A reclassification of the objects in our solar system by the International Astronomical Union reduced the number of planets to eight; asteroid Ceres, Pluto, and Eris are the first members of the "dwarf planet" category.

What's in a name? Amazingly, we did not have a scientific definition of what a planet is until August 24, 2006. Between 1930, when Pluto was discovered, and the early 1990s, we talked about the four terrestrial planets, the four Jovian planets, and Pluto, an odd planet that did not fit the other two categories. Discoveries of icy objects from hundreds to over 1000 km across in the region beyond Neptune forged a different picture of our solar system, one in which Pluto is but a nearby representative of the very populous class of icy dwarfs found in the Kuiper belt (the disk-shaped region between Neptune's orbit and 30–500 astronomical units [AU] from the Sun). A few of these icy objects have similar sizes to Pluto, and one of them is a bit larger. We discuss this class of objects and their region in Chapter 10.

What should we call these new objects? The International Astronomical Union (IAU) is the only body that can decide, and a fierce debate was reignited about the definition of a planet. At the end, the IAU resolved that objects in our solar system were classified into three categories as follows.

1. A **planet** is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydro-
2. **A dwarf planet** is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, (c) has not cleared the neighborhood around its orbit, and (d) is not a satellite.

3. All other objects except satellites orbiting the Sun shall be referred to collectively as **small solar-system bodies**.

As a result of this classification, there are now only eight planets in our solar system: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. Pluto is now a dwarf planet, along with the asteroid Ceres and Eris, an object a bit larger than Pluto in the Kuiper belt. The IAU will establish a process to assign borderline objects into either dwarf planet or other categories. The third category above includes most of the asteroids, most of the objects beyond the orbit of Neptune, comets, and other small bodies.

As expected, not everyone is happy with the new definition. The wording is indeed not precise, and most arguments are about the meaning of an object “clearing its neighborhood around its orbit”. The process of “clearing” is a continuous one and is related to how much an object dominates the dynamics of other objects in its neighborhood. The wording might need to be fixed still, but the concept is clear. The arguments have given us another example of how science is done, and along with our observations and the new discoveries of more Pluto-sized icy objects in the Kuiper belt that will surely follow, a new and exciting view of our solar system is emerging.

Much of what we know about the outer planets in our solar system and many of the photos of them in this book are the result of the Voyager missions, which we describe in a nearby Advancing the Model box. Before we begin to examine the individual planets and satellites in our solar system, we need to develop a common framework in order to understand similarities and differences among these objects. We cannot possibly expect to understand the universe by simply describing in detail all known characteristics of all its objects. The information we collect must be used to develop an understanding (a model) of how these characteristics developed and why certain objects (or groups of objects) seem to have similar or different characteristics from others in the same system. Such knowledge will allow us to make reasonable generalizations about similar systems everywhere in the universe.

In previous chapters we have pointed out some patterns among the planets of our solar system. For example, Kepler’s third law tells us of the relationship between a planet’s distance from the Sun and its period of revolution. Before turning to the individual planets, an examination of other patterns of similarities and differences among the planets will be helpful. In this chapter, we present our current understanding of our own planetary system and of how such systems form around stars. In the next three chapters, we study in detail the major objects in it.

### 7-1 Sizes and Distances in the Solar System

The Sun contains almost all the mass (about 99.85%) of the solar system and is about 10 times larger in diameter than the largest planet (Jupiter). Figure 7-1 shows the planets drawn to scale. At the bottom of the drawing, you see the partial disk of the Sun. If the Sun had been drawn as a complete circle fitting the page, many of the planets would have been too small to see. The Sun’s diameter is about 1,390,000 kilometers, whereas the Earth’s diameter is about 13,000 kilometers. Thus, the diameter of the Sun is about 110 times that of Earth. To picture this better, think of the Sun as an object the size of a basketball, a sphere 9.4 inches in diameter. On this
The Voyager Spacecraft

In the period 1976–78, an astronomical event took place that only occurs about once every 177 years. During this time the large outer planets Jupiter, Saturn, Uranus, and Neptune were bunched closely together looking out from Earth, as they traveled their orbits around the Sun. This had not happened since the time of Napoleon. Starting in 1972, NASA scientists and engineers planned to take advantage of this situation by sending out two space probes to explore these planets. Voyager 1 was launched on September 5, 1977, on a faster trajectory than Voyager 2, which was launched 16 days earlier. Over the next few years they revolutionized our understanding of the solar system.

Keeping in touch with the two tiny spacecraft turned out to be a trial in overcoming adversity and avoiding disaster. Voyager 2’s onboard computers often detected emergencies when none existed. For example, during the initial launch of the rocket from Earth, the computers interpreted the rapid acceleration of the spacecraft as outside normal operation and tried to reprogram the thrusters to slow it down. Later, the craft’s radio receiver blew a fuse and the craft could receive only a limited range of signals from Earth. NASA engineers overcame these problems, and the two space probes continued on their way.

Voyager 1 arrived at Jupiter in March of 1979, about 4 months earlier than Voyager 2, and the two craft sent back unprecedented views of the planet during the spring and summer. They discovered the rings of Jupiter, which had never before been seen, and then went on to explore the large moons Io, Ganymede, Callisto, and Europa.

Voyager 1 began making discoveries about Saturn in October 1980, when it was still 30 million miles away from the planet. Voyager 2 followed in August of 1981. Between them, the spacecraft sent back images of the complex structure of Saturn’s rings and the violent storms in Saturn’s atmosphere and detected an atmosphere on Titan, Saturn’s largest moon.

Four and a half years passed before Voyager 2 reached Uranus, making its closest approach in January 1986. It sent back photos of the Uranian rings and its major moons, before the craft was reprogrammed for the trip to Neptune. Voyager 2 passed within 3100 miles of Neptune in August 1989 and then went on into deep space.

(Voy you might think 3100 miles is a large distance, but remember that Neptune is 30,800 miles across and almost 2700 million miles from Earth. Sending a space probe that close to Neptune is like using a rifle to shoot a penny 2 miles away— and hitting it!)

The spacecraft are now on an extended mission, searching for the outer limits of the Sun’s magnetic field and outward flow of the solar wind (the heliopause boundary). After the spacecraft cross this boundary, they will be able to take measurements of the interstellar fields, particles, and waves without being influenced by the solar wind.

Voyager 1 has already passed the termination shock; this is the region where the solar wind meets the interstellar gas, thus quickly slowing down, becoming denser and hotter. Voyager scientists were surprised to find that the speed of the solar wind beyond the shock was much less than predicted and that at times it seemed to be flowing backward, suggesting a possible correlation with the less active phase of the solar cycle (which we discuss in Chapter 11). They also found that the direction of the interplanetary magnetic field beyond the shock varies much slower (every 100 days or so) than expected (every 13 days or so, half of the Sun’s rotational period); this field is carried out by the solar wind, with the alternating directions forming a pattern of stripes. More surprisingly, the shock region does not seem to be the source of cosmic rays; these are energetic charged particles that originate in outer space; they travel at nearly the speed of light and strike Earth from all directions. The intensity of these rays has been steadily increasing as the spacecraft moves farther from the shock, suggesting that their source is even farther from the Sun.

