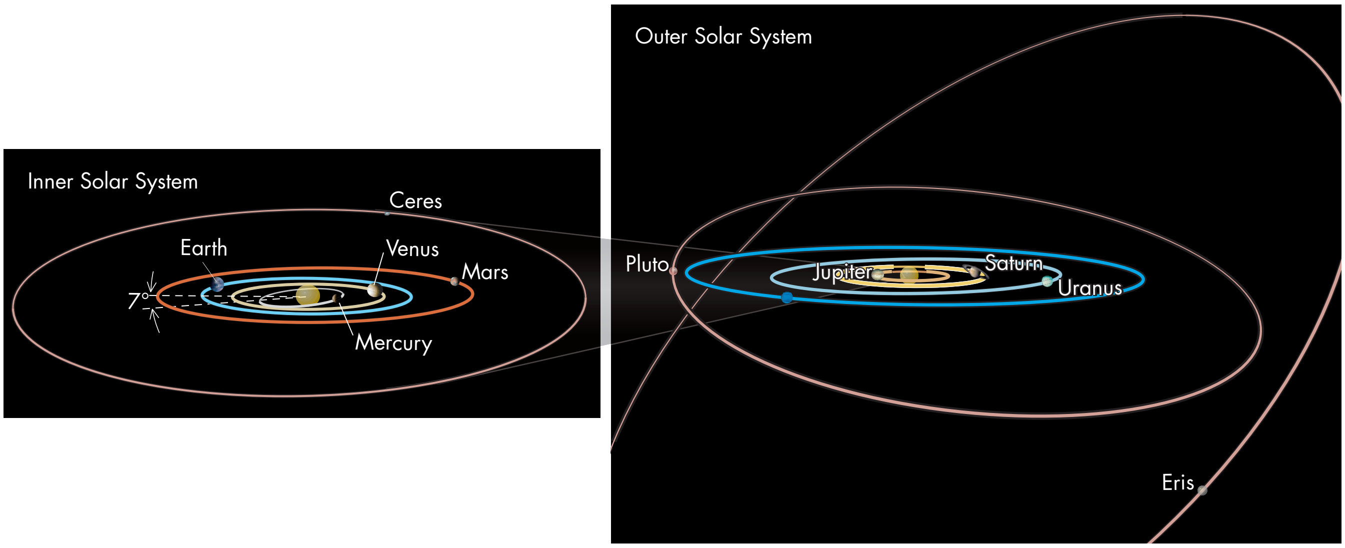

FIGURE 8.3
The planets' orbits from the side. The dwarf planets Ceres, Pluto, and Eris are also shown, illustrating their highly inclined orbits.

North Pole. We can see this flatness from Earth: it makes the planets all lie in an approximate line in the sky (fig. 8.4).

As the planets orbit the Sun, each also spins on its rotation axis. The spin is generally in the same direction as the planets' orbital motion around the Sun (again, counterclockwise, as seen from above the Earth's North Pole), and the tilt of the rotation axes relative to the plane of planetary orbits is generally not far from the perpendicular. However, there are two exceptions: Venus and Uranus. Uranus has an extremely large tilt to its rotation axis, which lies nearly in its orbital plane (fig. 8.5). Venus's rotation axis has such a large tilt that it spins backward, a motion technically called "retrograde rotation." However, despite this backward spin, Venus orbits the Sun in the same direction as the rest of the planets.

Its flattened structure, and the orderly orbital and spin properties of its planets, are two of the most fundamental features of the Solar System, and any theory of the Solar System must explain them. But a third and equally important feature is that the planets fall into two families called inner and outer planets based on their size, composition, and location in the Solar System.

The Solar System out to Neptune has about the same relative thickness as 3 CDs stacked together.

Two Types of Planets

The **inner planets**—Mercury, Venus, Earth, and Mars—are small rocky bodies with relatively thin or no atmospheres. The **outer planets**—Jupiter, Saturn, Uranus, and Neptune—are gaseous and liquid. They are much larger than the inner planets and have deep, hydrogen-rich atmospheres. For example, Jupiter is more than 10 times larger in diameter than the Earth and has 318 times its mass. These differences can be seen in figure 8.6, which also shows a small part of the edge of the Sun to illustrate how the Sun dwarfs even the large planets.

In describing the planets, we have used the terms *rock* and *ice*. By rock, we mean material composed of silicates, which are composed of silicon (Si) and oxygen (O) with an admixture of other heavy elements such as aluminum (Al), magnesium (Mg), sulfur (S), and iron (Fe). By ice, we mean frozen liquids and gases such as ordinary water ice (H_2O), frozen carbon dioxide (CO_2), frozen ammonia (NH_3), frozen methane (CH_4), and so on. If we consider the Solar System as a whole, rock is rare, because the silicon atoms that compose it are outnumbered more than 25,000 to 1 by hydrogen. However, in the warmth of the inner Solar System, rock dominates because intrinsically more abundant materials such as hydrogen, water, methane, and ammonia cannot condense to mingle with it. Thus, the inner planets are composed mainly of rock.

The outer planets have no true "surface"; rather, their atmospheres thicken with depth and eventually compress to liquid form despite high temperatures. They have no distinct boundary between "atmosphere" and "crust" as we have on the Earth. In the deep interior, the liquid may be compressed into a solid, as happens in the Earth's inner core, but the transition from liquid to solid is also probably not sharply defined. Thus, we can never "land" on Jupiter because we would simply sink ever deeper into its interior. By contrast, the inner planets have at most a thin layer of gas over their solid surface, and the least massive have too little gravity to retain any atmosphere at all.

Instead of "inner" and "outer" planets, astronomers sometimes use "terrestrial" and "Jovian" to describe the two types of planets. The **terrestrial planets** (Mercury to Mars) are so named because of their resemblance to the Earth. The **Jovian planets*** (Jupiter to Neptune) are named for their resemblance to Jupiter.

FIGURE 8.4
Sunset view of four planets strung along the zodiac on March 1, 1999. Their straight-line arrangement results from the flatness of the Solar System. From top to bottom, you can see Saturn, Venus, Jupiter, and Mercury (nearly lost in the twilight).

Although the two categories of planets neatly describe the larger objects that orbit the Sun, astronomers have found many smaller objects that fit neither category. Pluto has long failed to fit, because of its small size, composition of ice and rock, and odd orbit. (Not only is its orbit highly tilted with respect to the other planets, it also crosses Neptune's orbit). Moreover, in the last decade astronomers have discovered more than a

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*Some astronomers go further and divide the Jovian planets into *gas giants* (Jupiter and Saturn) and *ice giants* (Uranus and Neptune).

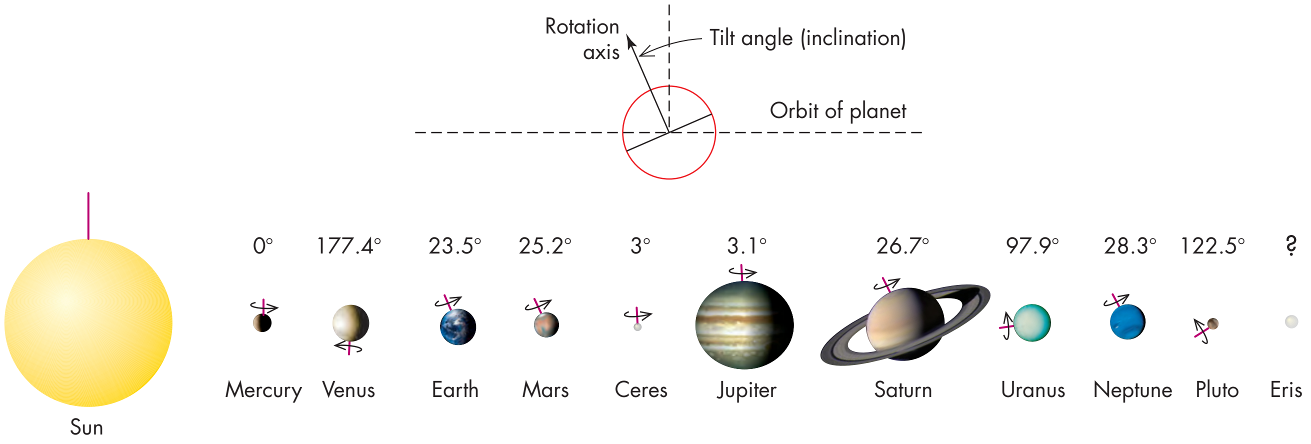

FIGURE 8.5
Sketches showing the orientation of the rotation axes of the planets and Sun. The figure illustrates that most of them spin in the same direction, counterclockwise as seen from above the Earth's North Pole. The dwarf planets Ceres, Pluto, and Eris are also shown. The bodies are not shown to the same scale.

thousand icy objects orbiting at similar distances from the Sun as Pluto. In 2005 it was discovered that one of these objects, named Eris, is an icy world slightly *larger* than Pluto that orbits about 68 AU from the Sun, roughly half again Pluto's distance from our star.

In response to the discovery of Eris and half a dozen other objects similar in size to Pluto, the International Astronomical Union introduced in 2006 a new category of Solar System objects called **dwarf planets.** Dwarf planets are objects that orbit the Sun, are massive enough that their gravity compresses them into an approximately spherical shape, but have not swept their orbital region clear of other objects that add up to a comparable mass as the planet. To recognize Pluto's important place in the history of the discovery of these objects, astronomers decided in 2008 to call dwarf planets that orbit beyond Neptune *plutoids*.

Satellites

As the planets orbit the Sun, most are themselves orbited by satellites. Jupiter, Saturn, Uranus, and Neptune have large families of 63, 60, 27, and 13 clearly identified moons, respectively.* Mars has 2, Earth has 1, while Venus and Mercury have none. Even some of the dwarf planets have moons. Pluto has 3 and Eris has 1.

The larger moons generally move along approximately circular paths that are roughly in the planet's equatorial plane, their orbits tilted like the planets themselves. Thus, each planet and its moons resemble a miniature Solar System—an important clue to the origin of these satellites. Some large moons and many of the smaller moons have much more irregular orbits, suggesting that they may have been captured.

Asteroids and Comets

Asteroids and comets are far smaller than planetary bodies. The **asteroids** are rocky or metallic bodies with diameters that range from a few meters up to about 1000 km (about one-tenth the size of the Earth). The **comets,** on the other hand, are icy bodies about 10 km (about 6 miles) or less in diameter that grow huge tails of gas and dust as they near the Sun and are partially vaporized by its heat. Thus, these minor bodies exhibit the same split into two families that we see for the planets; that is, rocky bodies and icy bodies.

