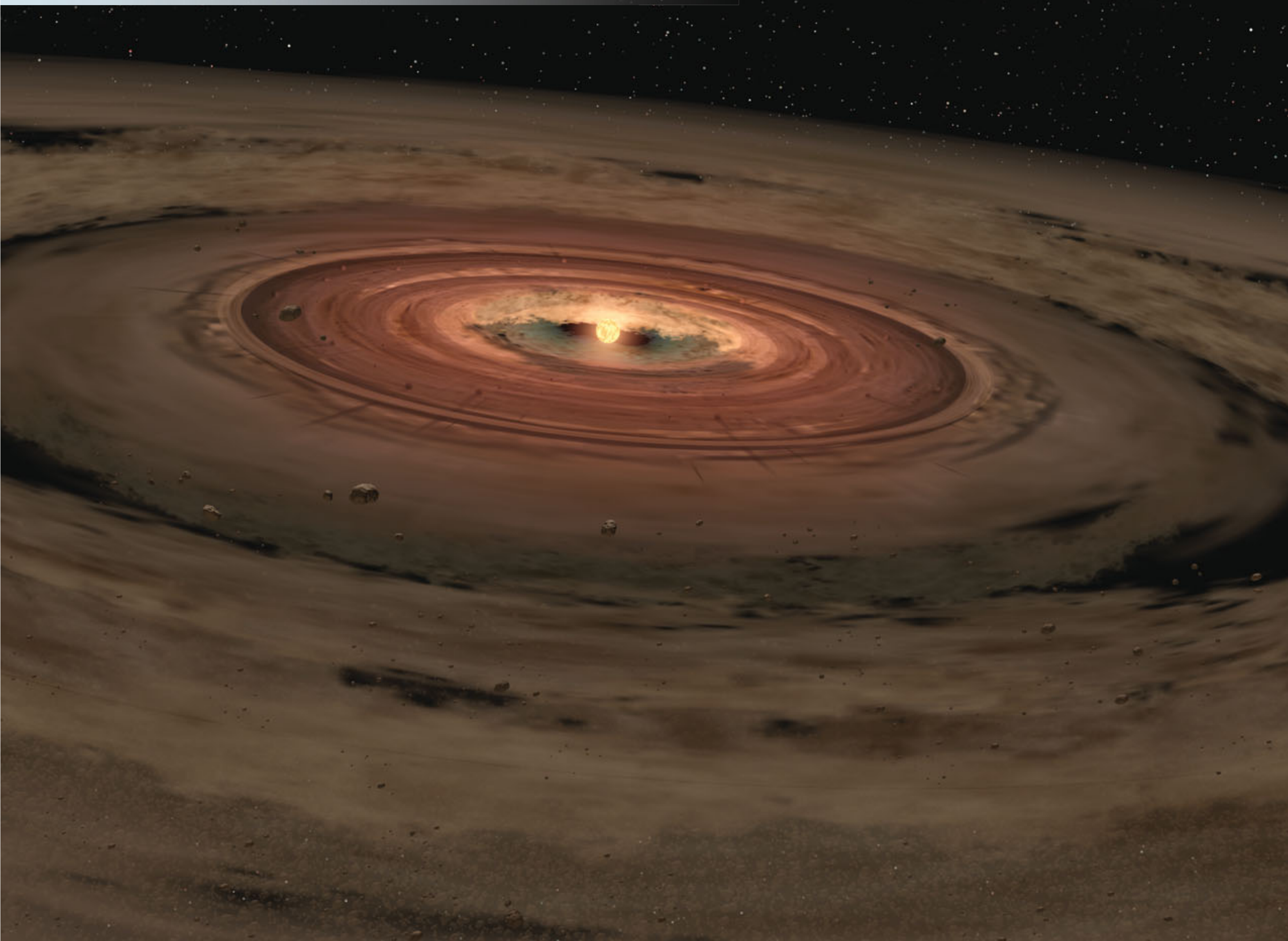
8

Survey of Solar Systems



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

Learning Objectives

Upon completing this chapter you should be able to:

- Identify the primary components of the Solar System, and describe their distinctive properties.
- Discuss the differences between terrestrial, Jovian, and dwarf planets, and their satellites, and recount why astronomers reclassified Pluto.
- Explain how astronomers measure masses and radii for bodies in the Solar System, and carry out a calculation to find a body's density from these measurements.
- Describe the densities of different classes of objects in the Solar System and relate this to their composition.
- Recall the age of the Solar System and explain how it is determined.
- Describe the steps in the formation of the Solar System according to the nebular theory and relate these to the properties of the planets and other bodies.
- Explain why disks are expected to form around stars, and describe the observations that indicate disks are present around young stars.
- Describe the role of planetesimals in planet formation and modification, and where some can still be found.
- Discuss the roles of rocky, icy, and gaseous materials in the formation of planets and their atmospheres.
- Explain the various methods currently being used to detect exoplanets, the information each provides about an exoplanet, and the limitations of these methods.
- Discuss the ways in which exoplanetary systems appear to differ from the Solar System.

Concepts and Skills to Review

- Law of gravity (3.5)
- Density (6.1)
- Modified form of Kepler's third law (3.6)

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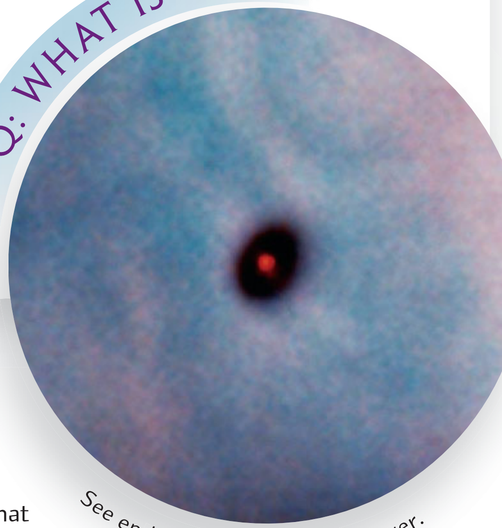


See end of chapter for the answer.

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 molten lava 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, over 4.5 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. However, astronomers have developed an array of techniques that have revealed hundreds of planets around other stars and even other "solar systems" in their first stages of formation. The other systems detected so far look very different from our own, challenging our 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.

8.1 Components of the Solar System

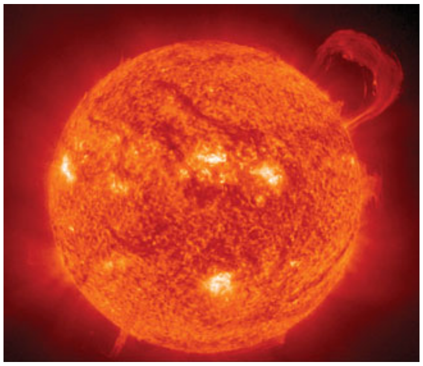


FIGURE 8.1
Image of the Sun made with an ultraviolet telescope that reveals high-temperature gases in the Sun's atmosphere.

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 Planets

The planets are much smaller than the Sun and orbit about it in nearly circular orbits. 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, as shown in figure 8.2. 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