The Voyager spacecraft continue to make surprising discoveries and have shown that the Sun’s interaction with the surrounding interstellar matter is more complex than we had imagined. In December 2006, Voyager 1 (Voyager 2) was at a distance of 101 AU (81 AU) from the Sun, escaping the solar system at a speed of about 3.6 AU/year (3.3 AU/year), 35° out of the ecliptic plane to the north (48° south). By about 2015, Voyager 1 is expected to cross into interstellar space, beyond the heliopause, followed by Voyager 2 about 5 years later. Electrical power on the Voyager spacecraft is produced from the heat generated by the natural decay of plutonium. The spacecraft have enough power to operate at least until 2020.
scale the Earth would be about the size of the head of a pin, a tenth of an inch in diameter (Figure 7-2). Jupiter is the largest planet, with a diameter about 11 times that of the Earth. On our scale, Jupiter would have a diameter of about an inch. The dwarf planet, Pluto has a diameter about one fifth that of Earth. In our scale model it would be a grain of sand, about 1/64 inch across! Appendix C lists the actual sizes of the planets, along with their sizes compared with the Sun and the Earth.

Now let us consider the distances between the planets. Table 7-1 shows the average distance of each planet from the Sun in astronomical units and according to our model. To continue the model in which the Sun is a basketball, we might put the basketball at one end of a tennis court. A pin at the opposite end of the tennis court would be the Earth. A 1-inch ball, one and a half football fields away would be

<table>
<thead>
<tr>
<th>Object</th>
<th>Distance from the Sun (AU)</th>
<th>Mean Diameter</th>
<th>On Our Scale Distance from Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>—</td>
<td>9.4 inches (23.88 cm)</td>
<td>33 feet (10 m)</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.39</td>
<td>0.03 inch (0.08 cm)</td>
<td>33 feet (10 m)</td>
</tr>
<tr>
<td>Venus</td>
<td>0.72</td>
<td>0.08 inch (0.21 cm)</td>
<td>61 feet (19 m)</td>
</tr>
<tr>
<td>Earth</td>
<td>1.0</td>
<td>0.09 inch (0.22 cm)</td>
<td>84 feet (26 m)</td>
</tr>
<tr>
<td>Mars</td>
<td>1.52</td>
<td>0.05 inch (0.12 cm)</td>
<td>128 feet (39 m)</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.20</td>
<td>0.97 inch (2.45 cm)</td>
<td>438 feet (134 m)</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.58</td>
<td>0.81 inch (2.07 cm)</td>
<td>807 feet (0.15 mile) (246 m)</td>
</tr>
<tr>
<td>Uranus</td>
<td>19.20</td>
<td>0.35 inch (0.88 cm)</td>
<td>1616 feet (0.31 mile) (493 m)</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.05</td>
<td>0.33 inch (0.85 cm)</td>
<td>2530 feet (0.48 mile) (771 m)</td>
</tr>
<tr>
<td>Pluto</td>
<td>39.24</td>
<td>0.02 inch (0.04 cm)</td>
<td>3303 feet (0.63 mile) (1007 m)</td>
</tr>
</tbody>
</table>

As we discuss the sizes of solar system objects and the distances between them, try to form a mental picture of the relative distances rather than just memorizing the values.
Jupiter. Pluto would be a grain of sand a kilometer away! Between these objects we put nothing—or almost nothing. There are only the other planets, all smaller than Jupiter, and some even smaller objects.

More than 4000 asteroids that are too small to include in our scale model have been discovered in the solar system. The largest of these asteroids has a diameter of about 1000 kilometers, or 600 miles. Perhaps another 100,000 much smaller asteroids orbit the Sun, most of them in the asteroid belt between Mars and Jupiter. In addition, trillions of comets orbit the Sun in a huge shell at a distance of about 40,000–100,000 AU. We discuss these objects in more detail in Chapter 10.

Figure 7-1 shows the planets as disks, but they are actually spheres. In trying to imagine their comparative sizes, keep in mind that the volume of a sphere is proportional to its radius cubed. For example, the Sun’s diameter is about 110 times that of Earth, but the Sun’s volume is about $110^3$ or 1.3 million times that of Earth’s. Similarly, Jupiter’s volume is about $11^3$ or 1400 times that of Earth’s.

### Measuring Distances in the Solar System

In Chapter 2 we discussed how Copernicus used geometry to calculate the relative distances to the planets. That is, he was able to calculate that Mars is 1.5 astronomical units (AU) from the Sun, although he could not determine the value of an astronomical unit. Today we can measure the distances to planets using radar. We send radar signals to a planet and measure the time required for the signal to reach the planet and bounce back. Then, knowing that radar signals travel at the speed of light ($3 \times 10^8$ m/s, or $3 \times 10^5$ km/s), we can calculate the distance to the planet.

When the nearest planet, Venus, is closest to Earth, a radar signal still requires nearly 5 minutes to get there and back. The great distances in the solar system become clearer when we realize that if such a signal could be emitted in New York City and reflected from something in Washington, D.C., only 0.002 second would be required for the round trip.

**EXAMPLE**

Suppose we bounce a radar signal off of Mars. The signal returns to Earth 22 minutes after being transmitted. How far away is Mars?

**SOLUTION**

First, we realize that 22 minutes is the time the signal takes to reach Mars and return to Earth. So a one-way trip requires 11 minutes. Now let’s change 11 minutes to seconds (as our signal speed is given in kilometers/second).

$$11 \text{ min} \times \frac{60 \text{ s}}{1 \text{ min}} = 660 \text{ s}$$

Now,

$$\text{distance} = \text{velocity} \times \text{time} = (3.0 \times 10^5 \text{ km/s}) \times (660 \text{ s}) = 2.0 \times 10^8 \text{ km}$$

To check that this is a reasonable answer, recall that one astronomical unit is $1.5 \times 10^8$ kilometers. Thus, our calculated distance is 1.33 AU. Because the orbit of Mars is 1.5 AU from the Sun, the distance from Earth to Mars varies from about 0.5 to 2.5 AU. Therefore, at some point in its orbit, it is possible for Mars to be at our calculated distance from Earth.

**TRY ONE YOURSELF**

When Venus is at its closest distance to Earth, it requires about 4.7 minutes for a radar signal to travel to Venus and back. What is the distance to Venus? Convert the answer to astronomical units and check it with the correct distance given in Table 7-1.
As we pointed out in Chapter 2, the relative distances to the planets (from Mercury to Saturn) were known in Copernicus’ time. We saw that Kepler used these data to formulate his third law. From the time of Copernicus, people have wondered if there is a pattern to the distances of the planets from the Sun.