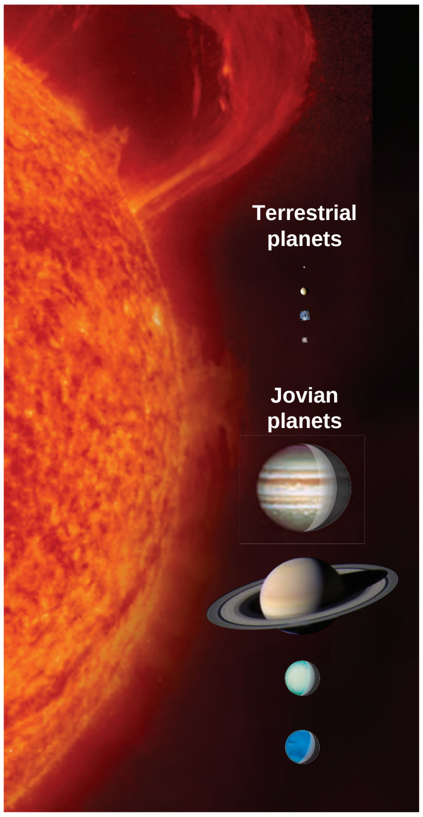

FIGURE 8.6
The planets and the Sun to scale.

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*Astronomers are finding new moons around these planets so rapidly that it is difficult to keep the numbers up-to-date. Most of the new discoveries are of very small bodies, sometimes just a few kilometers in diameter.

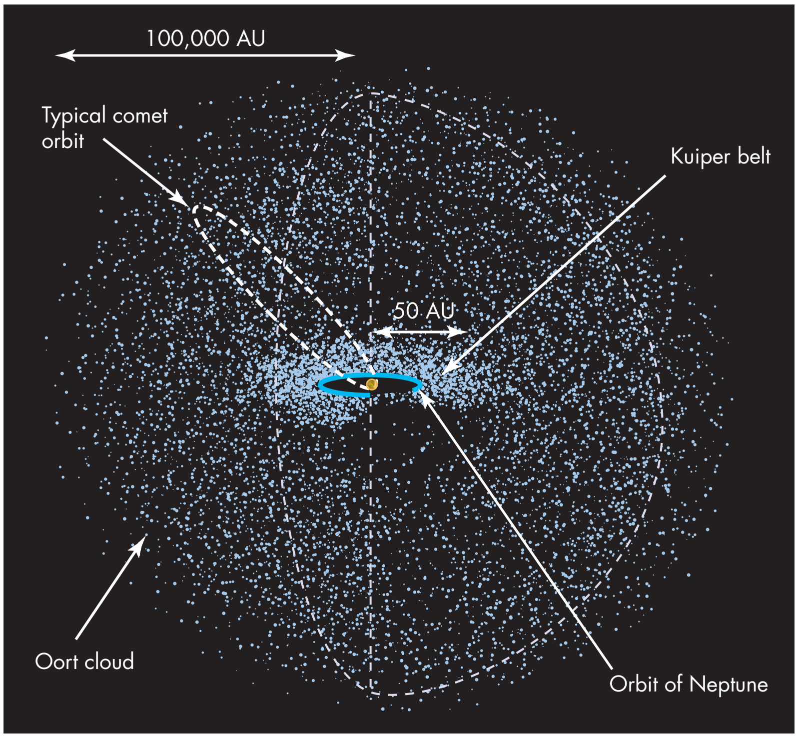

FIGURE 8.7
Sketch of the Oort cloud and the Kuiper belt. The scale shown is only approximate. Orbits and bodies are not to scale.

Asteroids and comets differ not only in their composition but also in their location within the Solar System. Most asteroids circle the Sun in the large gap between the orbits of Mars and Jupiter, a region called the **asteroid belt.** They are probably material that failed—perhaps as a result of disturbance by Jupiter's gravity—to aggregate into a planet.* Most comets, on the other hand, orbit far beyond Neptune in a region of the Solar System called the Oort cloud, and only rarely do they move into the inner Solar System.

The **Oort cloud,** named for the Dutch astronomer who proposed its existence, is thought to be a spherical region that completely surrounds the Solar System and extends from about 40,000 to 100,000 AU from the Sun (fig. 8.7). Although the majority of comets probably originate in the Oort cloud, some come from a disklike swarm of icy objects that lies just beyond the orbit of Neptune and extends to perhaps 50 AU from the Sun, a region called the **Kuiper belt.** We will discuss more details of the Oort cloud and Kuiper belt in chapter 11, but for now we simply note that together they probably contain more than 1 trillion (10^{12}) comet nuclei, thousands of larger objects, and several dozen dwarf planets, including Pluto.

ANIMATION
Oort cloud and Kuiper belt

Composition Differences Between the Inner and Outer Planets

We stated earlier that the inner planets are rocky and the outer planets are hydrogen-rich. These composition differences are so important to our understanding of the history of the Solar System that we should look at them more closely and see how we determine them.

Astronomers can deduce a planet's composition in several ways. From its spectrum, they can measure its atmospheric composition and get some information about the nature of its surface rocks. However, spectra give no clue as to what lies deep inside a planet where light cannot penetrate. To learn about the interior, astronomers must therefore use alternative methods.

We saw in chapter 6 how earthquake waves reveal what lies inside the Earth, but this method has not yet been used for other planets. Although quake detectors were landed on Mars, they did not work properly, and such detectors would require very special modification to work on the Jovian planets, which have no surface on which to land! Thus, we must try other means to study the interior of planets. One such technique uses the planet's density.

Density as a Measure of a Planet's Composition

The average density of a planet is its mass divided by its volume. Both of these quantities can be measured relatively easily. For example, we showed in chapter 3 how to determine a body's mass from its gravitational attraction on a second body orbiting around it by applying Newton's modification of Kepler's third law. Thus, from this law,

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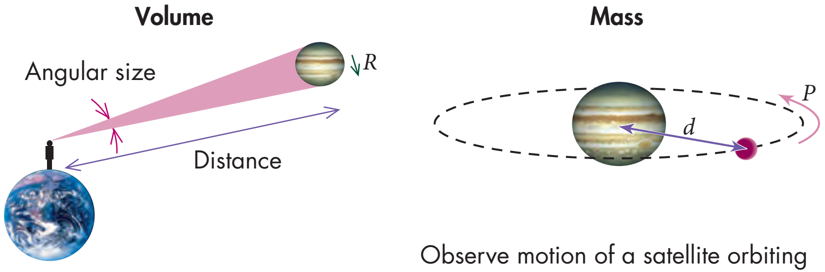
*A regular pattern of increasing spacing between planets suggested the existence of a body between Mars and Jupiter. See the Extending Our Reach box on p. 213.



Measure angular size of planet, and use relation between angular size and distance to solve for planet's radius, R. Calculate volume, $\mathcal{V}$, of planet:

$$\mathcal{V} = \frac{4\pi R^3}{3}$$

for a spherical body of radius R.

Observe motion of a satellite orbiting planet. Determine satellite's distance, d, from planet and orbital period, P. Use Newton's form of Kepler's third law:

$$M = \frac{4\pi^2 d^3}{GP^2}$$

Insert measured values of d and P, and value of constant G. Solve for M.

Average Density

Average density, ρ, equals mass, M, divided by volume, $\mathcal{V}$:

$$\rho = \frac{M}{\mathcal{V}}$$

FIGURE 8.8
Measuring a planet's mass, radius, and average density. Volume can be determined from the radius of a planet, which in turn is found from its distance and angular size (chapter 2). Mass can be determined from the orbit of a satellite (chapter 3).

Q. Suppose you are given a tiny box that has a volume of 10 cubic centimeters and a mass of 30 grams. What is its density? Is it more likely to contain solid iron or rock?

we can calculate a planet's mass by observing the orbital motion of one of its moons or a passing spacecraft. We can determine a planet's volume ($\mathcal{V}$) from the formula $\mathcal{V} = 4\pi R^3/3$, where R is the planet's radius. We can measure R in several ways—for example, from its angular size and distance, a technique we used in chapter 2 to measure the radius of the Moon. With the planet's mass, M, and volume, $\mathcal{V}$, known, we can calculate its average density straightforwardly by dividing M by $\mathcal{V}$ (fig. 8.8).

Once the planet's average density is known, we can compare it with the density of abundant, candidate materials to find a likely match. For example, we saw in chapter 6 that the average density of the Earth (5.5 grams per cubic centimeter) was intermediate between silicate rock (about 3 grams per cubic centimeter) and iron (7.9 grams per cubic centimeter). Therefore, we inferred that the Earth has an iron core beneath its rocky crust, a supposition that was verified from studies using earthquake waves.

Although density comparison is a powerful tool for studying planetary composition, it also has drawbacks. First, there may be several different substances that will produce an equally good match to the observed density. Second, the density of a given material can be affected by the planet's gravitational force. For example, a massive planet may crush rock whose normal density is 3 grams per cubic centimeter to a density of 7 or 8 grams per cubic centimeter. Thus, in making a match to determine the composition, we must take into account compression by gravity.

All the terrestrial planets have an average density similar to the Earth's (3.9 to 5.5 grams per cm^3). On the other hand, all the Jovian planets have a much smaller average density (0.7 to 1.7 grams per cm^3), similar to that of ice. After correcting for the above gravitational compression, we conclude that all the inner planets contain large amounts of rock and iron and that the iron has sunk to the core, as shown in figure 8.9. Likewise, the outer planets contain mainly light materials, as borne out by their spectra, which show them to be mostly hydrogen, helium, and hydrogen-rich material such as methane (CH_4), ammonia (NH_3), and water (H_2O).