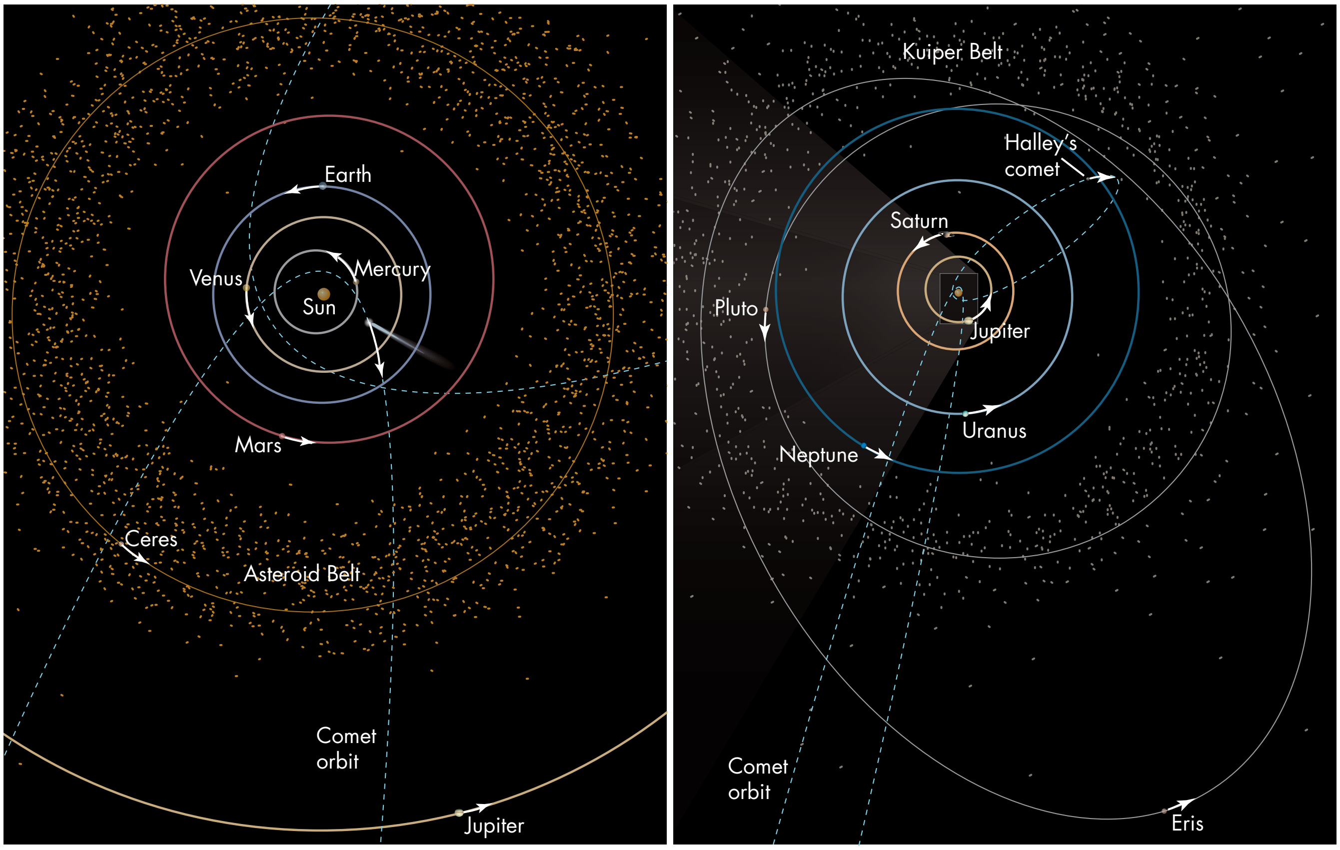


FIGURE 8.2
Diagrams of the Solar System from above. The orbits are shown in the correct relative scale in the two drawings. Because of the great difference in scale, the inner and outer Solar System are displayed separately.

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 8.3, which also shows a small part of the edge of the Sun to illustrate how the Sun dwarfs even the large planets.

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.

Although the two categories of planets neatly describe the eight most massive 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 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 more massive 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.** A dwarf planet is an object that orbits the Sun, is massive enough that its gravity compresses it into an approximately spherical shape, but has not swept its orbital region clear of other objects that add up to a mass comparable to its own mass. 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.*

As the planets orbit the Sun, most are themselves orbited by satellites. Jupiter, Saturn, Uranus, and Neptune have large families of 63, 61, 27, and 13 moons, respectively, discovered to date. Mars has 2, Earth has 1, while Venus and Mercury have none. Some of the dwarf planets also have moons: Pluto has 4 and Eris has 1. Some of these satellites are just a few kilometers in size and very difficult to detect, but others are so large that they would be termed planets or dwarf planets if they orbited the Sun themselves.

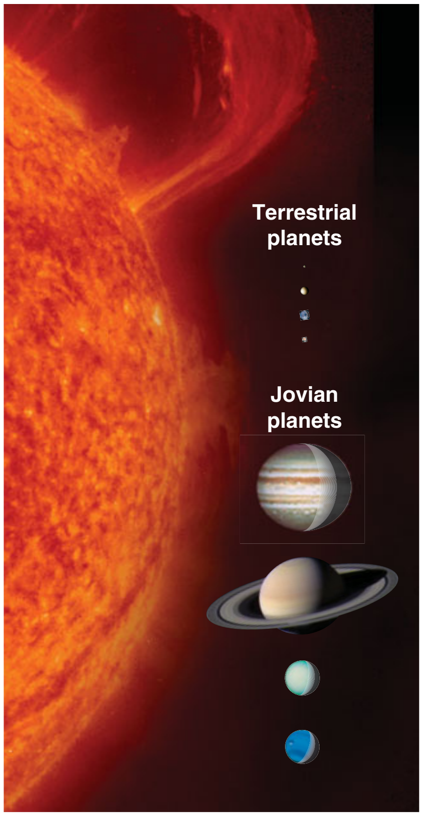


FIGURE 8.3
The planets and the Sun to scale.

Asteroids and Comets

The Solar System is filled with millions of objects far smaller than planetary bodies. The **asteroids** are rocky or metallic bodies, the largest of which is the dwarf planet Ceres with a diameter of about 970 kilometers (600 miles). Most asteroids orbit the Sun in the large gap between the orbits of Mars and Jupiter, a region called the **asteroid belt** (fig. 8.2). They are probably material that failed—perhaps as a result of disturbances by Jupiter’s gravity—to aggregate into a planet.

Beyond Neptune, extending to perhaps 50 AU from the Sun, is a region called the **Kuiper** *(KY-per)* **belt.** As seen in figure 8.2, the Kuiper belt looks similar to the asteroid belt, but the objects here are made mostly of ice. Pluto and dozens of other dwarf planet candidates orbit in the Kuiper belt, and uncounted icy bodies such as Eris orbit even farther from the Sun in a scattered region whose extent is not well known.

Objects at such large distances from the Sun are so dimly illuminated that they are very difficult to detect. Our main clue to what bodies orbit the Sun at even larger distances are the **comets.** These are icy bodies typically about 10 km (about 6 miles) in diameter that enter the inner Solar System on highly elongated orbits (fig. 8.2). When they approach the Sun, they grow huge tails of gas and dust as their ices are partially vaporized. Most comets orbit far beyond Neptune in a region of the Solar System called the **Oort cloud,** which may extend 100,000 AU from the Sun. Although the majority of comets probably originate in the Oort cloud, some come from 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, only a few of which get close enough to the Sun to be detected.

Oort cloud and Kuiper belt

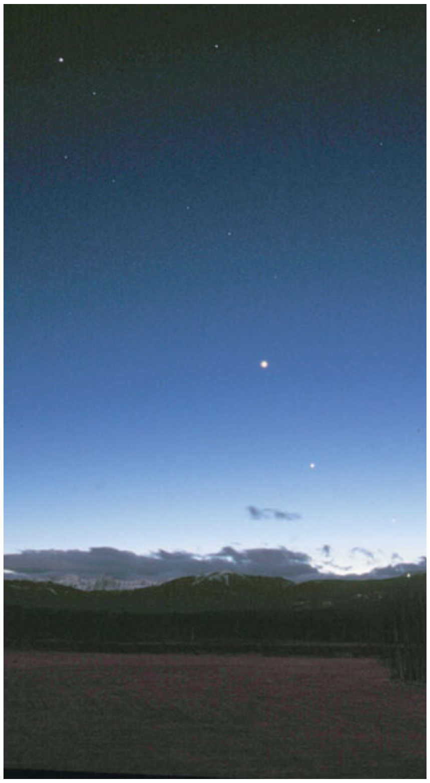


FIGURE 8.4
Sunset view of four planets strung along the zodiac on March 1, 1999. Their straight-line arrangement results from the flatness of the Solar System. From top to bottom, you can see Saturn, Venus, Jupiter, and Mercury (nearly lost in the twilight).

The Orbits and Spins of the Planets

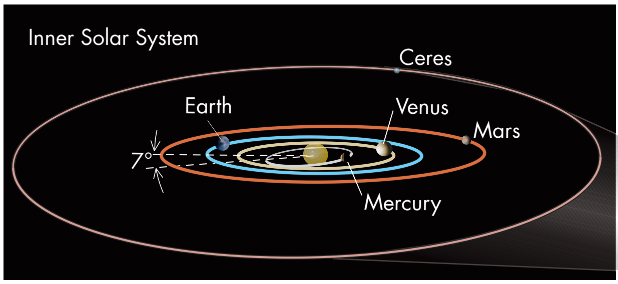
When several planets appear near each other in the evening sky, we can see that they lie along a linear band extending away from the Sun (fig. 8.4). The planets appear to lie along a line because their orbits, as well as the Earth's, all lie in nearly the same plane, as shown in the side view of the Solar System in figure 8.5. Mercury's orbit has the largest tilt, just 7° from the average of the rest of the planets. The Solar System out to Neptune has about the same relative thickness as 3 CDs stacked together. The planets also all travel around the Sun in the same direction: counterclockwise, as seen from above the Earth's North Pole, and this is the same direction in which the Sun itself spins.