In 1766, a German astronomer named Johann Titius found a mathematical relationship for the distances from the Sun to the various planets. The rule was publicized by Johann Bode, the director of the Berlin Observatory, in 1772, and is known today as the Titius-Bode law or simply Bode’s law. Table B7-1 illustrates how the law works. Column 1 shows a series of numbers starting with zero, jumping to three, and then doubling in value thereafter. Column 2 was obtained by adding 4 to each of those values. Finally, to get column 3, we divide each of the column 2 values by 10. Now compare these figures with the measured distances (in AU) of each of the planets from the Sun.

The table shows that the Titius-Bode law fits fairly well, except that there is a gap: The law seems to indicate that there should be a planet between Mars and Jupiter and, further, that the planet should be 2.8 AU from the Sun. In addition, the law predicts that if other planets were found beyond Saturn, the next one would be about 19.6 AU from the Sun. Indeed, in 1781, the planet Uranus was discovered at a distance of 19.2 AU from the Sun by William Herschel in England.

With this confirmation of the validity of the Titius-Bode Law, a group of German astronomers (who called themselves the Celestial Police) divided the zodiac into regions, planning to assign a specific region to each of a number of astronomers who would systematically search for the missing planet at 2.8 AU. The searchers did not find it, however. Instead, a monk who was working on a different project discovered the largest of the asteroids at the distance predicted for Bode’s missing planet. (See the Advancing the Model box on page 198.) Although it was first thought that this was the missing planet, the discovery within a few years of other objects at about the same distance made it obvious that things were not this simple. The Titius-Bode law could not account for the large number of “planets” between Mars and Jupiter. (However, it is possible that tidal interactions from Jupiter did not allow all these objects to coalesce and form a planet at this distance from the Sun.)

Neptune and Pluto were discovered after the discovery of the asteroids. How well do they fit the Titius-Bode law? Neptune does not fit the prediction at all, but Pluto’s distance of 39.24 AU comes fairly close. (Because Pluto’s characteristics are more like those of a satellite than a Jovian planet, it has been suggested that early in the history of the solar system, collisions and close encounters between the outer planets and Pluto-like objects could have changed Pluto from being a satellite to being a planet, while knocking Uranus on its side and moving Neptune closer to the Sun; however, recent work has all but ruled out the idea that Pluto was originally a satellite of Neptune. The suggested explanations for the rotation of Uranus, and for that matter Venus, are still at the speculative stage.)

Relationships such as the Titius-Bode law are said to be empirical. This means that they are found to work, but they are not related to any theoretical framework; we don’t know why they work. The Titius-Bode law isn’t a particularly good empirical law, however. The law is not accurate even for the planets it fits; it does not fit Neptune at all, and it is not internally consistent. (The number in column 1 of Table B7-1 is not doubled in one case. In this chapter, we show that theories proposed for the formation of the solar system account for the fact that the more distant a planet is from the Sun, the farther it is from other planets. Astronomers may be able to judge the significance of the Titius-Bode law better when, at some future date, they are able to observe planetary spacing around other stars.)
7-2 Measuring Mass and Average Density

How do we know the masses of the Sun and planets? To answer this we must return to Kepler’s third law, as modified by Newton, which relates each planet’s distance from the Sun to its period of revolution. Using standard units (meters for distance, seconds for period, and kilograms for mass), we saw in Chapter 3 that Newton’s formulation of Kepler’s third law is

\[
\frac{a^3}{P^2} = \frac{G}{4\pi^2} \cdot (m_1 + m_2)
\]

where \(a\) = semimajor axis of the orbit, \(P\) = period of the orbit, \(m_1, m_2\) = the masses of the two objects, and \(G\) = the gravitational constant.

In some cases, however, it is easier to measure the semimajor axis \(a\) in AU and the period \(P\) in years; then

\[
\frac{a_{\text{AU}}^3}{P_{\text{yr}}^2} = \frac{m_1 + m_2}{m_{\text{Sun}}}
\]

Let us now consider the case of a planet orbiting the Sun. Because the mass of even the largest planet, Jupiter, is less than 0.001 times the mass of the Sun, the sum of the two masses is essentially equal to the mass of the Sun \((m_1 + m_2 = m_{\text{planet}} + m_{\text{Sun}} = m_{\text{Sun}})\). Thus, for objects in orbit around the Sun, we can write the preceding equation as

\[
\frac{a^3}{P^2} = \frac{G}{4\pi^2} \cdot m_{\text{Sun}}
\]

Because the Sun’s mass is constant, the value on the right side of Newton’s equation is very nearly the same for each of the planets, just as Kepler said. Newton’s statement of the law, however, allows us to calculate something else—the mass of the Sun. All we need to know in order to do this is the semimajor axis of one planet’s elliptical orbit and that planet’s period of revolution around the Sun.

Even more important, Newton’s formulation of Kepler’s third law applies to any system of orbiting objects. For examples, Jupiter’s system of moons resembles the solar system, here the equation lets us calculate the mass of Jupiter, which is the central object in this case. As we discuss in Section 7-4, every planet except Mercury and Venus has at least one natural satellite. Thus, to calculate the mass of one of these planets, we need only know the distance and period of revolution of at least one of its satellites.

**Example**

The average distance of the Earth from the Sun is \(a = 1\) AU \(\approx 1.5 \times 10^{11}\) m and the Earth’s orbital period is \(P = 1\) year \(\approx 365.24\) days \(\approx 3.15 \times 10^7\) s. Using Kepler’s third law as modified by Newton, find the mass of the Sun.

**Solution**

The mass of the Earth is much smaller than the mass of the Sun. Therefore

\[
\frac{a^3}{P^2} = \frac{G}{4\pi^2} \cdot (m_{\text{Earth}} + m_{\text{Sun}}) \approx \frac{G}{4\pi^2} \cdot m_{\text{Sun}}
\]

and thus

\[
\frac{G}{4\pi^2} \cdot \frac{(1.5 \times 10^{11})^3}{(3.15 \times 10^7)^2} \approx 6.67 \times 10^{-11} \cdot 4 \cdot (3.14)^2 \cdot m_{\text{Sun}}
\]

Therefore, \(m_{\text{Sun}} \approx 2 \times 10^{30}\) kg.

**Try One Yourself**

The Moon orbits the Earth with a period of 27.32 days (which is \(2.36 \times 10^6\) seconds), and its semimajor axis is \(3.844 \times 10^8\) meters. Assuming that the Moon’s mass is negligible compared with Earth’s, use this data to calculate the mass of the Earth. When you check your answer in Appendix C, remember that the Moon’s mass is not really negligible compared with Earth’s.
What about Mercury and Venus, which have no moons? Their masses have been calculated on a few occasions by observing their effects on the orbits of passing asteroids and comets. No asteroid or comet has passed close enough to provide highly accurate data, however, and thus, the accuracy of the calculations was limited until space probes flew by these planets. If a space probe is put into orbit around a planet, the previous equation applies to it and allows us to calculate the mass of the planet. In practice, the space probe does not actually have to be put into orbit. By analyzing how the gravitational force of the planet changes the direction and speed of a probe during a flyby, we can calculate the planet’s mass, although by a more complicated method than the equation we have used.