The outer planets probably have cores of iron and rock about the size of the Earth beneath their deep atmosphere, as illustrated in figure 8.9. Astronomers deduce the existence of these cores in two ways. First, if the outer planets have the same relative amount of heavy elements as the Sun, they should contain several Earth masses of iron and silicates, and because these substances are much denser than hydrogen, they must sink to the planet's core. Secondly, detailed analyses of these planets' gravitational fields, determined from their effect on space probes, are best explained by dense cores. In the case

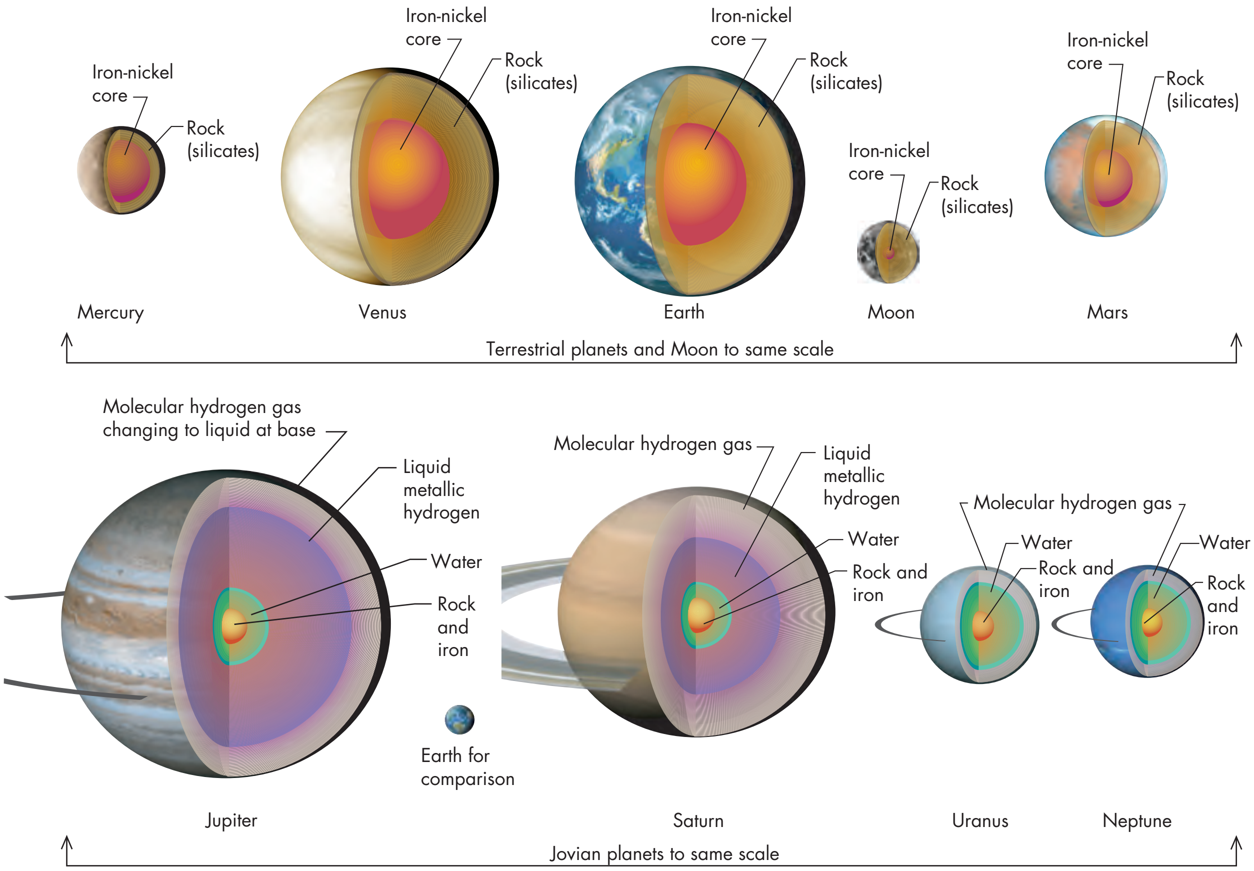


FIGURE 8.9
Sketches of the interiors of the planets. Details of sizes and composition of inner regions are uncertain for many of the planets.

of Jupiter, a core of about 7 times the Earth mass is estimated. However, there is a large uncertainty in the exact value, with some recent models estimating twice as much.

Our discussion of the composition of the planets not only underlines the differences between the two families of planets but also furnishes another clue to their origin: the planets and Sun were all made from the same material. Astronomers come to this conclusion because Jupiter and Saturn have a composition almost identical to that of the Sun, and the inner planets have a similar composition *if we were to remove the Sun's hydrogen and helium.** Thus, we can explain the compositional difference between the inner and outer planets by proposing a process that would keep the inner planets from collecting and capturing these light gases.

Age of the Solar System

An important clue to the origin of the Solar System comes from its age. Despite great differences in size, structure, and composition, the planets, asteroids, and comets all seem to have formed at nearly the same time. We can directly measure that date for the Earth, Moon, and some asteroids from the radioactivity of their rocks, and we find that none is more than about 4.6 billion years old. (Rocks from asteroids are the origin of many of the meteors that have reached Earth and are thus available for study, as we will discuss in chapter 11). Likewise, we find a similar age for the Sun, based on its current brightness and temperature and its presumed rate of nuclear fuel consumption.

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*Carbon, nitrogen, neon, and other elements normally in gaseous compounds are also relatively rare in the inner planets.

EXTENDING *our reach*

BODE'S RULE: THE SEARCH FOR ORDER

A curious and as yet unexplained feature of the orbits of the planets is their regular spacing. Very roughly, each planet is about twice as far from the Sun as its inner neighbor. This progression of distance from the Sun can be expressed by a simple mathematical relation known as **Bode's rule,** which works as follows: write down 0, 3, and then successive numbers by doubling the preceding number until you have nine numbers. That is, 0, 3, 6, 12, 24, and so on. Next, add 4 to each, and divide the result by 10, as shown in Box table 8.1. The resulting numbers, with two exceptions, are very close to the distances of the planets from the Sun in astronomical units.

Bode's rule was worked out before the discovery of Uranus, Neptune, and Pluto, and when Uranus was discovered and found to fit the law, interest was focused on the "gap" at 2.8 AU. Astronomers therefore began to search for a body in the gap, and, as we will see in chapter 10, Giuseppi Piazzi, a Sicilian astronomer, soon discovered the dwarf planet Ceres, which fitted the rule splendidly.

Ironically, the next planet to be found, Neptune, did not fit the rule at all, though the dwarf planet Pluto does, at least approximately. These irregularities show that Bode's rule is not a law like the "law of gravity," which is why we prefer to call it "rule" to emphasize this difference. It is not based on any (known) physical principles, but computer simulations of planet formation sometimes produce planets at similar spacing patterns. It may tell us that systems of planets are not likely to remain in stable orbits for billions of years unless their orbits are a factor of 1.5 to 2 times larger than the next planet interior to them. Or perhaps it merely shows the human fascination with patterns and our tendency to see order where none may actually exist.

BOX TABLE 8.1 BODE'S RULE

Bode's Rule	Number	Object	True Distance
(0 + 4)/10 =	0.4	Mercury	0.39
(3 + 4)/10 =	0.7	Venus	0.72
(6 + 4)/10 =	1.0	Earth	1.00
(12 + 4)/10 =	1.6	Mars	1.52
(24 + 4)/10 =	2.8	Ceres	2.77
(48 + 4)/10 =	5.2	Jupiter	5.2
(96 + 4)/10 =	10.0	Saturn	9.5
(192 + 4)/10 =	19.6	Uranus	19.2
		Neptune	30.1
(384 + 4)/10 =	38.8	Pluto	39.5

8.2 Formation of Planetary Systems

How did the Solar System form? What processes gave it the features we discussed in the previous section, such as its flatness and two main families of planets? Given that we were not around 4.6 billion years ago to witness its birth, our best explanation of its origin must be a reconstruction based on observations that we make now, billions of years after the event. Those observations, discussed above, are summarized below. Each must be explained by whatever theory we devise.

1. The Solar System is flat, with all the planets orbiting in the same direction.
2. There are two types of planets, inner and outer; the rocky ones are near the Sun and the gaseous or liquid ones are farther out.
3. The composition of the outer planets is similar to the Sun's, while that of the inner planets is like the Sun's minus the gases that condense only at low temperatures.
4. All the bodies in the Solar System whose ages have so far been determined are less than about 4.6 billion years old.

We have listed only the most important observed features that our theory must explain. There are many additional clues from the structure of asteroids, the number of craters on planetary and satellite surfaces, and the detailed chemical composition of surface rocks and atmospheres.

INTERACTIVE
Solar System builder

The currently favored theory for the origin of the Solar System derives from theories proposed in the eighteenth century by Immanuel Kant, the great German philosopher, and Pierre-Simon Laplace, a French mathematician. Kant and Laplace independently proposed what is now called the **solar nebula theory** that the Solar System originated from a rotating, flattened disk of gas and dust, with the outer part of the disk becoming the planets and the center becoming the Sun. This theory offers a natural explanation for the flattened shape of the system and the common direction of motion of the planets around the Sun. Since there is nothing about these processes that appears to be unique to the Solar System, we would expect to find evidence of similar processes occurring as other stars form. Therefore we can test this idea by searching for stars at various stages of this process.

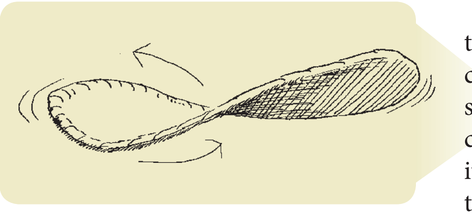
Interstellar Clouds

FIGURE 8.10
Photograph of an interstellar cloud (the dark region at center) that may be similar to the one from which the Solar System formed. The dark cloud is known as Barnard 86.

The modern form of the solar nebula theory proposes that the Solar System was born 4.6 billion years ago from an **interstellar cloud,** an enormous rotating aggregate of gas and dust like the one shown in figure 8.10. Such clouds are common between the stars in our Galaxy even today, and astronomers now think all stars have formed from them. Thus, although our main concern in this chapter is with the birth of the Solar System, we should bear in mind that our theory applies more broadly and implies that *most* stars could have planets, or at least surrounding disks of dust and gas from which planets might form.

Because interstellar clouds are the raw material of the Solar System, we need to describe them more fully. Although such clouds are found in many shapes and sizes, the one that became the Sun and planets probably was a few light years in diameter and contained about twice the present mass of the Sun. If it was like typical clouds we see today, it was made mostly of hydrogen (71%) and helium (27%) gas, with tiny traces of other chemical elements, such as gaseous carbon, oxygen, and silicon. In addition to the gases, interstellar clouds also contain tiny dust particles called **interstellar grains.**

Interstellar grains range in size from large molecules to micrometers or larger and are believed to be made of a mixture of silicates, iron compounds, carbon compounds, and water frozen into ice. Astronomers deduce the presence of these substances from their spectral lines, which are seen in starlight that has passed through dense dust clouds. Moreover, a few hardy interstellar dust grains, including tiny diamonds, have been found in ancient meteorites. This direct evidence from grains and the data from spectral lines shows that the elements occur in proportions similar to those we observe in the Sun. This is additional evidence that the Sun and its planets could have formed from an interstellar cloud.