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. 8.6). 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.

Many dwarf planets and other small bodies in the Solar System have highly inclined orbits and randomly oriented spins. Although the objects in the asteroid belt and Kuiper belt may have orbits tilted by up to about 45°, on average they are very close to same plane as the planets. On the other hand, the comets that arrive from the largest distances may have orbits oriented in any direction. This leads astronomers to conclude that the Oort cloud surrounds the Solar System in a roughly spherical shape.

Like the planets orbiting the Sun, most of the moons orbiting the planets 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.

The significance of another feature of the planets' orbits is a matter of some debate. In the 1700s astronomers noticed that the spacing between the orbits of the planets seems to follow a fairly regular progression. This mathematical progression may indicate something about the natural spacing between orbits of large bodies, or it may be a chance pattern as discussed in Astronomy by the Numbers: "Bode's Rule: The Search for Order."



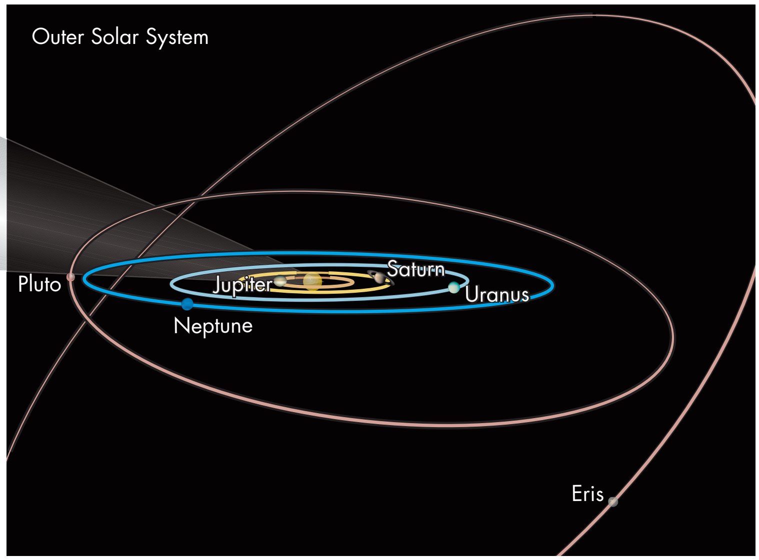


FIGURE 8.5
The planets' orbits from the side. The dwarf planets Ceres, Pluto, and Eris are also shown, illustrating their highly inclined orbits. This view also shows that while Pluto sometimes gets closer to the Sun than Neptune, its orbit actually remains well separated from Neptune's.

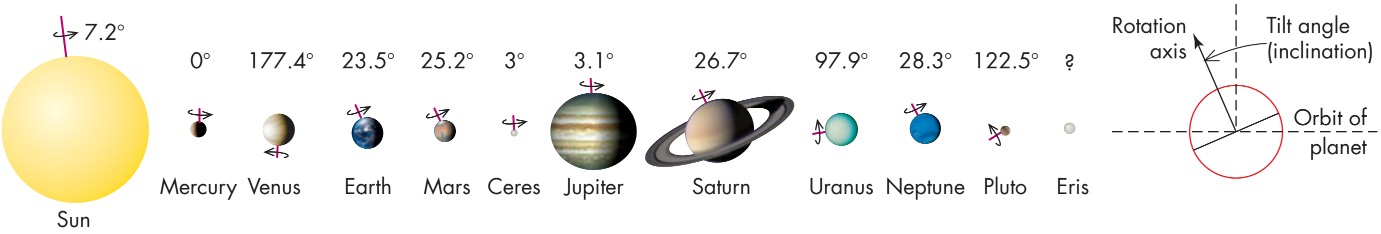
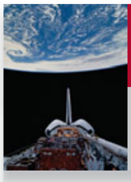


FIGURE 8.6
Sketches showing the orientation of the rotation axes of the planets and Sun. The figure illustrates that most of them spin in the same direction, counterclockwise as seen from above the Earth's North Pole. The dwarf planets Ceres, Pluto, and Eris are also shown. The bodies are not shown to the same scale.

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, as we discuss next.



ASTRONOMY *by the numbers*

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 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 fit 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.

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

Composition Differences Between the Inner and Outer Planets

The composition differences between the rocky inner planets and the hydrogen-rich outer planets are critcally important to our understanding of the history of the Solar System. Therefore we will look more closely at how we determine these properties.

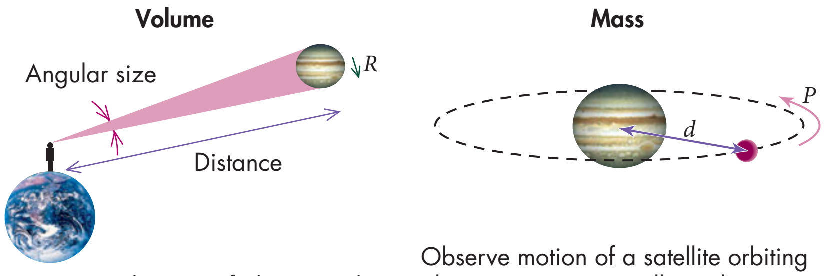
Astronomers can deduce a planet's composition in several ways. From its spectrum, they can measure its atmospheric composition and get some information about the nature of its surface rocks. However, spectra give no clue as to what lies deep inside a planet where light cannot penetrate. To learn about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

We saw in chapter 6 how earthquake waves reveal Earth's internal structure, but the only other planet where this has been possible is Mars, and only to a limited extent. Our main clue to a planet's composition is its density. 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, 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. 8.7).

Once the planet's average density is known, we can compare it with the density of common 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 (8 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

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?



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 8.7
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).

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). After correcting for 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 8.8. 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 molecules such as methane (CH_4), ammonia (NH_3), and water (H_2O).

When we speak of 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). 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 probably have cores of iron and rock roughly the size of the Earth beneath their deep atmosphere, as illustrated in figure 8.8. Astronomers deduce the