When we consider the masses of the objects that make up the solar system, we should be impressed by the fact that the Sun makes up almost the entire system. Table 7-2 shows the masses by percentages of the total; the Sun’s mass is almost 99.9 percent of the total. Jupiter makes up most of the rest, having more than twice as much mass as the remainder of the planets combined.

### Calculating Average Density

The density of an object is defined as the ratio of the object’s mass to its volume. In the previous section, we discussed how we could calculate the mass of a solar system object. We have also discussed (in Section 6-1) how to use the small-angle formula to find the diameters of objects if we know their distances from Earth and their angular size. Unless the object is too small, its angular size can be measured with observations. The object’s distance from Earth can be obtained by using the methods described in Section 7-1.

Knowing the mass \( m \) and radius \( R \) of an object, its average density is given by

\[
\text{average density} = \frac{\text{mass}}{\text{volume}} = \frac{m}{\frac{4}{3} \pi R^3} = \frac{3}{4 \pi} \cdot \frac{m}{R^3}
\]

where we assumed that the object is approximately spherical.

#### EXAMPLE

When Venus is close to Earth, we measure its angular size to be about 54 arcseconds. Its distance from Earth at that point is 44.8 million kilometers. Using the small-angle formula (Section 6-1), we find that Venus’ diameter is 12,100 kilometers, and therefore, its radius is about 6050 kilometers. Kepler’s third law allows us to find Venus’ mass, about \( 4.87 \times 10^{24} \) kilograms. Now we are ready to calculate Venus’ average density.

\[
\text{average density} = \frac{3}{4 \pi} \cdot \frac{4.87 \times 10^{24} \text{ kg}}{(6,050,000 \text{ m})^3} = 5250 \text{ kg/m}^3
\]

This is equal to 5.25 g/cm³, in good agreement with the value of 5.24 g/cm³ found in Appendix C.

#### TRY ONE YOURSELF

The angular size of the Moon is 0.52 degrees and its distance from Earth is 384,000 kilometers. The Moon’s mass is \( 7.35 \times 10^{22} \) kilograms. Using all of these data, find the average density of the Moon and compare it with the value given in Appendix D.

---

### Table 7-2

<table>
<thead>
<tr>
<th>Object</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>99.85</td>
</tr>
<tr>
<td>Jupiter</td>
<td>0.095</td>
</tr>
<tr>
<td>Other planets</td>
<td>0.039</td>
</tr>
<tr>
<td>Satellites of planets</td>
<td>0.00005</td>
</tr>
<tr>
<td>Comets</td>
<td>0.01 (?)</td>
</tr>
<tr>
<td>Asteroids, etc.</td>
<td>0.0000005 (?)</td>
</tr>
</tbody>
</table>

As we mentioned in Section 6-3, after we know the average density of an object we can compare it with the densities of well-known materials such as water, rock, and iron. This allows us to make a reasonable guess about its composition. For example, the average density of Jupiter is 1.33 g/cm³ barely greater than that of water.
(1 g/cm³) and less than silicate rock (about 3 g/cm³). We can infer that Jupiter consists mostly of low-density materials (gas, liquids) with a small (compared with its overall size) core of iron, rock, and water; however, knowing the value of an object’s average density does not mean we can accurately predict its exact composition. Different combinations of materials can result in the same average density and an object’s gravity can affect the density of certain materials; however, even though there are limitations, we can gain reasonable insights into the makeup of an object by calculating its average density.

### 7-3 Planetary Motions

Figure 7-3 illustrates the orbits of the planets, drawn to scale. They are all ellipses, as Kepler had written and most are very nearly circular. For comparison, the orbit of the dwarf planet Pluto is eccentric enough that it overlaps the orbit of Neptune. In 1979, Pluto moved to a location in its orbit where it was inside Neptune’s orbit. Until 1999 it remained closer to the Sun than Neptune was. For the next 220 years Pluto will be farther from the Sun than Neptune.

All of the planets revolve around the Sun in a counterclockwise direction as viewed from far above the Earth’s North Pole. Their paths are very nearly in the same plane. This means that we can draw them on the same piece of paper without having to change their paths to view them face-on.

In Section 2-9 we showed that the eccentricity of an elliptical orbit is a measure of how much the orbit is less than perfectly circular. The eccentricities of the planets’ (and Ceres’ and Pluto’s) orbits are given in Appendix C. Notice how much Pluto and Mercury differ from the other planets in eccentricity.

All of the planets except Mercury and Venus have natural satellites revolving around them, just as the Earth does. The direction of revolution of most of these satellites is also counterclockwise, although there are some exceptions. Finally, as we see in the next section, most of the planets also rotate counterclockwise about an axis.

The fact that the planets have their orbits in basically the same plane, that they all orbit in the same direction, that most of them rotate in that same direction, and...
that most of their satellites revolve in that direction cannot be coincidence. We will recall these similarities when we discuss theories concerning the formation of the solar system; we must be sure that the theories explain these properties.

7-4 Classifying the Planets

When we examine the properties of individual planets in the following chapters, it will be clear that they divide easily into two groups. It is convenient to classify the four innermost planets—Mercury, Venus, Earth, and Mars—in one group, which we call the terrestrial planets because of their similarity to Earth (in Latin, “earth” is “terra”). The next four planets—Jupiter, Saturn, Uranus, and Neptune—are called the Jovian planets because of their similarity to Jupiter. As already noted, Pluto is unusual in several ways and it has been classified as a dwarf planet.

Size, Mass, and Density

The diameters of the planets, in kilometers and as ratios to Earth’s diameter, are given in Appendix C. Although the four terrestrial planets differ quite a bit from one another, they are all much smaller than the Jovian planets. Although the dwarf planet Pluto is out beyond the Jovian planets, it has a size more like the terrestrials.

The masses of the planets, given in Appendix C, present even bigger differences between the terrestrial and Jovian planets. Many people have a tendency to skip over tables and graphs. You are not expected to memorize the values given, but a few minutes looking at patterns and thinking of their meaning will yield much knowledge about the solar system. Study the values of the masses of the planets in terms of Earth’s mass. Notice the tremendous difference between the two classifications of planets. Earth is the most massive of the terrestrial planets, but the least massive Jovian planet has more than 14 times the mass of Earth. Again, Jupiter stands out as the giant.

Density values, given in Appendix C, differ between the terrestrial planets and the Jovian planets. The terrestrials are denser. This is because they are primarily solid, rocky objects, whereas the Jovians’ are composed primarily of liquid. At one time Jovian planets were commonly called “gas planets,” but now we know that they actually contain much more liquid than gas. The average density of the four terrestrial planets is about 5 g/cm³ (or five times that of water), whereas the average density of the four Jovian planets is about 1.2 g/cm³.

Satellites and Rings

Table 7-3 shows the number of natural satellites of each planet. Although there is no obvious pattern, the Jovian planets have more satellites. More details of the planetary satellites are found in Appendix D and in discussions of the planets in future chapters.