The cloud began its transformation into the Sun and planets when the gravitational attraction between the particles in the densest parts of the cloud caused it to collapse inward, as shown in figure 8.11. The collapse may have been triggered by a star exploding nearby or by a collision with another cloud. But regardless of its initial cause, the infall was not directly to the center. Instead, because the cloud was rotating, it flattened. Flattening occurred because rotation retarded the collapse perpendicular to the cloud's rotation axis. A similar effect happens in an old-fashioned pizza parlor where the chef flattens the dough by tossing it into the air with a spin.

ANIMATION
Flattening and spreading up of a collapsing interstellar cloud

Formation of the Solar Nebula

It took a few million years for the cloud to collapse and become a rotating disk with a bulge in the center. The disk is called the **solar nebula,** and it eventually condensed into the

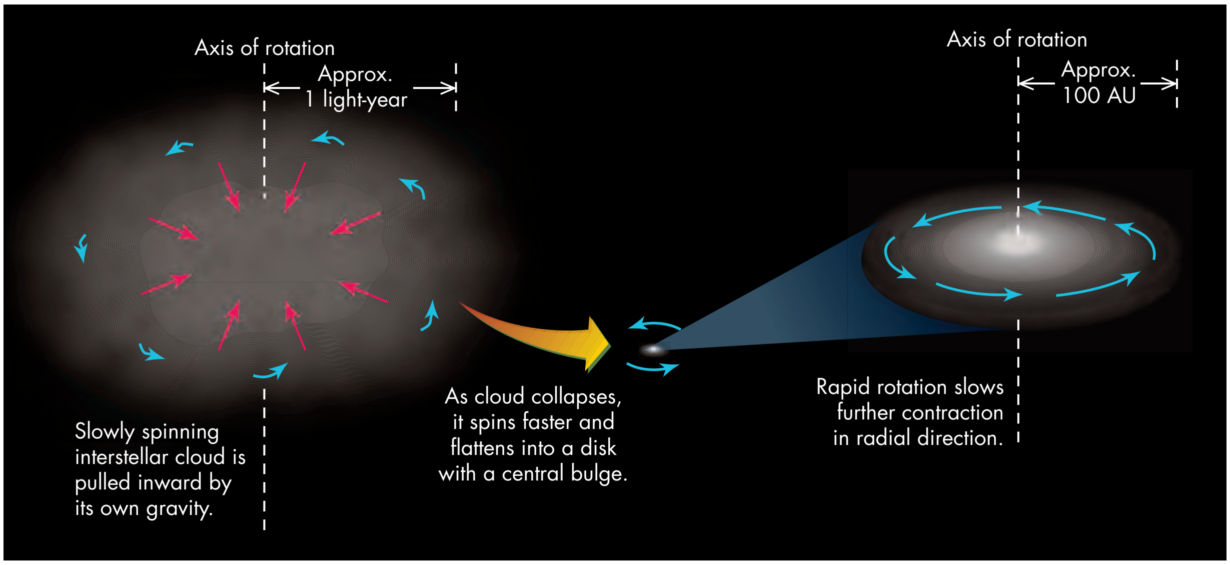


FIGURE 8.11
A sketch illustrating the collapse of an interstellar cloud to form a rapidly spinning disk. Note that the final size of the disk is not shown to scale—in actuality it would be thousands of times smaller than the cloud from which it formed.

planets while the bulge became the Sun. This explains the first obvious property of the Solar System—its disklike structure—which we mentioned at the beginning of this section.

The solar nebula was probably about 200 AU in diameter and perhaps 10 AU thick. Its inner parts were hot, heated by the young Sun and the impact of gas falling on the disk during its collapse, but the outer parts were cold, far below the freezing point of water. We are fairly certain of these dimensions and temperatures because we can observe disks around other stars and, in a few cases, can even detect other planets. For example, figure 8.12A shows a picture made with the Hubble Space Telescope of gas and dust disks near the Orion Nebula. The stars at the centers of these disks have not yet become hot enough to emit much visible light. Figure 8.12B, on the other hand, shows a disk (seen nearly edge-on) in which the star has reached full brilliance. Although the picture is grainy and in false color in order to emphasize the limited detail, you can see the disk edge-on.

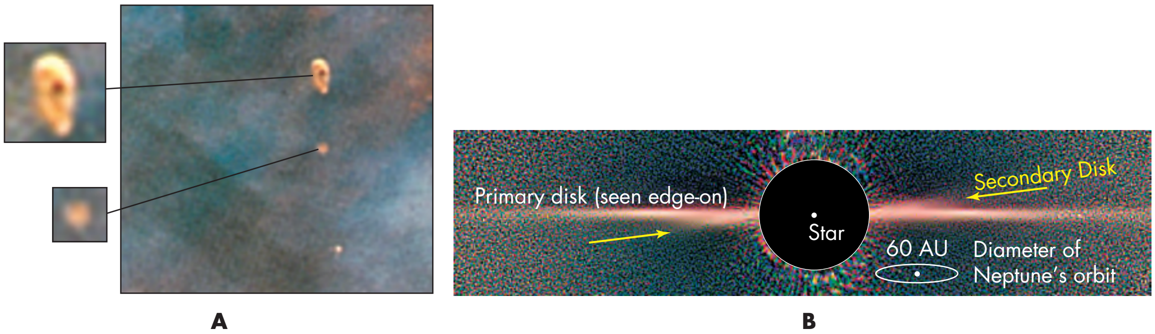


FIGURE 8.12
(A) The small blobs in this picture are stars in the process of formation (protostars) and their surrounding disk of dust and gas. These are in the Orion Nebula, a huge gas cloud about 1500 light years from Earth. (B) Picture in false color of a disk of dust around the young star β Pictoris made with the Hubble Space Telescope. A small mask in the telescope blots out the star's direct light, which would otherwise overexpose the image. Note the second faint dust disk, which is probably produced by a planet orbiting at a small angle relative to the primary disk.

Q. How does the process illustrated in figure 8.13 explain why you can see your breath on a cold morning?

Condensation in the Solar Nebula

Condensation occurs when a gas cools and its molecules stick together to form liquid or solid particles.* For condensation to happen, the gas must cool below a critical temperature (the value of which depends on the substance condensing and the surrounding pressure). For example, suppose we start with a cloud of vaporized iron at a temperature of 2000 K. If we cool the iron vapor to about 1300 K, tiny flakes of iron will condense from it. Likewise, if we cool a gas of silicates to about 1200 K, flakes of rocky material will condense.

At lower temperatures, other substances will condense. Water, for instance, can condense at room temperature, as you can see as steam escapes from a boiling kettle (fig. 8.13). Here, water molecules in the hot steam come into contact with the cooler air of the room. As the vaporized water cools, its molecules move more slowly, so that when they collide, electrical forces can bind them together, first into pairs, then into small clumps, and eventually into the tiny droplets that make up the cloud we see at the spout.

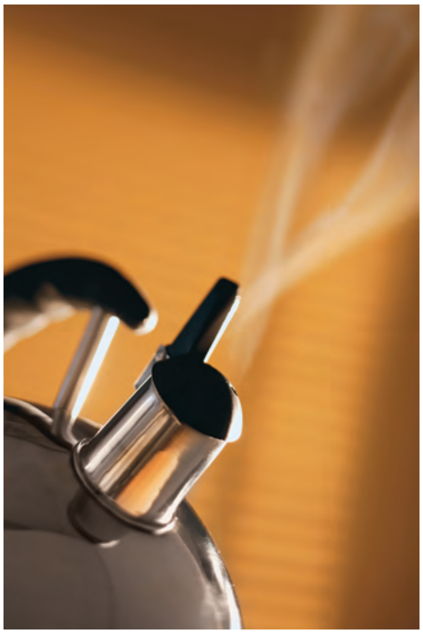


FIGURE 8.13
Water vapor cools as it leaves the kettle. The cooling makes the vapor condense into tiny liquid water droplets, which we see as the "steam."

An important feature of condensation is that when a mixture of vaporized materials cools, the materials with the highest vaporization temperatures condense first. Thus, as a mixture of gaseous iron, silicate, and water cools, it will make iron grit when its temperature reaches 1300 K, silicate grit when it reaches 1200 K, and finally water droplets when it cools to only a few hundred degrees K. It is a bit like putting a jar of chicken soup in the freezer. First the fat freezes, then the broth, and finally the bits of chicken and celery.

However, the condensation process stops if the temperature never drops sufficiently low. Thus, in the example above, if the temperature never cools below 500 K, water will not condense and the only solid material that forms from the gaseous mixture will be iron and silicates.

This kind of condensation sequence occurred in the solar nebula as it cooled after its collapse to a disk. But because the Sun heated the inner part of the disk, the temperature from the Sun to almost the orbit of Jupiter never dropped low enough for water and other substances with similar condensation temperatures to condense there. On the other hand, iron and silicate, which condense even at relatively high temperatures, could condense everywhere within the disk. Thus, the nebula became divided into two regions: an inner zone of silicate-iron particles, and an outer zone of similar particles on which ices also condensed, as illustrated schematically in figure 8.13. Water, hydrogen, and other easily vaporized substances were present as gases in the inner solar nebula, but they could not form solid particles there. However, some of these substances combined chemically with silicate grains so that the rocky material from which the inner planets formed contained within it small quantities of water and other gases.

Accretion and Planetesimals

In the next stage of planet formation, the tiny particles that condensed from the nebula must have begun to stick together into bigger pieces in a process called **accretion.**

The process of accretion is a bit like building a snowman. You begin with a handful of loose snowflakes and squeeze them together to make a snowball. Then you add more snow by rolling the ball on the ground. As the ball gets bigger, it is easier for snow to stick to it, and it rapidly grows in size.

Similarly in the solar nebula, tiny grains stuck together and formed bigger grains that grew into clumps, perhaps held together by electrical forces similar to those that make lint stick to your clothes. Subsequent collisions, if not too violent, allowed these smaller particles to grow into objects ranging in size from millimeters to kilometers. These larger objects are called **planetesimals** (that is, small, planetlike bodies) (fig. 8.14).

Because the planetesimals near the Sun formed from silicate and iron particles, while those farther out were cold enough that they could incorporate ice and frozen gases as well,

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*Technically, condensation is the change from gas to liquid, and deposition is the change from gas to solid. However, we will not make that distinction here.