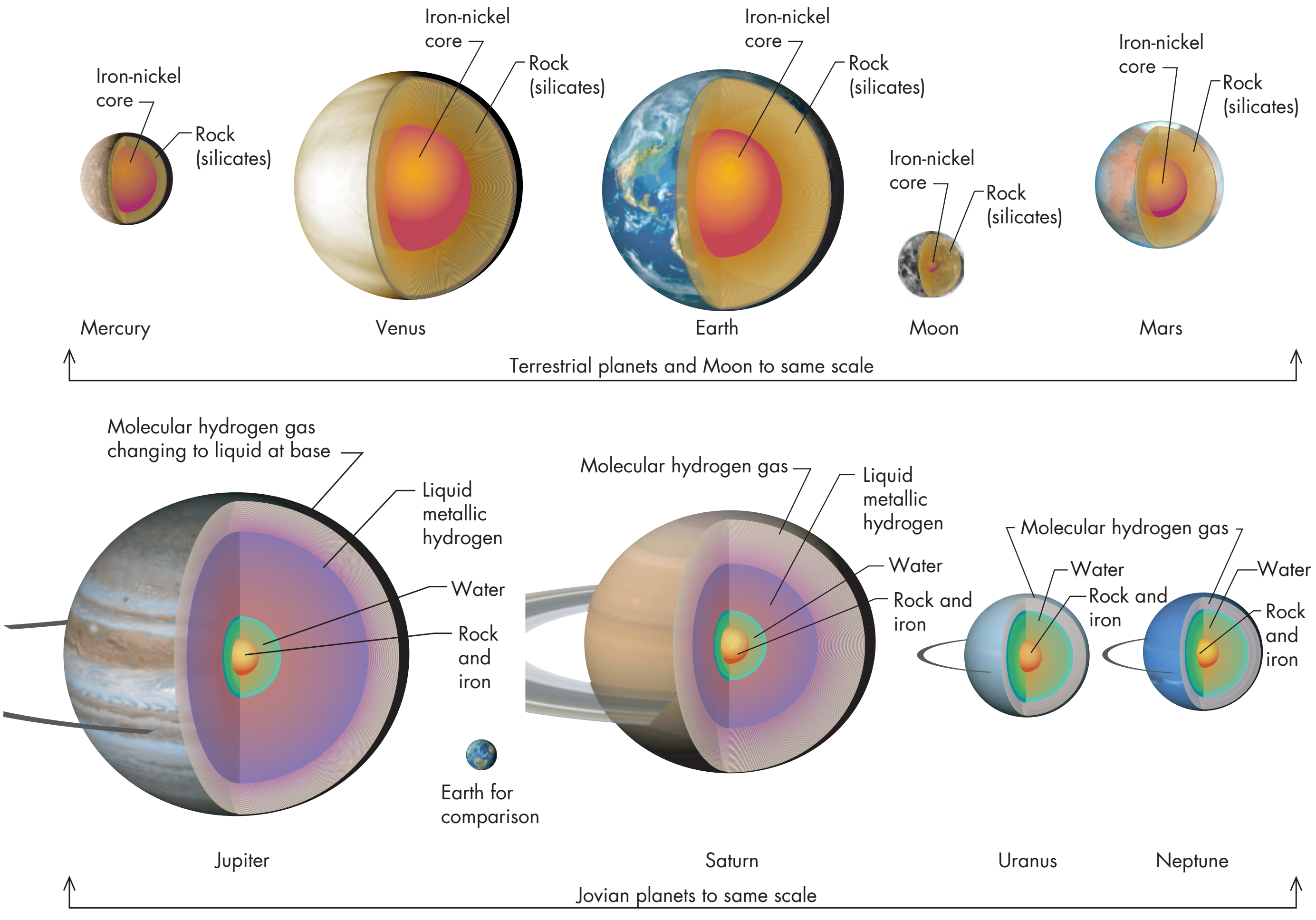


FIGURE 8.8
Sketches of the interiors of the planets. Details of sizes and composition of inner regions are uncertain for many of the planets.

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

The Jovian 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 a thin "atmosphere" and a solid "crust" as we have on the Earth. Thus, we can never "land" on any of the gas giants because we would simply sink ever deeper into their atmospheres into an interior that contains extremely hot gas/liquid that is denser than rock.* 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.

FIGURE 8.9
Galileo spacecraft image of Ganymede, the largest satellite of Jupiter, and even larger than Mercury, but with a density of only about 1.9 grams per cm^3.

The satellites of the Jovian planets and the objects orbiting beyond Neptune have densities similar to the Jovian planets, typically about 1.5 grams per cm^3 (fig. 8.9). These bodies do not have atmospheres, for the most part, but are instead made up of ice and rock. By ice, we mean frozen liquids and gases such as ordinary water ice (H_2O), frozen carbon dioxide (CO_2), frozen ammonia (NH_3), and frozen methane (CH_4). Some of these satellites have diameters comparable to Mercury's, although they are much less massive because they are built from lower-density materials. Asteroids and comets show the same split into two families; that is, rocky bodies and icy bodies.

Our discussion of the composition of the bodies in the inner and outer Solar System furnishes another clue to its origin: the planets and Sun were all made from the same material. Astronomers come to this conclusion because Jupiter and Saturn have a composition very similar to that of the Sun, and the inner planets have a similar composition *if we were to remove the Sun's hydrogen, helium, and other elements normally found in gaseous compounds.* 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 large amounts of gas.

Age of the Solar System

An important clue to the origin of the Solar System comes from its age. The best evidence implies that, despite their great differences in size, structure, and composition, the Sun, planets, asteroids, and other bodies all formed at nearly the same time.

We can estimate the date when the Earth, Moon, and some asteroids formed from the radioactivity of their rocks. As discussed in chapter 6, by-products of radioactive decay remain trapped in rocks until they melt and recrystallize. Therefore, the oldest rocks we can find on Earth give us a lower limit to the planet's overall age. Some Earth rocks are dated to over 4 billion years old; some individual crystals embedded in old rocks are arguably as old as 4.4 billion years. The Earth has had such an active geology that it is not easy to find rocks that have remained unaltered since the Earth formed. By contrast, because there has been relatively little activity on the Moon, lunar rock samples tend to be at least several billion years old; some rocks returned by the Apollo missions are as old as 4.5 billion years. Meteorites, which are pieces of asteroids that have fallen to Earth (chapter 11), have radioactive ages of up to about 4.6 billion years.

The radioactive dates are all consistent with the planets beginning to form about 4.6 billion years ago, with the smaller bodies cooling first. We find a similar age for the Sun, based on its current brightness and temperature and its rate of nuclear fuel consumption. Thus, it appears that the Solar System formed between about 4.6 and 4.5 billion years ago, creating most of the bodies that we still see today.

* Models of Uranus and Neptune suggest that their interiors may contain large amounts of liquid water, and other "molten ices." Some astronomers suggest they might be called *ice giants* instead of gas giants.

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. These basic features of the Solar System 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 bodies, inner and outer; the rocky ones are near the Sun and the gaseous or icy 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.

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. Because 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.

INTERACTIVE

Solar System builder

Interstellar Clouds

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. The dust in this interstellar cloud blocks the light of background stars and glowing gas. Such clouds are common between the stars in our Galaxy even today, and astronomers now think all stars formed from them. Thus, although we are discussing 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 at least 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,

FIGURE 8.10
Hubble Space Telescope image of an interstellar cloud in which dust blocks background light. This may be similar to the one from which the Solar System formed.

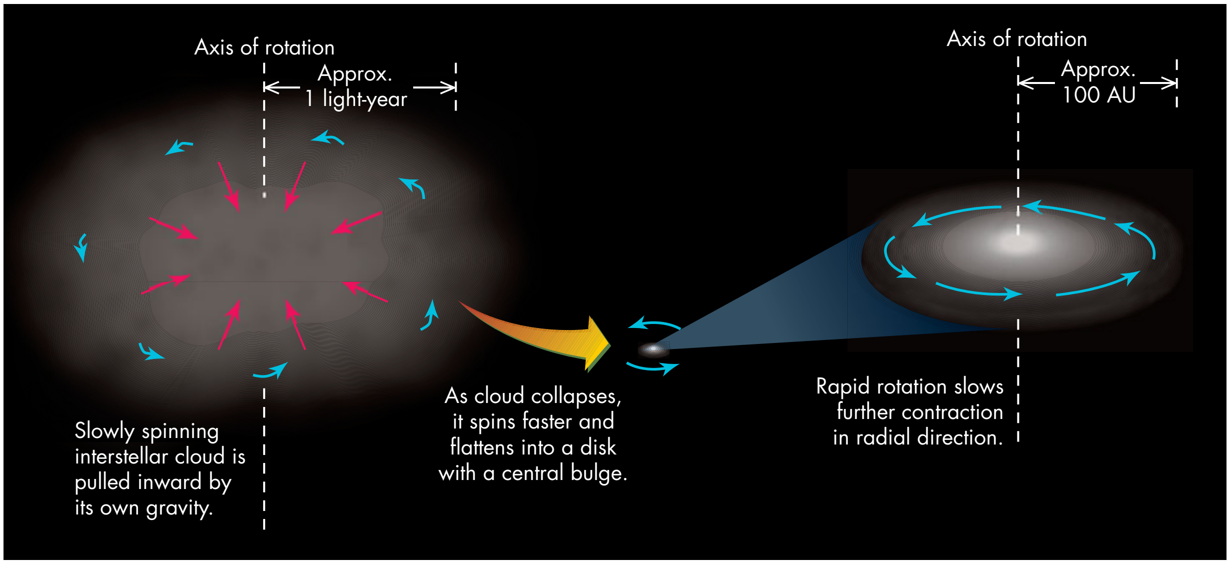
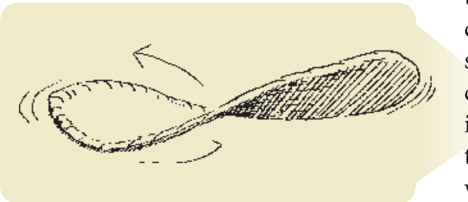


FIGURE 8.11
A sketch illustrating the collapse of an interstellar cloud to form a rapidly spinning disk. Note that the final size of the disk is not shown to scale—in actuality it would be thousands of times smaller than the cloud from which it formed.

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 illustrated 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.

Formation of the Solar Nebula

It took a few million years for the cloud to collapse and become a rotating disk with most of the mass concentrated in the center. The disk is called the **solar nebula,** and it eventually condensed into the planets while the bulge became the Sun. This explains the first obvious property of the Solar System—its disklike structure—which we noted at the beginning of this section.

ANIMATION

Solar System formation from an interstellar cloud

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 ring of material orbiting a star that is estimated to be about 200 million years old. A ring of material, perhaps similar to the Kuiper belt, orbits about 150 AU from the star. A planet may help to shape the ring, much as it is thought Neptune interacts with the Kuiper belt, but sightings of a possible planet have not been confirmed.