The table also indicates that all Jovian planets have rings. A planetary ring is simply planet-orbiting debris, ranging in size from a fraction of a centimeter to several meters. Motions of particles within the rings are extremely complex, due largely to gravitational interactions with nearby planetary satellites. In a sense, each particle of a ring may be considered a satellite of the planet, but if we do so, counting satellites becomes meaningless. Thus, we continue to speak only of the larger “moons” as being planetary satellites.

Rotations

We discussed planetary rotations in Section 1.8. The sidereal periods of planetary rotations are given in Appendix C. The sidereal rotational periods of the terrestrial planets differ considerably from one another; they range from Earth’s period of...
about 23.9 hours to Venus’ period of about 243 days; however, all of the Jovian planets rotate faster than Earth. They range from Jupiter’s period of about 9.9 hours to Uranus’ period of about 17.2 hours.

As we saw in Section 7-3, every planet revolves around the Sun in a counterclockwise direction when viewed from above the Earth’s North Pole. We know from previous chapters that when viewed from this perspective, the Earth rotates on its axis in this same counterclockwise direction and that the Moon also orbits the Earth in a counterclockwise direction. We might ask if this pattern holds elsewhere in the solar system. The answer is yes, in most cases. As shown in Figure 7-5, all of the planets except Venus, Uranus (and dwarf planet Pluto) rotate in a counterclockwise direction as seen from far above the Sun’s North Pole.

### The Discovery of the Asteroids

Johannes Kepler once proposed that there might be an undiscovered planet between Mars and Jupiter, because the large distance between their orbits does not follow the pattern of other orbits. The Titius-Bode law also seemed to predict such a planet. This led Francis von Zach, a German baron, to plan a systematic search for the planet. Giuseppe Piazzi, a Sicilian astronomer and monk, was one of the astronomers who had been chosen to search in one of the sectors into which von Zach had divided the sky. Before he was notified where he was to search, however, Piazzi discovered (on January 1, 1801) what he first thought was an uncharted star in Taurus. The object was far too dim to see with the naked eye. He named it Ceres after the goddess of the harvest and of Sicily. Continuing to observe it, he saw that it moved among the stars, and by January 24, he decided that he had discovered a comet. He wrote two other astronomers (including Bode) of his discovery, but on February 11, he became sick and was unable to continue his observations. By the time the astronomers received their letters (in late March), the object was too near the Sun to be observed.

Bode was convinced that the hypothesized new planet had been discovered, but he also realized that it would not be visible again until fall. By that time, it would have moved so much that astronomers would have a difficult time finding it again. This was because relatively few observations had been made of the object’s position, not enough for the mathematicians of the time to calculate its orbit. Fortunately, a young mathematician named Carl Friedrich Gauss, one of the greatest mathematicians ever, had recently worked out a new method of calculating orbits. He worked on Bode’s project for months and was able to predict some December positions for the object. On December 31, 1801, von Zach rediscovered the object.

The elation over finding the predicted planet did not last long, however, for another “planet” was found in nearly the same orbit about a year later. Its discoverer, Heinrich Olbers, was looking for Ceres when he discovered another object that moved. He sent the results of a few nights’ observations to Gauss, and the mathematician calculated its orbit. The object was given the name Pallas, and a new classification of celestial objects had been found: The new objects were called asteroids.

By 1890, about 300 asteroids had been found using the tedious method of searching the skies and comparing the observations to star charts, looking for uncharted objects. In 1891, a new method was introduced: A time exposure photograph of a small portion of the sky was taken, and the photograph was searched for any tiny streaks. The streaks (Figure B7-2) would be caused by objects that did not move along with the stars. These objects were then watched very closely and their orbits determined. Using such methods, well over 4000 asteroids are now known and named, and it is predicted that some 100,000 asteroids are visible in our largest telescopes.

![Figure B7-2](image)

The two streaks (arrows) on the time exposure photo are caused by the motion of two asteroids as the camera follows the stars’ apparent motions across the sky.
Long before people visited the Moon, we knew that it contained no air and no liquid water. This had been predicted by applying Newton's law of gravity, and the same law can also be applied to make predictions concerning planetary atmospheres. To see the connection between the law of gravity and an object's lack of atmosphere, we first discuss how to escape from Earth's gravity. This discussion leads to an idea that will help us understand not only why some planets have no atmosphere, but also—in Chapter 15—what a black hole is.

We start by imagining an Earth with no air. On such an Earth, if we throw something upward, it is not slowed by air friction. It still feels the effect of gravity, however, and thus, it slows down, stops, and then falls back to Earth. So we throw it harder. It rises farther, and as it gets higher, the force of gravity on it is less. Thus, its rate of slowing—its deceleration—is less at greater heights. Could we throw the object fast enough so that Earth's gravity could not stop it and bring it back down? The answer is yes. We can calculate from the laws of motion and gravitation that the minimum speed needed to escape Earth's gravity, assuming we start at the surface, is about 11 km/s; this is much greater than the speed of sound in air at the Earth's surface (which is about 0.3 km/s). An object fired upward from Earth at this speed or greater will continue to rise, slowing down all the time, but never stopping. We call this speed the escape velocity from Earth.

The reason that we imagined an Earth without air friction is that, in practice, if we fired an object from the surface at 11 km/s, it would be slowed—and probably destroyed—by air friction. In the space program we have sent probes into space with a velocity exceeding escape velocity; the probes were not destroyed by air friction because rockets carried them above the atmosphere before increasing their speed to escape velocity (Figure 7-6).

The escape velocity of a projectile launched from an astronomical object depends on the gravitational force at the object's surface (or from whatever height we are launching the projectile). The gravitational force at the surface of the Moon is only one sixth of that at the surface of Earth; a 120-pound astronaut weighs only about 20 pounds on the Moon. The escape velocity from the Moon is therefore less than that from Earth. It is only about 2.4 km/s.

**Escape Velocity** The minimum velocity an object must have to escape the gravitational attraction of another object, such as a planet or star.

Even though we use the terms "speed" and "velocity" as if they are the same, they are not. An object's velocity tells us not only how fast it is moving (its speed), but also the direction of its motion.

1 km/s = 3600 km/hr = 2237 mi/hr

**Figure 7-6**
Sixty seconds after takeoff, the main engines on the space shuttle cut back to 65% thrust to avoid stress on the wings and tail from the Earth's atmosphere. When the shuttle reaches thinner air at higher altitudes, the engines resume full power until the shuttle reaches orbiting speed.
The escape velocity from Phobos, a Martian moon, is only 50 km/hr (30 miles/hour). If you have a good arm, you could throw a ball from Phobos so that it would never return.

To see what escape velocity has to do with the question of the atmosphere of an astronomical object, we must briefly discuss the nature of a gas.