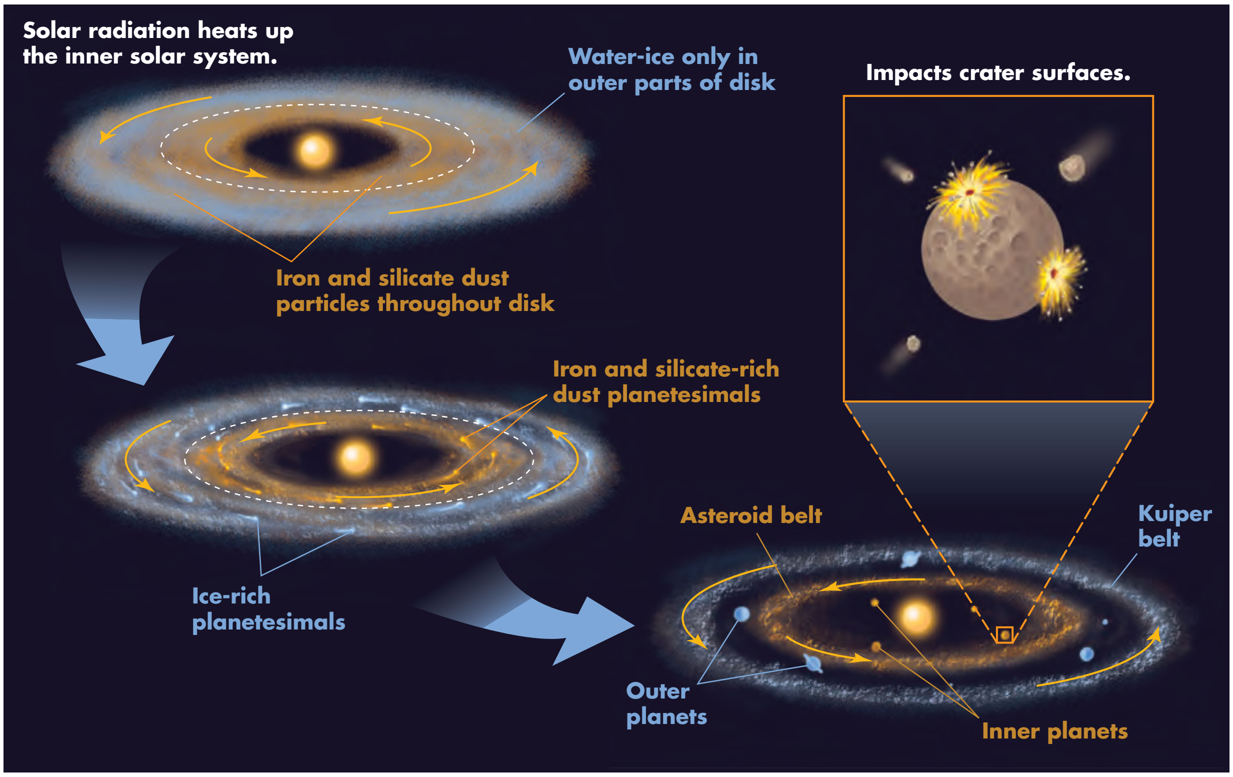


FIGURE 8.14
An artist's depiction of how the planets may have formed in the solar nebula.

there were two main types of planetesimals: rocky-iron ones near the Sun and icy-rocky-iron ones farther out. This then explains the second observation we described at the beginning of this section—that there are two types of planets—as described below.

Formation of the Planets

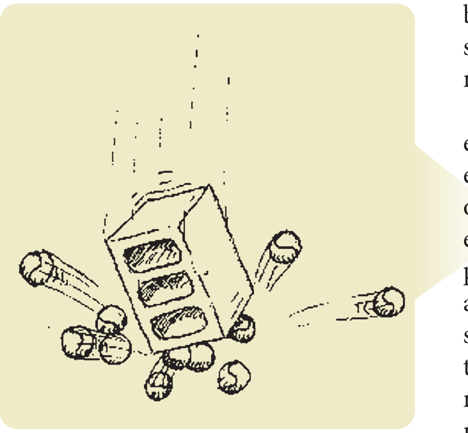
As planetesimals moved within the disk and collided with one another, planets formed. Computer simulations show that some collisions led to the shattering of both bodies, but gentler collisions led to merging, with the planetary orbits gradually becoming approximately circular. Moreover, in some such simulations, the distance between orbits is similar to that given by Bode's rule.

Merging of the planetesimals increased their mass and thus their gravitational attraction. That, in turn, helped them grow even more massive by drawing planetesimals into clumps or rings around the Sun. Within these clumps, growth went even faster, so that over a time lasting several million years, larger and larger objects formed.

Planetesimal growth was especially rapid beyond 4 or 5 AU from the Sun. Planetesimals there had more material from which to grow, because there ice could condense and it is about 10 times more abundant than silicate and iron compounds. Thus, planetesimals in the outer solar nebula could in principle become 10 times larger than those in the inner nebula.

Additionally, once a planet grew somewhat larger than the diameter and mass of the Earth, it was able to attract and retain gas by its own gravity. Because hydrogen was overwhelmingly the most abundant material in the solar nebula, planets large enough to tap that reservoir could grow vastly larger than those that formed only from solid material. Thus, Jupiter, Saturn, Uranus, and Neptune may have begun as Earth-size bodies of ice and rock, but their gravitational attraction resulted in their becoming surrounded by the huge envelopes of hydrogen-rich gases that we see today. The smaller and warmer

ANIMATION
Planet formation from the solar nebula



bodies of the inner Solar System could not capture hydrogen and therefore remained small and lack that gas. This explains the third observation we mentioned at the beginning of the section—that the outer planets have a composition similar to the Sun's.

As planetesimals struck the growing planets, their impact released gravitational energy that heated both the planetesimal and the planet. Gravitational energy is liberated whenever something falls. For example, when a cinder block falls onto a box of tennis balls, the impact scatters the balls in all directions, giving them kinetic energy—energy of motion. In much the same manner, planetesimals falling onto a planet's surface give energy to the atoms in the crustal layers, energy that appears as heating. You can easily demonstrate that motion can generate heat by hitting a steel nail a dozen or so times with a hammer and then touching the nail to your lip: the metal will feel distinctly hot. Imagine now the vastly greater heating created as mountain-size masses of rock plummet onto a planet. The heat so liberated, in combination with the radioactive heating described earlier, melted the planets and allowed matter with high density (such as iron) to sink to their cores, while matter with lower density (such as silicate rock) "floated" to their surfaces. We saw in chapter 6 that the Earth's iron core probably formed by this process, and astronomers believe that the other terrestrial planets formed their iron cores and rocky crusts and mantles the same way. A similar process probably occurred for the outer planets when rock and iron material sank to their cores.

Final Stages of Planet Formation

The last stage of planet formation was a rain of planetesimals that blasted out the huge craters such as those we see on the Moon and on all other bodies in the Solar System with solid surfaces. Figure 8.15 shows some of the planets and moons bearing vivid testimony to this role of planetesimals in planet building.

Occasionally an impacting body was so large that it did more than simply leave a crater. For example, we saw in chapter 7 that the Moon may have been created when the Earth was struck by a Mars-size body. Likewise, as we will discuss in chapter 9, Mercury may have suffered a massive impact that blasted away its crust. The peculiar rotation of Uranus and Venus may also have arisen from planetesimal collisions. In short, planets and satellites were brutally battered by the remaining planetesimals.

Although planet building consumed most of the planetesimals, some survived to form small moons, the asteroids, and comets. Rocky planetesimals and their fragments remained between Mars and Jupiter, where, stirred by Jupiter's gravitational force, they were unable to assemble into a planet. We see them today as the asteroid belt. Jupiter's gravity (and that of the other giant planets) also disturbed the orbits of icy planetesimals, tossing some in toward the Sun and others outward in elongated orbits to form the swarm of comet nuclei of the Oort cloud. The few that remain in the disk from Neptune's orbit out to about 50 AU form the Kuiper belt.

Formation of Satellite Systems

The large systems of satellites around the outer planets probably were formed from planetesimals orbiting the growing planets. Once a body grew massive enough that its gravitational force could draw in additional material, it became ringed with debris. Thus, moon formation was a scaled-down version of planet formation, and so the satellites of the outer planets have the same regularities as the planets around the Sun.

All four giant planets have flattened satellite systems in which the larger satellites (with few exceptions) orbit in the same direction. Many of these satellites are about as large as Mercury, and they would be considered full-fledged planets were they orbiting the Sun along an isolated orbit. A few of these bodies even have atmospheres, but they have too little mass (and thus too weak a gravitational attraction) to have accumulated

Mercury

Manicouagan Crater on Earth

Dione

Mars

Tethys

FIGURE 8.15
Pictures taken by spacecraft showing craters on Mercury, Earth, Mars, and a few of the moons of the outer planets. Included are Dione and Tethys, moons of Saturn. Note: Objects are shown to different scales.

Q. In the picture of Mars, what evidence can you see that Mars has an atmosphere?

large quantities of hydrogen and other gases from the solar nebula as their parent planets did. Thus, these moons are composed mainly of rock and ice, giving them solid surfaces—surfaces that are generally cratered and that, in a few cases, show signs of volcanic activity. These distant moons might in the future be ideal bases for studying those planets that have no surface to land on.

Formation of Atmospheres

Atmospheres were the last part of the planet-forming process. The inner and outer planets are thought to have formed atmospheres differently, a concept that explains their very different atmospheric composition. The outer planets probably captured most of their atmospheres from the solar nebula, as mentioned above; because the nebula was rich in hydrogen, so are their atmospheres.

SCIENCE *at work*

DIRECT FORMATION OF GIANT PLANETS

Because astronomers have no direct way to observe how the Solar System formed, they rely heavily on computer simulations to study that distant time. Computer simulations try to solve Newton's laws of motion for the complex mix of dust and gas that we believe made up the solar nebula. The solutions then can reveal what might have happened as the dust particles stuck together to form planetesimals and how the planetesimals then drew together under the influence of their gravity to form planets.

One of the more interesting findings of such calculations is that Jupiter may have formed directly from slightly denser regions of gas in the disk. Far from the Sun, where the gas is cold, gravity can more easily overcome the resistance of warmer gas to being squeezed into a smaller region. (Think of how a balloon resists being squeezed.) This may have allowed gravity to pull gas together to make a giant planet without the need to first form cores from planetesimals. Does this make the planetesimal theory wrong? No, just incomplete. Moreover, because this is an area of active research, astronomers still await definitive answers.