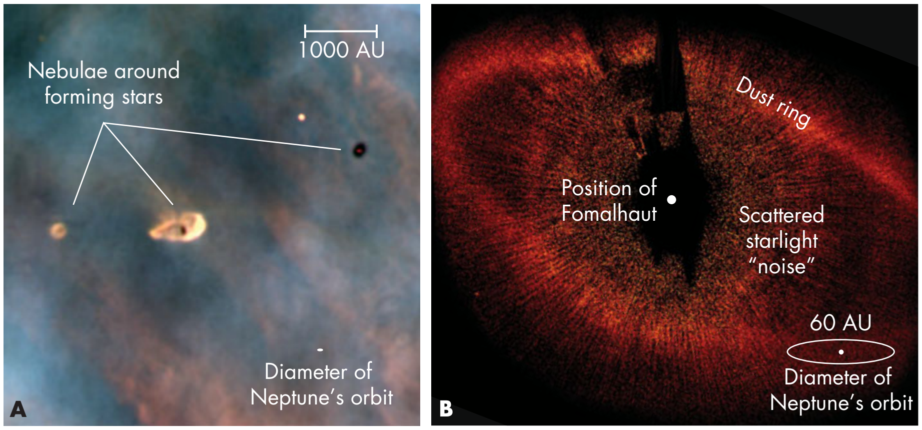


FIGURE 8.12
(A) The small blobs in this picture are stars in the process of formation (protostars) and their surrounding disk of dust and gas. These are in the Orion Nebula, a huge gas cloud about 1500 light-years from Earth. (B) Image of a dust ring that surrounds the star Fomalhaut. A small mask in the telescope blots out the star's direct light, which would otherwise overexpose the image. This ring of material may be similar to the Kuiper belt, and its sharp inner edge is probably the result of a planet orbiting inside the ring.

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.

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 8.14. 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.

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

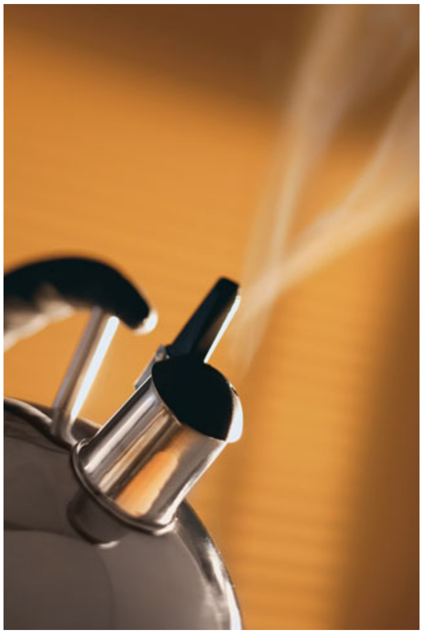


FIGURE 8.13
Water vapor cools as it leaves the kettle. The cooling makes the vapor condense into tiny liquid water droplets, which we see as the "steam."

* 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.

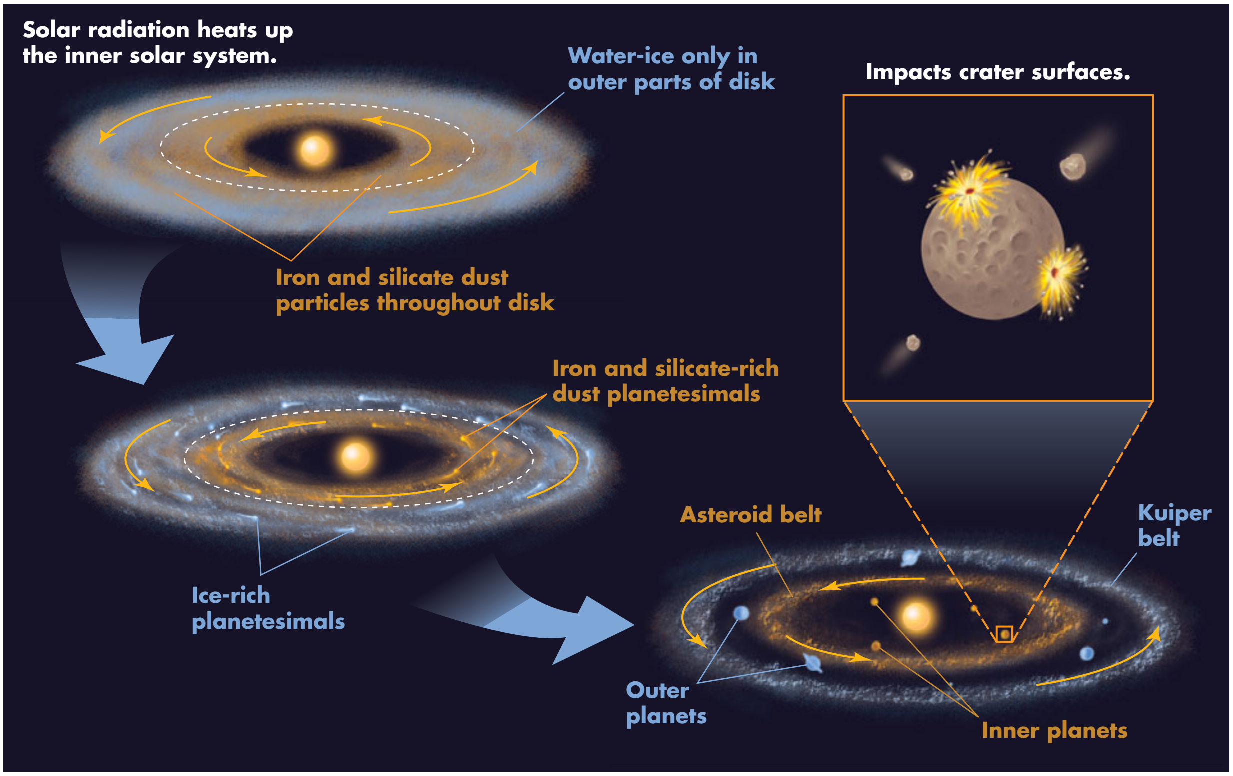


FIGURE 8.14
An artist's depiction of how the planets may have formed in the solar nebula.

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, 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 different types of planets in the inner and outer Solar System.

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. 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 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 the ices that could condense there are about 10 times more abundant than the silicate and iron compounds that were the only materials condensing in the inner Solar System.

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. (As discussed in the box below, some scientists think that there may have been enough gas for Jupiter to have formed directly from the gas, skipping the planetesimal phase.) The smaller and warmer 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 this 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: 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 radioactive heating, 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 think 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.

EXTENDING *our reach*

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 remote 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 warmer gas's resistance 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 are still searching for other evidence and performing more-detailed simulations.

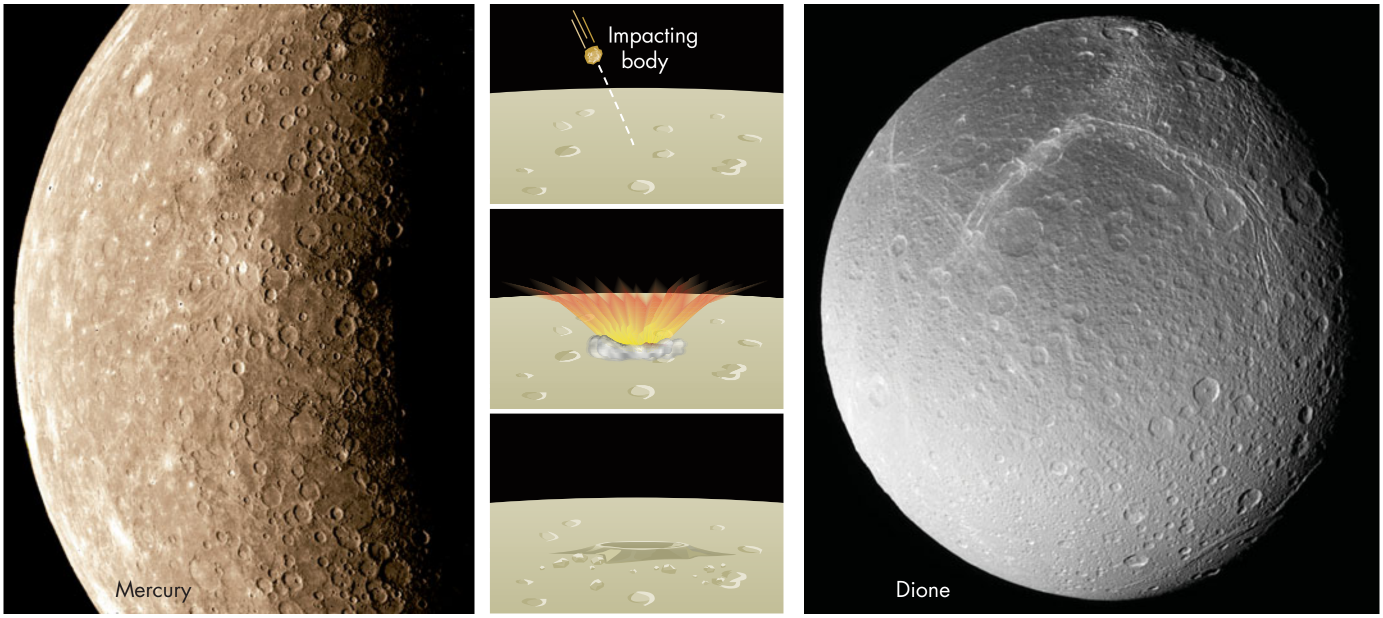


FIGURE 8.15
Pictures taken by spacecraft showing craters on Mercury and Saturn's moon Dione.