**Gases and Escape Velocity**

There are three states of matter in our normal experience: solid, liquid, and gas. Some understanding of the gaseous phase is necessary to understand planetary atmospheres. To envision a gas, picture a great number of molecules bouncing around in a container (Figure 7-7). We must keep in mind the following:

1. The average distances between molecules are greater than their sizes.
2. Compared with the volume occupied by the gas, the volume of a molecule is much smaller.
3. Molecules move in straight lines until they collide, either with one another or with the walls of the container. Then they bounce off and move in straight lines again.
4. There is empty space between the molecules.
5. As gas molecules bounce around, at any given time, different molecules have different speeds. Some will be moving fast and some will be moving slow.
6. The average speed of the molecules depends on the temperature of the gas. Gases at higher temperature have faster moving molecules.
7. At the same temperature, less massive molecules have greater speed. For example, because a molecule of oxygen has less mass than a molecule of carbon dioxide, in a mixture of oxygen and carbon dioxide gases, the oxygen molecules will, on the average, be moving faster.

Now let’s consider the Earth’s atmosphere, which is held near the Earth by gravitational forces. Consider a molecule at great heights above Earth where the atmosphere has a low density. This means that the molecules are much farther apart than down here at the surface. Suppose that at some instant a particular molecule up there happens to be moving away from Earth. There are very few other molecules around; thus, a collision is unlikely and our molecule acts just like any other object moving away from Earth. The force of gravity slows it down. Whether the molecule returns to Earth or escapes depends on how the speed of the molecule compares with the Earth’s escape velocity. If the molecule’s speed is greater than escape speed, the molecule is gone, never to return to Earth.

The fact that the Earth has an atmosphere means that the velocities reached by molecules of the air do not exceed escape velocity. Recall, however, that molecules of lower mass have greater speeds. It is therefore no coincidence that there is little hydrogen in the Earth’s atmosphere: Hydrogen molecules have less mass than those of any other element, and the temperature of the upper atmosphere is high enough for hydrogen molecules to escape. Any pure hydrogen that is released into the Earth’s atmosphere is eventually lost. The chemical element hydrogen does not exist alone in our atmosphere, but only as part of more massive molecules (such as a molecule of water vapor).

As noted earlier, the escape velocity from the surface of the Moon is about 2.4 km/s. At the temperatures reached on the sunlit side of the Moon, all but the most massive gases attain speeds greater than this, and therefore, the Moon has essentially no atmosphere. The Apollo astronauts were not surprised to find no air to breathe when they landed on the Moon.

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**Figure 7-7**

Atmospheric gas molecules move at different speeds and in random patterns, but molecules are very tiny; their average speed depends on temperature; and less massive molecules have higher speeds.

In fact, the temperature of a gas is defined as a measure of the average energy of motion of the gas molecules: average kinetic energy = \( \frac{3}{2} k_B T \), where \( T \) is the temperature in kelvin and \( k_B \) is Boltzmann’s constant.

The escape velocity of a projectile at a distance \( r \) from the center of a celestial object of mass \( M \) is given by

\[
v_{\text{esc}} = \sqrt{\frac{2GM}{r}}
\]

where \( G \) is the gravitational constant.
The Atmospheres of the Planets

The average speed of a particular type of molecule depends on the temperature of the atmosphere, but at any given time, some molecules are traveling faster than average. This means that although the average speed of a molecule of a particular gas in the atmosphere may be less than the escape velocity from a planet, the atmosphere may still gradually lose some of the gas because the speed of a small fraction of the gas molecules exceeds the escape velocity. Because of this, we must use a multiple of the average speed in considering whether or not a gas will escape from a planet. Theory shows that rather than the average speed, the value we should use in determining whether the planet will retain the gas for billions of years is about 10 times the average speed of the molecules of that gas.

Figure 7-8 is a graph of the average speeds of various molecules versus their temperatures. The dashed lines represent 10 times the average molecular speed. All of the planets, Pluto, as well as some planetary satellites, are plotted on the graph at their respective temperatures and escape velocities. A planet can retain a gas if the planet lies above the dashed line for that gas. Find the Moon on the graph and notice that the average molecular speed for every gas is greater than escape velocity. The planet Mercury is similar. On the other hand, only hydrogen and helium escape from Earth and Venus. The four Jovian planets retain all of their gases, including hydrogen and helium.

Even though a graph such as the one in Figure 7-8 is a powerful tool, we can only accurately find the chemical composition of an object’s atmosphere by using spectroscopy. This is necessary because we have directly examined samples of only four worlds: Earth, Moon, Venus, and Mars. Spectroscopy, the analysis of reflected sunlight from a distant object, allows us to find the chemical composition of the object’s atmosphere.

As light from the Sun penetrates a planet’s or satellite’s atmosphere before it gets reflected back into space, some of its wavelengths are absorbed. The spectrum we observe from the reflected light has absorption lines. As we discussed in Chapter 4, every element has its own unique spectral “fingerprint”; thus, by studying the specific absorption lines we can infer the chemical composition of the atmosphere. (Of course, we must take into account that some of these lines result from absorption that occurs in the atmospheres of the Sun and Earth.)

If an object does not have an atmosphere, we can still use spectroscopy to get useful information about the chemical composition of the object’s surface. In this case, the observed absorption lines are broad, instead of the sharp lines produced by molecules in a gas.

Table 7-4 summarizes the differences we have discussed between the terrestrial and Jovian planets. You should keep these differences in mind as we discuss theories of the origin of the solar system, as any successful theory must be able to explain these differences.
More than 5 billion years ago, the atoms and molecules that now make up the planets—and our own bodies—were dispersed in a gigantic cloud of dust and gas. In Chapter 13, we examine how such an interstellar cloud condenses to form a star, but with what we have learned about the patterns within the solar system, we can discuss its formation. A study of the beginnings of the solar system is interesting as an example of the way science in general (and astronomy in particular) progresses, because the theory is still in its early development and many gaps remain. The search for answers here resembles a mystery story where there are many clues; new ones appear all the time and some of the clues seem to contradict others.

There are two main categories of competing theories to explain the origin of the solar system: evolutionary theories and catastrophe theories. This section examines the evidence for each and shows why one is gaining favor among astronomers.

**Evidential Clues From the Data**

As we discussed earlier, any successful theory of the solar system’s origin must explain the patterns exhibited by its members and should also be able to account for exceptions to the patterns. Here is a list of significant data that must be explained.

1. All of the planets revolve around the Sun in the same direction (which is the direction the Sun rotates), and all planetary orbits are nearly circular.
2. All of the planets lie in nearly the same plane of revolution.
3. Most of the planets rotate in the same direction as they orbit the Sun, the exceptions being Venus and Uranus.
4. The majority of planetary satellites revolve around their parent planet in the same direction as the planets rotate and revolve around the Sun. In addition, most satellites’ orbits are in the equatorial plane of their planet.
5. There is a pattern in the spacing of the planets as one moves out from the Sun, with each planet being about twice as far from the Sun as the previous planet.
6. The chemical compositions of the planets have similarities, but a pattern of differences also exists, in that the outer planets contain more volatile elements and are less dense than the inner planets.
7. All of the planets and moons that have a solid surface show evidence of craters, similar to those on our Moon.
8. All of the Jovian planets have ring systems.
9. Asteroids, comets, and meteoroids populate the solar system along with the planets, and each category of object has its own pattern of motion and location in the system.
10. The planets have more total angular momentum (to be described later in this section) than does the Sun, even though the Sun has most of the mass.
11. Planetary systems in various stages of development exist around other stars.