The inner planets were not massive enough and were too hot to capture gas from the solar nebula (as mentioned earlier) and are therefore deficient in hydrogen and helium. Venus, Earth, and Mars probably created their original atmospheres—by volcanic eruptions and by retaining gases from infalling comets and icy planetesimals that vaporized on impact. In fact, as a general rule, bodies too small to have captured atmospheres directly but that show clear signs of extensive volcanic activity (now or in the past) have atmospheres. More quiescent ones do not. Moreover, small bodies such as Mercury and our Moon keep essentially no atmosphere at all because their weak gravitational force means that their escape velocity is rather small, and atmospheric gases tend to escape easily from them.

Cleaning Up the Solar System

Only a few million years were needed to assemble most of the mass of the planets from the solar nebula, though the rain of infalling planetesimals lasted several hundred million years. Such a time is long in the human time frame but short in the Solar System's. All the objects within the Solar System are about the same age—the fourth property of the Solar System, mentioned at the beginning of this section.

One process still had to occur before the Solar System became what we see today: the residual gas and dust must have been removed. Just as a finished house is swept clean of the debris of construction, so too was the Solar System. In the sweeping process, the Sun was probably the cosmic broom, with its intense heat driving a flow of tenuous gas outward from its atmosphere. As that flow impinges on the remnant gas and dust around the Sun, the debris is pushed away from the Sun to the fringes of the Solar System. Such gas flows are seen in most young stars, and astronomers are confident the Sun was no exception. Even today, some gas flows out from the Sun, but in its youth, the flow was more vigorous.

The above theory for the origin of the Solar System explains many of its features, but astronomers still have many questions about how the Sun and its family of planets and moons formed. Is there any way, therefore, we can confirm the theory? For example, according to the solar nebula theory, planet formation is a normal part of star formation. So, do other planetary systems exist and do they resemble ours? Might we even be able to discover very young stars in the process of forming their planets and see the process at work?

8.3 Other Planetary Systems

Astronomers have long searched for planets orbiting stars other than the Sun. Their interest in such **exoplanets*** (as these distant worlds are called) is motivated not merely by the wish to detect other planets. Equally important is the hope that study of such systems will help us better understand the formation of the Solar System.

Planets are, of course, very small, so the light they reflect is drowned by that of their star. However, as we saw in section 8.2, young stars are often surrounded by a disk of dust and gas tens of astronomical units across. In 2008, the Hubble Space Telescope succeeded in detecting a large planet orbiting within a debris disk orbiting the star Fomalhaut (fig. 8.16). Fomalhaut is estimated to be about 200 million years old, so most of the dusty disk of material has been consumed, probably in forming planets. The ring of material that remains appears similar to our Kuiper belt, and the planet orbiting at the inner edge of the ring has probably grown by accreting material from the ring. The planet is more than a billion times fainter than Fomalhaut itself, making it extremely difficult to see in images; however, astronomers have discovered another way of detecting exoplanets.

Most present evidence for exoplanets comes from their effect on the star they orbit. As a planet orbits its star, the planet exerts a gravitational force back on the star as a result of Newton's third law—the law of action–reaction. That force makes the star's position wobble slightly, just as you wobble a little if you swing a heavy weight around you. The wobble creates a Doppler shift in the star's light that astronomers can measure (fig 8.17). From that shift and its change in time, astronomers can deduce the planet's orbital period, mass, and distance from the star. Using this Doppler method, astronomers had discovered over 300 exoplanets by early 2009, and figure 8.18 shows diagrams of many of the systems where more than one planet has been detected orbiting the star.

Looking at figure 8.18, you can see that none of these exoplanetary systems looks much like our own. First, most of the planets found so far have a mass comparable to

INTERACTIVE
Exoplanets

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*A number of astronomers use the term extra-solar planets. However, this is a bit peculiar because, after all, Earth is extra-solar too, in the sense that it is orbiting outside the Sun.

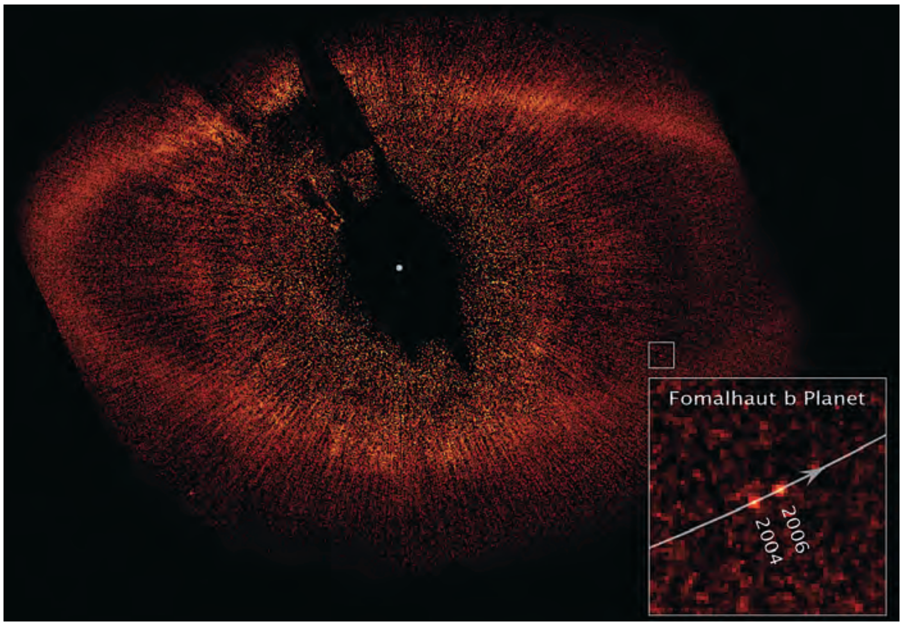

FIGURE 8.16
An icy ring surrounding the star Fomalhaut. Fomalhaut has about twice the Sun's mass and is about 200 million years old. The star itself has been blotted out by a small disk in the telescope so that its glare will not hide the faint ring of material, which is about twice the diameter of the Kuiper belt. A planet, magnified in the inset image, orbits along the inside edge of the ring. The planet's mass is estimated to be a few times Jupiter's mass.

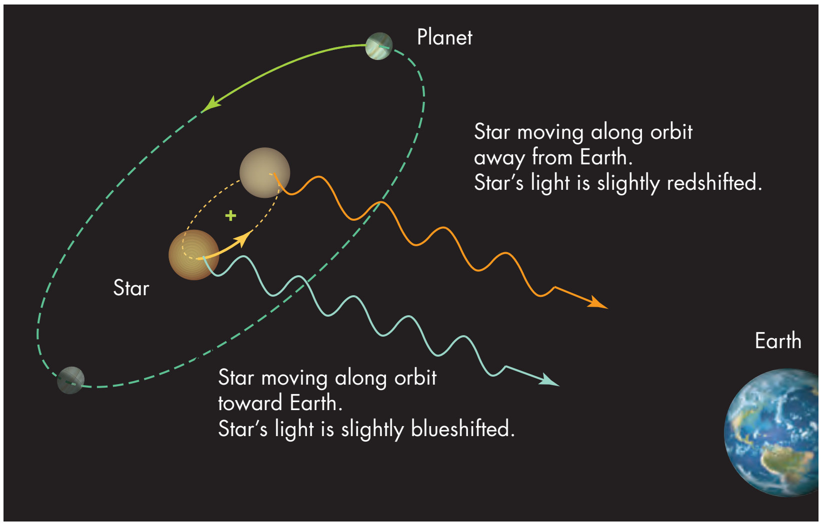

FIGURE 8.17
Detecting a planet from the motion of the star it orbits.

Jupiter's.* However, unlike Jupiter, many of these objects orbit extremely close to their star. Does this imply that our model for planet formation is wrong? Perhaps, but more likely we are seeing what is simply the outcome of the way we search. That is, the technique we use to find planets works best if the planet is massive and near its star. The reason for this selection is that only for such planets is the tug they exert on the star large enough to detect by the Doppler-shift method. Given that limitation, is there some way we can search for planets that more closely resemble our Earth? One way is to use a discovery made by Einstein in the early 1900s.

Einstein showed, as part of his general theory of relativity, that a mass bends space in its vicinity and that this bending creates the mass's gravity. As a result, if a ray of light passes near a mass, the bent space around the mass deflects the light and can bring it to a focus, as figure 8.19 schematically shows. Such bending of light by gravity may sound like science fiction, but as long ago as 1916, astronomers, following Einstein's suggestion, detected the bending of light from a distant star as the star's light traveled past our Sun (see essay 2). By analogy with the focusing ability of an ordinary lens, astronomers call such deflection of light **gravitational lensing.**

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*Using the Doppler technique, astronomers have detected two planets with masses of about 4 or 5 Earth masses, but they are orbiting so close to their stars that they complete an orbit in under two weeks.

ANIMATION
The position and Doppler shift of a star orbiting its common center of mass with a planet