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 illustrates that bodies in both the inner and the outer Solar System were brutally battered by violent collisions.

As more and more large bodies built up from smaller planetesimals, there were occasional impacts between bodies so large that they did not just 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 the next two chapters, Mercury may have suffered a massive impact that blasted away much of its crust, and the peculiar rotation of Uranus and Venus may also have arisen from planetesimal collisions.

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. Studies of lunar rocks suggest that there may have been a period of heavy bombardment about 600 million years after the Solar System began forming, which some astronomers hypothesize was a period of heavy interaction between the giant planets and remaining planetesimals. The few that remain in the disk from Neptune's orbit out to about 50 AU form the Kuiper belt.

Formation of Satellite Systems

All four giant planets have flattened satellite systems in which the larger satellites (with few exceptions) orbit in the same direction as the planet spins. Several 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 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 that often record heavy cratering from the early history of the Solar System. Not all of them preserve this record, because volcanic activity and processes unique to their icy composition have sometimes melted their surfaces, erasing the craters.

The large systems of satellites around the outer planets probably were formed from the same set of planetesimals that was building the planets themselves. Once a body grew massive enough that its gravitational force could draw in additional material, it became surrounded with debris that settled into a flat disk or rings. 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. This is particularly striking around Uranus, which has a system of rings and moons that orbit around its equator despite its extremely large tilt to the ecliptic (fig. 8.16).

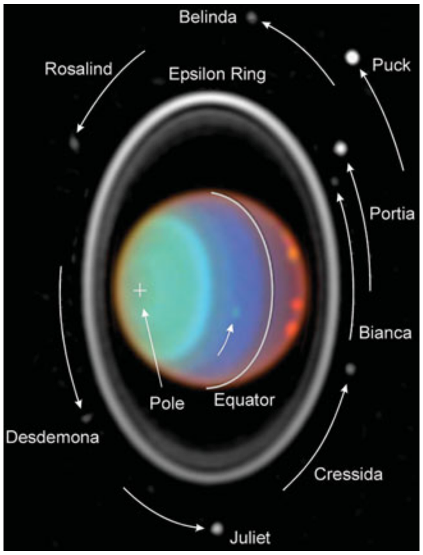


FIGURE 8.16
Hubble Space Telescope false-color infrared image of Uranus. The rings and satellites orbit around Uranus's equator even though the planet is tilted almost perpendicular to the plane of the Solar System, implying that these bodies all formed in place from a disk of material around the planet as it formed, like a miniature Solar System.

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 directly from the solar nebula, and because the nebula was rich in hydrogen, so are their atmospheres.

The inner planets were not massive enough, and were too hot, to capture gas from the solar nebula, 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? The answer seems to be that they exist in large numbers, but many have quite unexpected features.

8.3 Other Planetary Systems

INTERACTIVE

Exoplanets

The Discovery of Planets Beyond the Solar System

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.

Spotting a planet orbiting a star is a little like trying to spot a gnat flying near a lightbulb from miles away. Planets are so very small that the light they reflect is almost completely drowned by the light of their star. However, astronomers have been able to image a few exoplanets at infrared wavelengths. This has proved more successful than visible-wavelength observations because the star is dimmer in the infrared, and large planets often remain quite warm from their formation process for many millions of years. (We will see in chapter 9 that most of the large planets in the Solar System radiate more energy than they receive from the Sun, even though it has been billions of years since they formed.) Two examples of planets detected around stars in the infrared are shown in figure 8.17. The red object in figure 8.17A appears to be a young gas giant planet orbiting at a distance even farther than Neptune is from the Sun. Figure 8.17B and C show an infrared image of several gas giants orbiting a star and illustrates the difficult problem that astronomers face in removing scattered light from the star to reveal the planets. Even though their reflected light is difficult to see, astronomers have developed a variety of successful techniques for detecting exoplanets.

In fact, the first direct evidence for exoplanets came in the 1990s not from imaging but by observing how their gravitational pull affected the star they orbit. When a planet orbits its star, the planet exerts a gravitational force back on the star as a result

* 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.

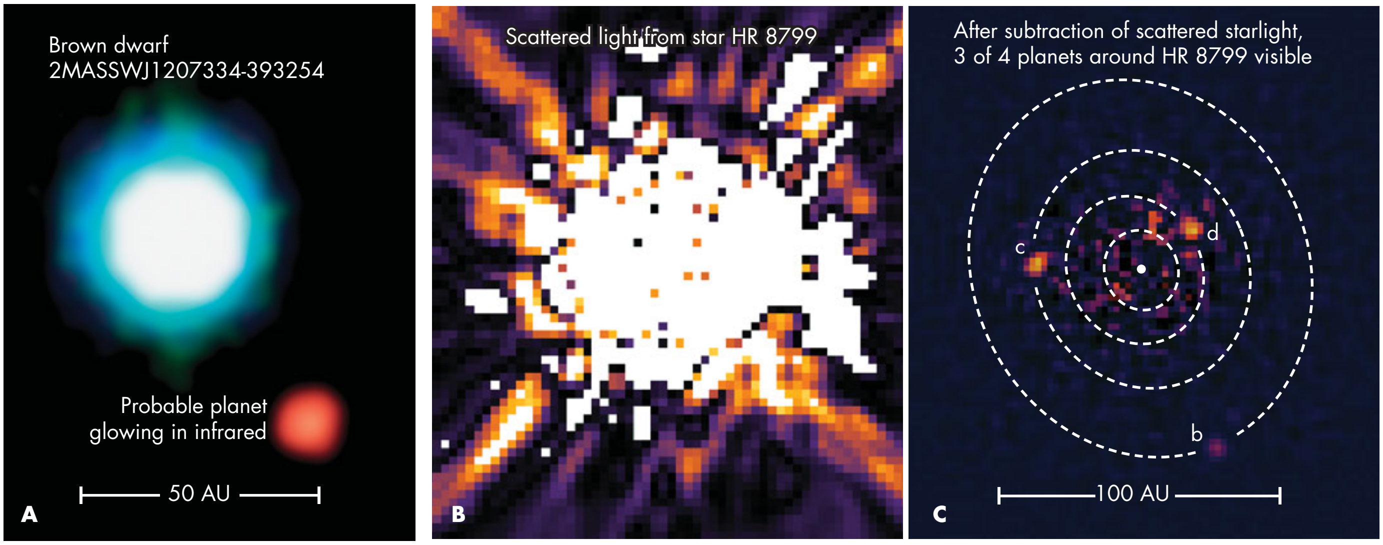


FIGURE 8.17
(A) The first image of an exoplanet was made at infrared wavelengths with the 8-meter Very Large Telescope (VLT) in Chile using adaptive optics. The exoplanet, which is seen glowing red from its infrared emission, is about 50 AU from the star it orbits, which is actually a low-mass "brown dwarf." (B) A Hubble Space Telescope infrared image of the star HR 8799 shows the challenge for finding planets produced by scattered light from the star. (C) Careful analysis of the scattered light allows most of it to be removed, revealing the presence of three giant planets orbiting the star. A fourth planet is known from other observations.