Any successful theory of the origin of the solar system must explain these clues and should be consistent with the theory of star formation.

**Evolutionary Theories**

There is no single evolutionary theory for the solar system’s origin, but there are several theories that have in common the idea that the solar system came about as part of a natural sequence of events. These theories have their beginning with one proposed by René Descartes in 1644. He suggested that the solar system formed out of a gigantic whirlpool, or vortex, in some type of universal fluid and that the planets formed out of small eddies in the fluid. This theory was rather elementary and contained no specifics...
as to the nature of the universal fluid. It did, however, explain the observation that the planets all revolve in the same plane, the plane of the vortex.

After Isaac Newton showed that Descartes’s theory would not obey the rules of Newtonian mechanics, Immanuel Kant (in 1755) used Newtonian mechanics to show that a rotating gas cloud would form into a disk as it contracts under gravitational forces (Figure 7-9). Thus, to explain the disk aspect of the solar system (our clue #2), Kant changed the philosophical “universal fluid” of Descartes into a real gas subject to the natural laws of mechanics. Later, in 1796, the French mathematician Pierre Simon de Laplace found that such a rotating disk would break up into rings similar to the rings of Saturn. He suggested that perhaps these rings could form into the individual planets while the Sun was coalescing from material in the center.

However, application of Newtonian mechanics to such a contracting gas cloud caused another problem. To understand this problem, consider what happens when a spinning ice skater pulls in his arms: His rotation speed increases greatly (Figure 7-10). This increase in speed is predicted by Newton’s laws and is a result of the law of conservation of angular momentum. We do not define angular momentum mathematically, but simply state that the angular momentum of a rotating (or revolving) object is a direct measure of how fast the object rotates (or revolves) and how far it is from its axis of rotation (or revolution). In other words, an object’s angular momentum is greater if the object is rotating (or revolving) faster or if the object is farther from the axis of its rotation (or revolution). As the skater pulls in his arms, he decreases their distance from the axis of rotation; in the process, he decreases their angular momentum. To make up for this, his entire body increases its rotation speed, keeping the total angular momentum approximately constant (“conserved”). (The total angular momentum would remain perfectly constant if it were not for air resistance and small friction forces with the ice.)

The law of conservation of angular momentum must also apply to a contracting, rotating cloud of gas. Like the ice skater, the cloud speeds up its rotation as its parts come closer to the center of rotation. When calculations are made for a cloud contracting to form the Sun and planets, we find that the Sun should rotate much faster than it does; it should spin around in a few hours instead of the observed period of rotation of about a month. This means that the angular momentum possessed by the Sun is much less than the theory predicts. In fact, the total angular momentum of the planets (because of their greater distance from the center) is observed to be much greater than the angular momentum of the Sun. This should not occur, according to Newton’s laws.

The contradiction of these well-established laws caused the evolutionary theories to lose favor early in the 20th century. The alternative theory was a catastrophe theory.

**Catastrophe Theories**

In contrast to what the name may imply, a catastrophe theory does not refer to a disaster, but rather to an unusual event—in this case, the formation of the solar system by an unusual incident. In 1745, Georges Louis de Buffon proposed such an event: the passage of a comet close to the Sun. Buffon suggested that the comet pulled matter out of the Sun to form the planets. In Buffon’s time, comets were thought to be quite massive, but in the 20th century, we learned that a comet’s mass is not great enough to cause this breakup of the Sun; however, his basic idea—that a massive object exerted gravitational forces on the Sun, pulling material out and causing it to

**Figure 7-9**

As a cloud contracts, its rotational motion causes it to form a disk.

**conservation of angular momentum**

A law that states that the angular momentum of a system does not change unless there is a net external influence acting on the system, producing a twist around some axis.

**angular momentum**

An intrinsic property of matter. A measure of the tendency of a rotating or revolving object to continue its motion.

**Figure 7-10**

If an ice skater begins a spin with his arms extended (a), he will spin faster and faster as he draws his arms in (b). This effect is explained by the law of conservation of angular momentum.
sweep around the Sun until it eventually coalesced to form the planets—still seemed a reasonable hypothesis. Such an event as the passage of a massive object so near the Sun would be very unusual, but not impossible.

More recently, it was suggested that the Sun was once part of a triple-star system, with the three stars revolving around one another. As we see, such star systems are common, and thus, this in itself is not a far-fetched idea. This particular catastrophe theory holds that the configuration was unstable and that one of the stars came close enough to cause a tidal disruption of the Sun, producing the planets. The close approach of this star also caused the Sun to be flung away from the other two stars.

Starting around the 1930s, astronomers began to find major problems with catastrophe theories. First, calculations showed that material pulled from the Sun would be so hot that it would dissipate rather than condense to form planets. A second problem involved deuterium, an isotope of hydrogen. Even the outer portions of the Sun are too hot for deuterium to be stable, and thus, not much deuterium exists in the Sun; however, much more deuterium is found on the planets than in the Sun, indicating that the material of the planets could not have been part of the Sun.

Finally, as we discuss later, we now know that other nearby stars have planetary systems around them. A catastrophe theory would predict that such systems are rare, since they are produced by unusual events. If we find planetary systems elsewhere, there is probably some common process that forms them.

At the same time as these problems were becoming apparent, a solution appeared for the angular momentum problem of the evolutionary theories; as a result, catastrophe theories have been nearly abandoned in favor of modern evolutionary theories.

Present Evolutionary Theories

In the 1940s, the German physicist Carl von Weizsäcker showed that a gas rotating in a disk around the Sun would rotate differentially (the inner portion moving faster than the outer). This would result in the formation of eddies, as shown in Figure 7-11. As the figure shows, the eddies would be larger at greater distances from the Sun. According to his view, these eddies are the beginnings of planet formation, and the eddies therefore explain the pattern of distances between the planets.

A real breakthrough occurred when it was realized that a mechanism exists to account for why the Sun does not rotate faster than it does. First, however, let’s consider the beginning of the scenario that today’s theory envisions.

In Chapter 13 we explain that new stars form from enormous interstellar clouds of gas and dust. Figure 7-12 shows the Rosette nebula and the Tarantula nebula, which are stellar nurseries where newly formed stars can be seen. When an interstellar dust cloud collapses, any slight rotation that it had at the beginning, before the collapse, results in a greatly increased speed of the central portion (explained by the conservation of angular momentum). The material in the center becomes a star—the Sun in the case of our solar system. During the few million years that this is occurring, the matter surrounding the newly forming Sun is condensing into a disk.
(a) The bright bluish stars visible in the Rosette nebula are apparently hot, young ones forming from dense dust clouds. The nebula is about 3000 light-years away. (b) Hodge 301, at lower right, is a cluster of massive, brilliant stars in the Tarantula nebula, about 160,000 light-years away. Many of the stars in the cluster have exploded as supernovae, blasting material into the nebula at high speed. These explosions compress the gas into filaments, seen at upper left. Near the center of the image are small, dense gas globules and dust columns where new stars are being formed today.