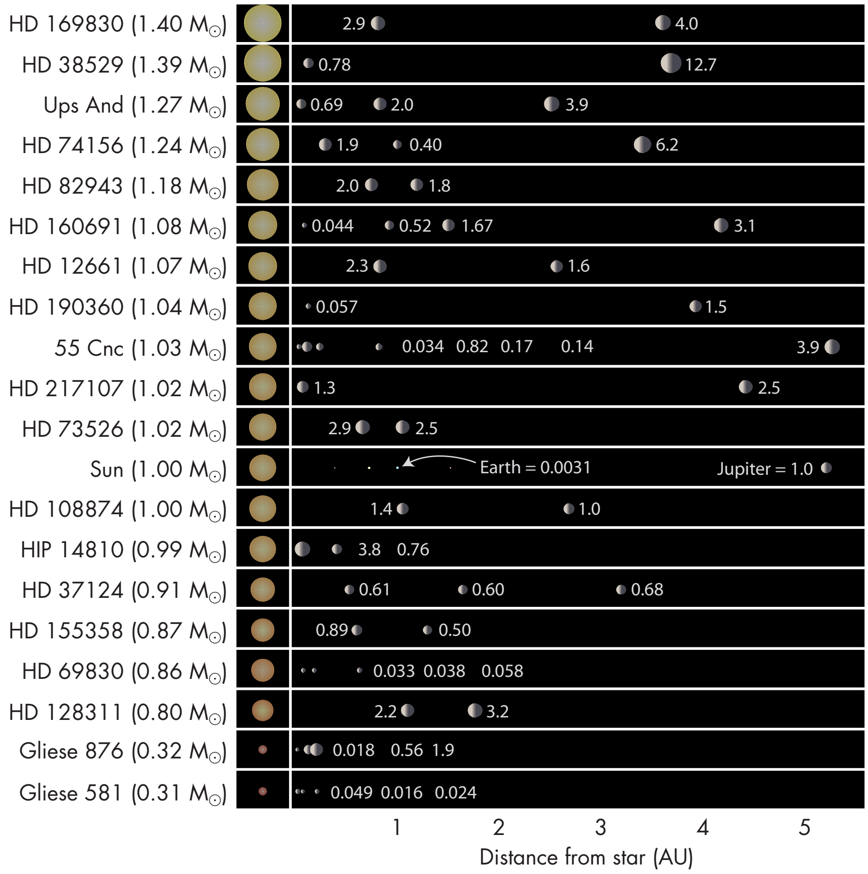
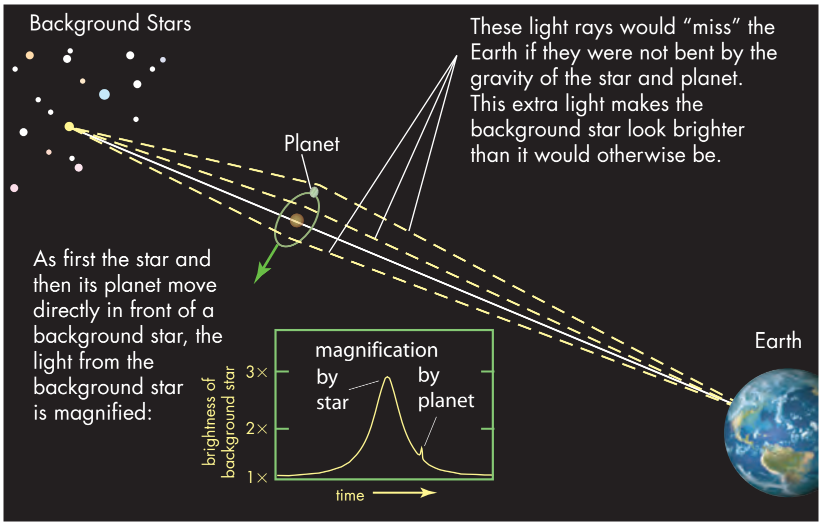


FIGURE 8.18
Comparison of the orbital radii and relative sizes of exoplanets with the Solar System. Most of the systems with two or more known exoplanets are shown, organized according to the mass of the star that they orbit. The sizes of the dots are based on the mass of each planet, and approximately indicate their true relative size. The numbers indicate the mass of each planet in units of Jupiter's mass.



These light rays would "miss" the Earth if they were not bent by the gravity of the star and planet. This extra light makes the background star look brighter than it would otherwise be.

As first the star and then its planet move directly in front of a background star, the light from the background star is magnified:

FIGURE 8.19
Detecting a planet by the slight bending of light from a background star caused by the planet's gravity.

Gravitational lensing has proved to be a powerful tool for detecting low-mass planets. The method works approximately as follows. Suppose we look at some distant star and measure its brightness. Suppose further that, by chance, a star at an intermediate distance moves between us and the distant star. Rays of the distant star's light that would have traveled past us in the absence of the intermediate star are now bent so that they reach us (see fig. 8.19). Thus, we observe *more* light from the distant star when an intermediate-distance star is present. Moreover, we receive even more light (although only a very tiny amount more) if a planet is orbiting the intermediate-distance star.

It is very rare to find an intermediate star with an orbiting planet that is properly positioned. Thus, to search for planets by this method, astronomers monitor the brightness of millions of stars, and computers scan millions of bits of data for the tiny increase in brightness of a lensing event. For example, in 2005, astronomers detected a brightening event in OGLE-2005-BLG-390.* Calculations based on the light change show that the dim (and cool) star contains a little less than one-quarter as much matter as our Sun and that the planet is only about six times more massive than the Earth and orbits its star at distance of about 2.9 AU (roughly three times the Earth–Sun distance). The planet's small mass implies that it could not have drawn in a significant quantity of hydrogen or helium, so it cannot be a gas giant planet like Jupiter. Moreover, because the star turns out to be so cool and because the planet is farther from its star than the Earth is from the Sun, the planet must also be very cold. Thus, it is probably an icy planet, perhaps like a huge Pluto. Six more of these brightening events were detected in the following three years, including one planet that is only about 40% more massive than Earth.

Our inability, so far, to directly see the majority of exoplanets greatly limits what we can learn about them. However, astronomers can partly overcome this limitation for planets whose orbits carry them in front of their stars from our vantage point. For example, a planet of the Sun-like star HD209458 orbits so that it passes between us and the star every 3.5 days. At such times, the planet blocks a tiny amount of the star's light. From the amount of dimming, astronomers can deduce the diameter of the planet, which turns out to be about 1.3 times the diameter of Jupiter. Moreover, a tiny fraction of the star's light leaks through the planet's atmosphere so that gas in the planet's atmosphere imprints very weak absorption lines on the spectrum. The lines are from hydrogen, sodium, carbon, oxygen, and even water vapor. Analysis of the line strengths suggests that the planet is a gas giant planet similar to Jupiter. Notice, however, the extremely short orbital period of 3.5 days. Using Kepler's third law, astronomers deduce that this planet orbits a mere 0.05 AU from its star, roughly one-tenth the distance that Mercury orbits from our Sun—vastly nearer than where we expect a giant planet to orbit. In fact, from the extent of the absorption lines seen, it appears that the planet is surrounded by a cloud of evaporating gas. The planet may have lost as much as a quarter of its mass over several billion years, according to some estimates.

Astronomers have found no system of exoplanets yet that looks particularly like our own. The nearest match so far is the system of planets orbiting the star 55 Cancri. This Sun-like star has five planets orbiting within 6 AU of the star, just as in the Solar System (see fig. 8.20). However, all of these planets are massive, at least 10 times

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*This name identifies the star as having been found by the *O*ptical *G*ravitational *L*ensing *E*xperiment against the bulge of stars (= BLG) in the center of our Galaxy.

SCIENCE *at work*

MIGRATING PLANETS

With the discovery of massive planets orbiting close to other stars, astronomers have been forced to think more critically about how our own Solar System formed.

Until very recently, most astronomers assumed that the Solar System's planets move along orbits that lie close to where the planets formed. But the discovery of planets with masses comparable to Jupiter's orbiting close to their star, like our terrestrial planets, has led astronomers to propose that planets may form at one distance from a star and then "migrate" to a new distance.

Can this proposal be tested? We can't watch real planets shift their orbits, but we can make computer simulations that follow a planet for millions of years under conditions similar to the early stages of our Solar System. These simulations show that interactions between the forming planets and leftover material in the disk of dust and gas can shift the planets' orbits either inward or outward, depending on the circumstances. The amount of such shifting in our Solar System is unknown, but according to some models, Neptune may have formed less than 20 AU from the Sun and moved past Uranus to its present distance of about 30 AU during the first several hundred million years of the Solar System.

Migration of planets has important consequences for planetary systems. For example, if a giant planet migrates inward toward its star, it will probably destroy smaller, Earth-size planets as it passes them. Thus, small planets, suitable for life as we know it, may form but fail to survive in such systems.

Yet another consequence of planet migration is that as a planet changes its orbital distance from its star, it encounters regions still rich with small bodies. These may be captured or flung into new orbits. This in turn may explain a surge of impacts that appears to be recorded on the Moon's surface about 600 million years after the Solar System's formation. This late bombardment may mark the time when the giant planets reached their final orbital positions.

Earth's mass, and three of the planets orbit at distances much closer than Mercury's distance from the Sun.

The presence of gas giant planets so near their stars presents a challenge to our understanding of how the Solar System formed. According to the solar nebula theory, gas giants should form only beyond several astronomical units from a star, where hydrogen-rich compounds can condense. If gas giants can form so close to a star, we need to understand what is different in these systems, or find a new mechanism to

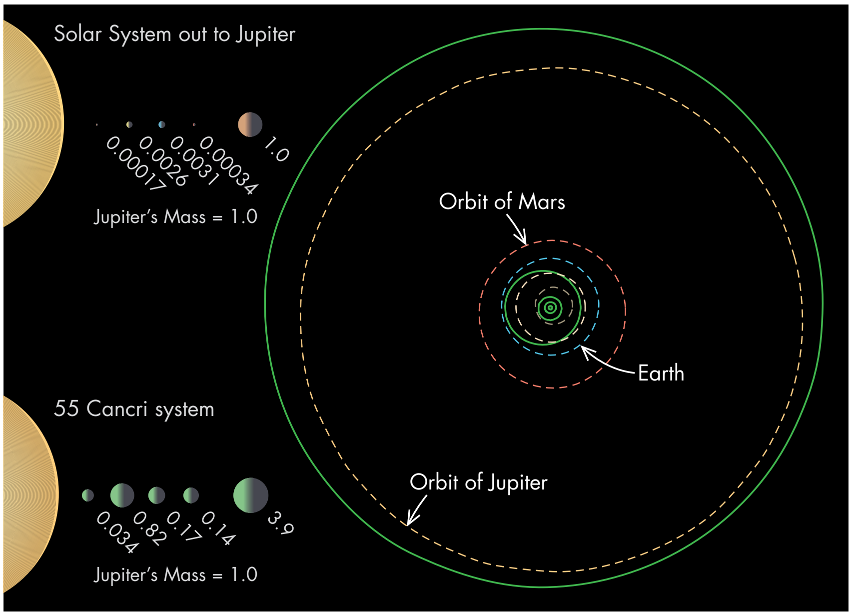

FIGURE 8.20
The 55 Cancri system contains five known planets around a star that is very similar to the Sun. The estimated masses (compared to Jupiter) for these planets and their orbits are compared with the five innermost planets in the Solar System. The figure also shows the approximate relative sizes of the planets. The fourth planet out in the 55 Cancri system orbits its star at about the same distance as the Earth from the Sun, but its mass is more than twice that of Neptune.

explain their formation. However, perhaps these planets did not actually form so close to their star, but instead "migrated" inward from an initial location much farther out (see Science at Work: "Migrating Planets").