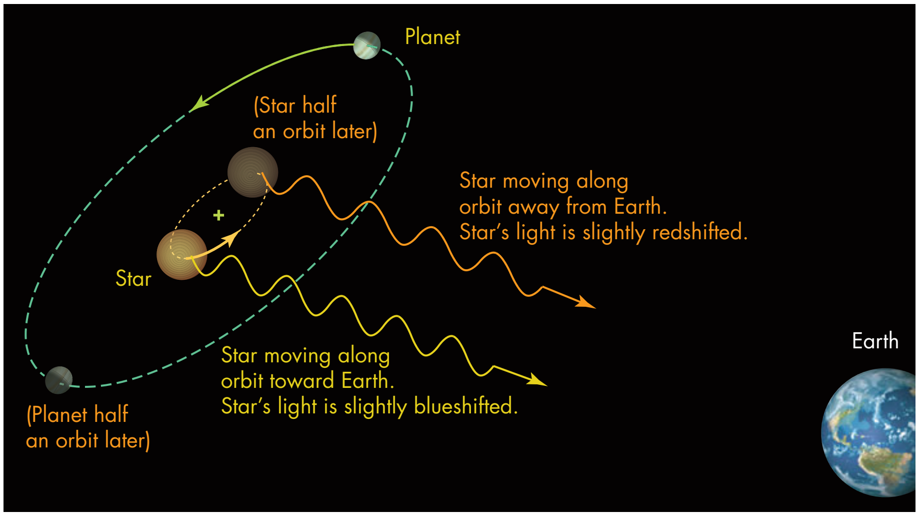


FIGURE 8.18
Detecting a planet from the motion of the star it orbits. The star's light is alternately redshifted and blueshifted as it responds to the gravitational pull of the planet.

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. 8.18). 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 500 exoplanets by early 2012, and it is even possible to detect multiple planets orbiting a star because each planet's pull produces a wobble with a different period.

ANIMATION

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

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. 8.19). However, all of these planets are massive, at least 10 times Earth's mass, and three of the planets orbit at distances much closer than Mercury's distance from the Sun.

The Doppler method for detecting exoplanets works best for massive planets that orbit near their star. This makes the star's wobble larger and faster. At present we would probably not be able to detect the planets in a system that was just like our

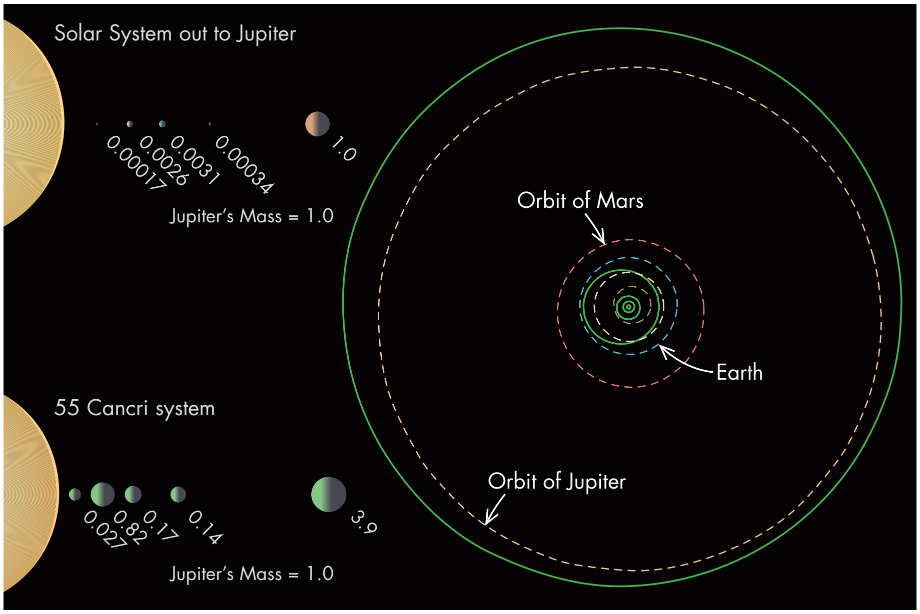


FIGURE 8.19
The 55 Cancri system contains five known planets around a star that is very similar to the Sun. The estimated masses (compared to Jupiter) for these planets and their orbits are compared with the five innermost planets in the Solar System. The figure also shows the approximate relative sizes 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.

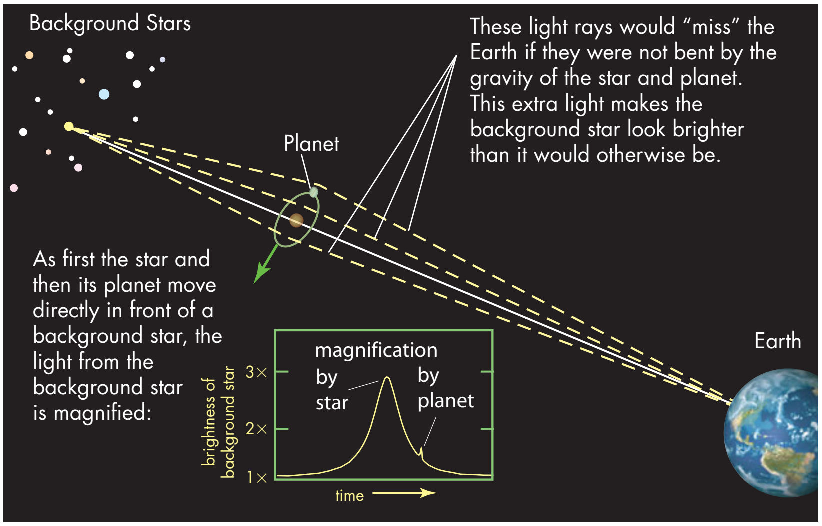


FIGURE 8.20
Detecting a planet by the slight bending of light from a background star caused by the planet's gravity.

Solar System except possibly Jupiter. 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 8.20 schematically shows. 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.**

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. 8.20). 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 mass 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 large Pluto. More than a dozen more of these brightening events were detected in subsequent years, including one planet that is only about 40 percent more massive than Earth. This gravitational lensing method shows promise for detecting low-mass planets, but recently another technique has succeeded in detecting even smaller exoplanets.

* 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.

Transiting Exoplanets

Another method for detecting exoplanets has become the major source of new discoveries in recent years. This method works for exoplanets whose orbits are aligned so the planet passes in front of, or **transits,** their star. As the planet transits in front of the star, the light is slightly dimmed, as illustrated in figure 8.21. At first this method was successfully applied only to a few relatively large planets, but the *Kepler* satellite launched by NASA in 2009 has much better precision than any Earth-based telescope, and is monitoring nearly 150,000 stars. So far it has identified more than 2000 candidate planets transiting their stars, although fewer than 100 have been confirmed. Nevertheless, these include some of the smallest exoplanets yet found, systems with as many as 6 exoplanets, and unusual systems, such as Kepler-35 in which a Saturn-size planet orbits a pair of stars.

Figure 8.22 shows diagrams of all of the systems where four or more planets have so far been detected orbiting their star. These include planets discovered by the Doppler and the transit methods. Looking at figure 8.22, you can see that none of these exoplanetary systems looks very much like our own. All of these systems have planets orbiting closer to their star than Mercury's distance from the Sun, and in fact this is true of about half of the nearly 800 exoplanets now known. We should keep in mind that the Doppler and transit methods favor finding planets that orbit close to their stars, so exoplanets with small orbits may be overrepresented in our sample. Nevertheless, even exoplanets with masses implying that they are gas giants are orbiting at these small distances.

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

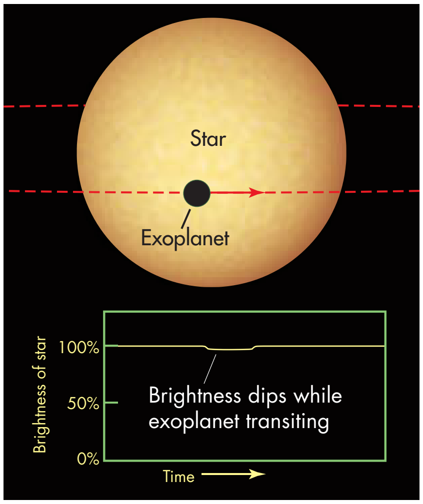


FIGURE 8.21
Detecting an exoplanet by the transit method. If a planet passes in front of (transits) its star, it diminishes the light we see. A planet with 10% the radius of its star, as shown, blocks 1% of its area.