Not only are the giant planets "too close" to their star, many also are in very elliptical orbits (rather than the essentially circular ones in our own system). That so many extra-solar systems have a massive planet on a very elliptical orbit does not bode well for the existence of Earth-like planets in these systems. As a massive planet sweeps into the inner portion of a star system, it will, over time, disturb the orbit of smaller planets, either ejecting them from the system or causing them to fall into their star. Some evidence suggests this fate may have befallen planets in a few of these remote systems. A number of the stars with exoplanets are appreciably richer in iron than our Sun. One suggestion for why these stars are so iron-rich is that they have swallowed Earth-like planets and vaporized them. The iron from the vaporized planet's core then enriches the star, making its spectrum lines of iron stronger. This is not the only interpretation, however. Perhaps it is easier to make planets in the first place if a star has a higher-than-average concentration of iron. Which interpretation is correct? We do not yet know.

SUMMARY

The Solar System consists of a star (the Sun) and planets, asteroids, and comets, which orbit it in a broad, flat disk. All the planets circle the Sun in the same direction, and most of them spin in the same direction. Their moons also form flattened systems, generally orbiting in the same direction. The planets fall into two main categories: small, high-density bodies (the inner, or terrestrial, planets) and large, low-density bodies (the outer, or Jovian, planets). The former are rich in rock and iron; the latter are rich in hydrogen and ice.

These features of the Solar System can be explained by the solar nebula theory. In this theory, the Solar System was born from a cloud of interstellar gas that collapsed to a disk called the solar nebula. The center of the nebula became the Sun, and the disk became the planets. This explains the compositional similarities and the common age of the bodies in the system.

The flat shape of the system and the common direction of motion around the Sun arose because the planets condensed within the nebula's rotating disk. Planet growth occurred in two stages: dust condensed and clumped to form planetesimals; and then later the planetesimals aggregated to form planets and satellites. Two kinds of planets formed because lighter gases and ice could condense easily in the cold outer parts of the nebula but only rocky and metallic material could condense in the hot inner parts. Impacts of surviving planetesimals late in the formation stages cratered the surfaces and may have tilted the rotation axes of some planets. Some planetesimals (and/or their fragments) survive to this day as the asteroids and comets.

Astronomers have found many planets orbiting other stars. Study of these exoplanets helps us better understand the origin of planetary systems, although most systems found so far indicate major differences from the patterns seen in the Solar System. One reason for these differences is that current methods for detecting planets are mainly able to detect only massive planets close to their stars. Nevertheless, it is surprising to find that so many giant exoplanets do orbit very close to their star.

QUESTIONS FOR REVIEW

1. (8.1) Name the eight planets in order of increasing distance from the Sun.
2. (8.1) Make a sketch of the Solar System showing top and side views.
3. (8.1) Make a table listing separately the inner and outer planets.
4. (8.1) What properties, apart from position, distinguish the inner and outer planets?
5. (8.1) What is the Oort cloud? Where is it located, and what kind of objects come from it?
6. (8.1) How do we know the composition of Jupiter?
7. (8.1) What is Bode's rule?
8. (8.2) What is an interstellar cloud? What does it have to do with the Solar System?
9. (8.2) What is the solar nebula? What is its shape and why?
10. (8.2) Why are there two main types of planets?
11. (8.2) What is the difference between condensation and accretion?
12. (8.2) What are planetesimals?
13. (8.2) Describe the planetesimal theory of planet formation.
14. (8.2) How does the planetesimal theory of planet formation explain the asteroids?

15. (8.2) How did the craters we see on many of the planets form?
16. (8.2) Describe a theory of how planets may have formed their atmospheres.
17. (8.2) How would you describe the formation of the Solar System to a little brother or sister?
18. (8.3) What observations of other solar systems have been made that support the solar nebula hypothesis?
19. (8.3) What are two methods used to find exoplanets?
20. (8.3) How do some exoplanets differ from what we might expect? Does this prove the nebula theory is wrong?

THOUGHT QUESTIONS

1. (8.2) What kinds of physics would be important to include in a computer simulation of solar system formation?
2. (8.3) How are the kinds of exoplanets found by the Doppler method a biased sample of exoplanets? Give an example of a survey method that might give a biased result in everyday life.
3. (8.3) How do some exoplanets differ from what we might expect? Does this prove the nebula theory is wrong?

PROBLEMS

1. (8.1) Calculate the densities of Venus and Jupiter (use the masses and radii given in the appendix). How do these numbers compare with the density of rock (about 3 grams per cm^3) and water (1 gram per cm^3)? (Note: Be sure to convert kilometers to centimeters and kilograms to grams if you are expressing your answer in grams per cm^3.)
2. (8.1) Look up the orbital periods of the Earth and Jupiter in the appendix. If you started measuring when the Earth and Jupiter were at their closest to each other, how many years would it be until they returned to that position again?
3. (8.1/3.8) Look up the mass and radius of Mercury and Jupiter and calculate their escape velocities, using the expression in chapter 3. Does this help you see why the one body has an atmosphere but the other doesn't? (Note: Be sure to convert kilometers to meters or the appropriate unit.)
4. (8.1/3.8) Look up the mass and radius of Neptune and Mars and calculate their escape velocities, using the expression in chapter 3. Compare both with that of the Earth (see section 3.8). What is different about the atmospheres of these three planets? (Note: Be sure to convert kilometers to meters or the appropriate unit.)
5. (8.3/2.3) Suppose an exoplanet orbits a star of 1 solar mass. Suppose the orbital period is 5 days. What is the semimajor axis of the orbit in AU?
6. (8.3) Calculate the maximum Doppler shift that could be observed for the planet in question 5.
7. (8.3) Using the modified form of Kepler's laws given in figure 8.8, calculate the orbital period for Gliese 851d, an exoplanet with a mass about 7.1 times the mass of Earth. The star Gliese 851 is a red dwarf with a mass of 0.31 solar masses and the planet orbits with a semi-major axis of 0.22 AU. (Remember to convert distances to meters and masses to kilograms when using the equation).

TEST YOURSELF

1. (8.1) Which of the following objects are primarily rocky with iron cores?
   (a) Venus, Jupiter, and Neptune
   (b) Mercury, Venus, and Pluto
   (c) Mercury, Venus, and Earth
   (d) Jupiter, Uranus, and Neptune
   (e) Mercury, Saturn, and Eris
2. (8.2) One explanation of why the planets near the Sun are composed mainly of rock and iron is that
   (a) the Sun's magnetic field attracted all the iron in the young Solar System into the region around the Sun.
   (b) the Sun is made mostly of iron. The gas ejected from its surface is therefore iron, so that when it cooled and condensed, it formed iron-rich planets near the Sun.
   (c) the Sun's heat made it difficult for other substances such as ices and gases to condense near it.
   (d) the statement is false. The planets nearest the Sun contain large amounts of hydrogen gas and subsurface water.
   (e) the Sun's gravitational attraction pulled iron and other heavy material inward and allowed the lighter material to float outward.
3. (8.2) Which of the following features of the Solar System does the solar nebula theory explain?
   (a) All the planets orbit the Sun in the same direction.
   (b) All the planets move in orbits that lie in nearly the same plane.
   (c) The planets nearest the Sun contain only small amounts of substances that condense at low temperatures.
   (d) All the planets and the Sun, to the extent that we know, are the same age.
   (e) All of the above
4. (8.2) The numerous craters we see on the solid surfaces of so many Solar System bodies are evidence that
   (a) they were so hot in their youth that volcanos were widespread.
   (b) the Sun was so hot that it melted all these bodies and made them boil.
   (c) these bodies were originally a mix of water and rock. As the young Sun heated up, the water boiled, creating hollow pockets in the rock.

(d) they were bombarded in their youth by many solid objects.
(e) all the planets were once part of a single, very large and volcanically active mass that subsequently broke into many smaller pieces.

5. (8.3) The Doppler-shift method for detecting the presence of exoplanets is best able to detect
   (a) massive planets near the star.
   (b) massive planets far from the star.
   (c) low-mass planets near the star.
   (d) low-mass planets far from the star.
6. (8.3) The transit method for detecting exoplanets works best for
   (a) very massive planets.
   (b) solar systems seen face-on.
   (c) planets very far from their stars
   (d) solar systems seen edge-on.
   (e) planets very close to their stars.

KEY TERMS

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FURTHER EXPLORATIONS

Beatty, J. Kelly, Carolyn Collins Petersen, and Andrew Chaikin. *The New Solar System.* 4th ed. Cambridge: Sky Publishing Company, 1999.

Gingerich, Owen. "Losing It in Prague: The Inside Story of Pluto's Demotion." *Sky and Telescope* 112 (November 2006): 34.

Jayawardhana, Ray. "Are Super-Sized Earths the New Frontier?" *Astronomy* 36 (November 2008): 26.

Lin, Douglas N.C. "The Genesis of Planets." *Scientific American* 298 (May 2008): 50.

Malhotra, Renu. "Migrating Planets." *Scientific American* 281 (September 1999): 56.

Seager, Sara. "Unveiling Distant Worlds." *Sky and Telescope* 111 (February 2005): 28.

Seager, Sara. "Alien Earths from A to Z." *Sky and Telescope* 115 (January 2008): 22.

Soter, Steve. "What Is a Planet?" *Scientific American* 296 (January 2007): 34.

Weinberger, Alycia J. "Building Planets in Disks of Chaos." *Sky and Telescope* 116, (November 2008): 32.

Website

Visit the *Explorations* website at **http://www.mhhe.com/arny** for additional online resources on these topics.

Q FIGURE QUESTION ANSWERS

WHAT IS THIS? (chapter opening): This is a disk of gas and dust around a forming star. The dark disk is visible in silhouette against the glow of emission from the Orion nebula. The forming star glows red at its center.

FIGURE 8.8: The density is the mass (30 grams) divided by the volume (10 cm^3). 30 grams/10 cm^3 = 3 grams/cm^3. Iron's density is about 8 gm/cm^3, while a typical silicate rock's density is about 3 gm/cm^3. It is thus more likely to be rock.

FIGURE 8.13: When you breathe out, warm moist air from your lungs comes in contact with the cold air outside. The moisture in your breath condenses and makes a tiny "cloud."

FIGURE 8.15: Above the edge of the planet, especially on the left, you can see thin wispy clouds.

PROJECT

Extrasolar planets: Look on the Web for results of searches for exoplanets and young solar systems. Try to find an example of a star system in each of the primary phases believed to have occurred in the formation of the Solar System, starting with an interstellar cloud. For example, you can easily find images of protoplanetary disks in the Hubble Space Telescope archive. For established solar systems, actual images are rare, but you may be able to find a diagram or chart of the planets in the system. Record the mission, masses of the planet(s), and method of detection for each. Of the stars you can find that have planets, which star has a mass closest to that of the Sun? Of the planets that have currently been found, which has a mass closest to that of the Earth?