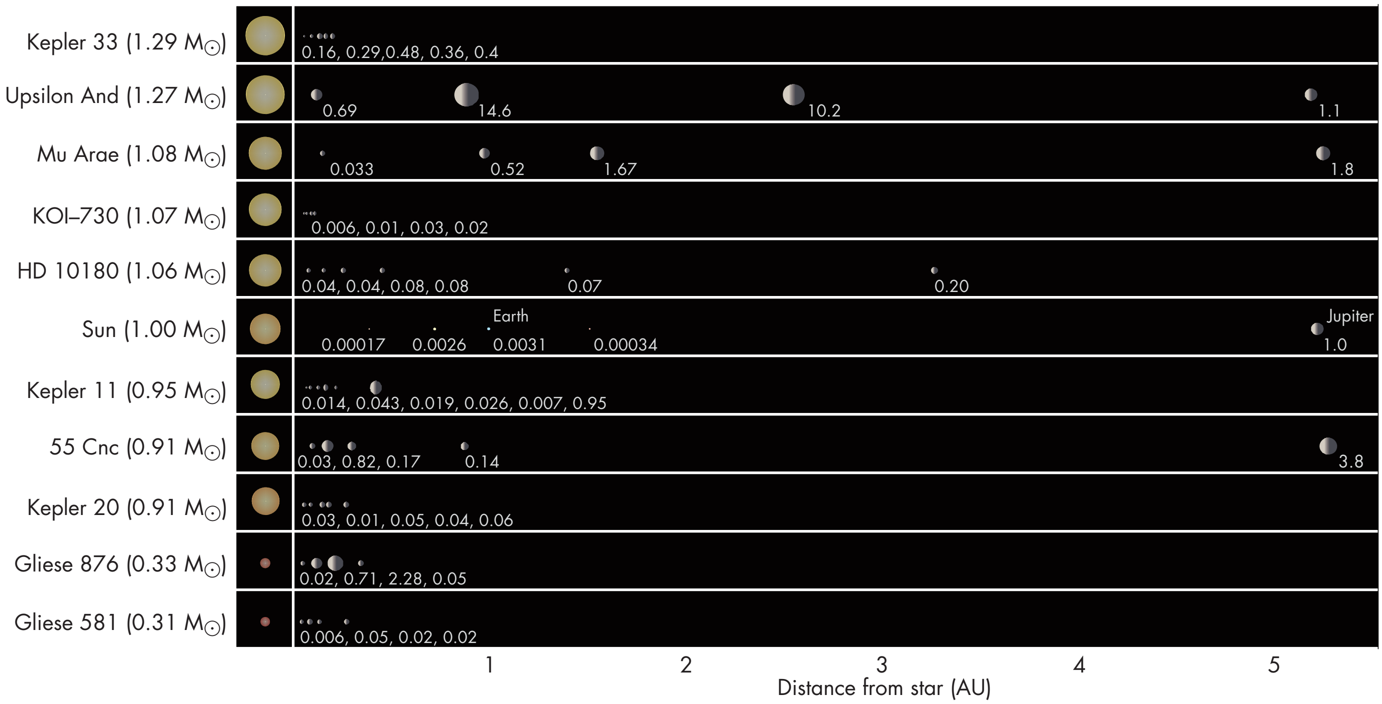


FIGURE 8.22
Comparison of the orbital radii and relative sizes of exoplanetary systems with the Solar System. Systems with four or more known exoplanets are shown, organized according to the mass of the star that they orbit. The sizes of the dots are based on the mass of each exoplanet, and approximately indicate their true relative size. The numbers indicate the mass of each planet in units of Jupiter's mass.

EXTENDING *our reach*

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.

need to understand what is different in these systems, or find a new mechanism to 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 Extending Our Reach: "Migrating Planets").

One of the interesting features of the transit method is that it gives us information about the radius of the exoplanet from the amount of dimming that is observed. The smallest of these that have been confirmed are similar in size to the Earth, as illustrated in figure 8.23. The three small exoplanets shown that are part of the KOI-961 system all orbit at less than 1/60th of an AU, and presumably are heated to high temperatures by their star. If we can also make mass estimates using the Doppler method, we can find an exoplanet's density. When the density is low, we can infer that the planet is a gas giant, and when it is high, a terrestrial planet. Some exoplanets with masses comparable to Jupiter's appear to have densities more like Earth. Given the uncertainties in some of the measurements, it may be too early for firm conclusions, but it appears that there may be both giant terrestrial exoplanets and mini Jovian exoplanets.

Transiting exoplanets offer us additional opportunities to study their composition. For example, a planet of the Sun-like star HD209458 orbits so that it passes between us and the star every 3.5 days. The exoplanet's mass is about 70% of Jupiter's mass, and

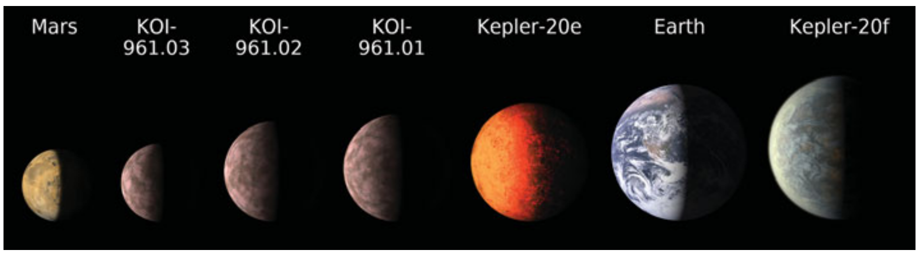


FIGURE 8.23
Artist's impression of the smallest exoplanets found by the *Kepler* satellite compared to Earth and Mars.

from the amount of the star's light it blocks, astronomers deduce that its diameter is about 1.3 times Jupiter's. This tells us that its density is less than one-third of Jupiter's density. 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.

Not only are many of the giant exoplanets "too close" to their star, many also are in very elliptical orbits (rather than the essentially circular ones in our own system). That 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, but our rapidly expanding knowledge about exoplanetary systems is beginning to shed light on just how different they may be from our Solar System.

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. Which are inner and outer planets?
2 (8.1) What is Pluto, and why isn't it a planet?
3. (8.1) Where are the asteroid belt, the Kuiper belt, and the Oort cloud? What kind of objects are in or come from them?
4. (8.1) Make a sketch of the Solar System showing top and side views.
5. (8.1) What is Bode's rule?
6. (8.1) How do we know the composition of Jupiter?
7. (8.1) What properties, apart from position, distinguish the terrestrial and Jovian planets?
8. (8.1) How old is the Solar System? How do we know?
9. (8.2) What is an interstellar cloud? What does it have to do with the Solar System?
10. (8.2) What is the solar nebula? What is its shape and why?
11. (8.2) Why are there two main types of planets?
12. (8.2) What is the difference between condensation and accretion?
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 moons form around outer planets?
16. (8.2) How did the craters we see on many of the planets form?
17. (8.2) Describe a theory of how planets may have formed their atmospheres.
18. (8.2) How would you describe the formation of the Solar System to a little brother or sister?
19. (8.3) What observations of other solar systems have been made that support the solar nebula hypothesis?
20. (8.3) What methods are used to find exoplanets?
21. (8.3) How do some exoplanets differ from what we might expect? Does this prove the nebula theory is wrong?

THOUGHT QUESTIONS

1. (8.1) Make arguments supporting the rules adopted for defining planets and dwarf planets, or, create and justify your own set of rules.
2. (8.2) What kinds of physics would be important to include in a computer simulation of solar system formation?
3. (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.
4. (8.3) How do some exoplanets differ from what we might expect? Does this prove the nebula theory is wrong?

PROBLEMS

1. (8.1) (a) By what factor would the Sun be shrunk to be the size of a large beach ball, 1 meter in diameter? (b) Calculate the distances and diameters of Mercury, Earth, Ceres, Jupiter, Neptune and Pluto if the whole Solar System were shrunk. (b) and their masses be if their density stayed the same?
2. (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.)
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) Kepler 30-b is an exoplanet orbiting a star of about 1 solar mass. Its orbital period is nearly 29 days. Calculate the semimajor axis of its orbit in AU. (Use Kepler's laws.)
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 8.7, 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 semimajor axis of 0.22 AU. (Remember to convert distances to meters and masses to kilograms when using the equation.)
8. (8.3) Imagine an alien is detecting the Earth as it transits our Sun. Compute the ratio of the areas of the Earth's disk and the Sun's to roughly estimate what percentage of the Sun's light the Earth blocks mid-transit. What percentage would Jupiter block?

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. (8.1) Which of the following best describes the planets' spins?
   (a) All spin counterclockwise.
   (b) Very few spin at all.
   (c) The spins often reverse.
   (d) Most spin counterclockwise.
   (e) The spins are random.
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. (8.2) Suppose a number of planets all have the same mass but different sizes and temperatures. Which of the following planets is most likely to retain a thick atmosphere?
   (a) Small, hot
   (b) Small, cool
   (c) Large, hot
   (d) Large, cool
6. (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.
7. (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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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 8.7: 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."

PROJECT

Exoplanets: 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?