As the gases in the disk cool, they begin to condense to liquids and solids, just as water vapor condenses on the cool side of an iced drinking glass. Nonvolatile elements such as iron and silicon condense first, forming small chunks of matter, or dust grains. Each of these grains has its own elliptical orbit about the center, and as time passes, more matter condenses onto its surface. The orbits of these tiny objects are elliptical so that they intersect one another. The resulting collisions between particles have two effects: (1) particles involved in gentle collisions (as if they were rubbing shoulders with one another as they orbit) occasionally stick together and form larger particles, and (2) particles are forced into orbits that are more nearly circular.

As the matter sticks together, small chunks grow into larger chunks. Their increased mass causes nearby particles and molecules of gas to feel a greater gravitational force toward them. Because this force is still very small, the coalescing is a very slow process, but over a few hundred thousand years, larger particles—now called planetesimals—sweep up smaller ones. Some planetesimals, resembling miniature solar systems, have dust and gas orbiting them—material that eventually condenses to become the moons we know today.

As the force of gravity shrinks a celestial object, gravitational energy causes it to heat up. A simple case of gravitational energy being converted to thermal energy occurs whenever you drop something. The object hits the floor and heats up slightly. (The heating is very slight, and to experience it, you should probably cheat and throw an object, such as modeling clay, down to the floor a few times.) Perhaps you can visualize a release of heat when an object falls from the heavens onto a planet, but the

**planetesimal** One of the small objects that formed from the original material of the solar system and from which a planet developed.

In Chapter 9, we present evidence that Jupiter has not yet lost all of the excess thermal energy that resulted from its formation.
same effect occurs when gravitational forces cause the collapse of a cloud of gas and dust. The material heats up as it falls toward the center.

This heating effect occurs with our solar system-in-formation. The material that falls inward to form the Sun gets hot, and the high temperatures near the new Sun do not allow for condensation of the more volatile elements. Thus, it is difficult for a planet-in-formation near the Sun to accrete gases; as we discussed earlier, higher temperatures result in higher speeds for gas particles, which allows them to overcome the gravitational pull of the planet. As a result, the planet does not increase its mass by accretion as quickly as a planet at great distances from the Sun, where the temperatures are lower. In addition, lower masses result in weaker gravitational pulls, which makes it even harder for planets near the Sun to increase their sizes. This explains why the terrestrial planets are smaller in size than the Jovian planets and why they are primarily composed of nonvolatile, dense material, compared with the mostly gaseous Jovian planets.

The differences in densities between the forming planets have an interesting effect on their oblateness (that is, how “flattened” they are). Under spherically symmetric conditions, a nonrotating self-gravitating cloud will end up as a perfectly spherical object; every particle will move on radial lines toward the center of the cloud; however, as we discussed earlier, rotation will tend to flatten the object in a direction perpendicular to the rotation axis (Figure 7-9). The more gaseous the planet, and the faster it rotates, the greater its oblateness. Even the least oblate Jovian planet, Neptune, is five times more oblate than Earth, whereas Saturn is about 30 times more so.

According to Newtonian mechanics, the gravitational influence of the new Sun (the protosun) gets weaker with distance; at greater distances matter orbits at a more leisure pace, and the swirling eddies around protoplanets are more prominent. The situation at this time is illustrated in Figure 7-13.
A particularly large outer planet, Jupiter, gravitationally stirs the nearby planetesimals of the inner system so that the weak gravitational forces between them cannot pull them together. Today’s asteroids are the remaining planetesimals.

While planet formation is taking place, the Sun continues to heat up. It heats the gas in the inner solar system and causes electrons there to leave their atoms, forming charged atoms (ions) and electrons. A magnetic field does not exert a force on an uncharged object, but if a magnetic field line sweeps by a charged object, a force is exerted on that object. This is what must have slowed the Sun’s rotation; the magnetic field of the rapidly rotating Sun exerted a force on the ions in the inner solar system, tending to sweep them around with it; however, Newton’s third law tells us that if the Sun’s magnetic field exerts a force to increase the rotational speed of these particles, they must exert a force back on the Sun to decrease its rotational speed. Thus, it is the magnetic field of the Sun, discovered rather recently, that provides the explanation for why the Sun rotates so slowly—a fact that was once a stumbling block for evolutionary theories.

The solar system of our story is getting close to what we see today; however, gas and dust were still more plentiful between the planets than in today’s solar system, and the inner solar system of our story contained much more hydrogen and other volatile gases than exist there today. To help answer the question of how these gases were moved to the outer solar system and how, in general, the system was “cleaned up,” we can again look into space at interstellar dust clouds.

In these clouds we see stars at various stages of formation. There is evidence that many newly forming stars go through a period of instability during which their stellar wind increases in intensity. The stellar wind, called the solar wind in the case of our Sun, consists of an outflow of particles from the star. It continues throughout a star’s lifetime, as we explain in Chapter 14. If the instabilities we observe in other stars occurred during the formation of the Sun, the pulses of solar wind would sweep the volatile gases from the inner solar system. Even without this increased activity, it is expected that the solar wind would gradually move this material outward, but if the Sun did go through this active period, there is certainly no difficulty explaining why hydrogen and helium exist on the outer planets but not the inner. Once in the outer system, this material would gradually be swept up by the giant planets there. Also, recall Figure 7-8 and our discussion in Section 7-5 about planetary atmospheres: The proximity of the terrestrial planets to the Sun and their weak gravitational fields (as compared with the Jovian planets) make it easier for gases such as hydrogen to escape the pull of the terrestrial planets.

### Explaining Other Clues

As millions of years passed, remaining planetesimals crashed onto the planets and moons, resulting in the craters we see on these objects today.

Comets are thought to be material that coalesced in the outer solar system, the remnants of small eddies. These objects would feel the gravitational forces of Jupiter and Saturn, and many would fall onto those planets. (Recall the discussion at the start of Chapter 1 of Comet Shoemaker-Levy 9 crashing onto Jupiter.) Small objects that formed beyond the giant planets’ orbits, however, would be accelerated by Jupiter and Saturn as those planets passed nearby and would be pushed outward. As we explain in Chapter 10, there is reason to think that great numbers of comets exist in a region far beyond the most distant planet.

The evolutionary theories explain that nonvolatile elements would condense in the inner solar system, but volatiles would be swept outward by the solar wind. This accounts for the differences in the planets’ chemical composition. In fact, astronomers find that when compression forces are taken into account in calculating density, planets closest to the Sun contain the most dense and least volatile material, as would be expected from the theories.

Further confirmation of evolutionary theories is found in Jupiter’s Galilean satellites. As we point out in Chapter 9, these satellites also decrease in density and
increase in volatile elements as we move outward from Jupiter. The formation of Jupiter and its moons must have resembled the formation of the solar system; thus, we see the same density pattern in Jupiter’s system.

The next two chapters examine each planet in turn and point out some exceptions to the patterns described here. Some of the exceptions are easy to explain using evolutionary theories. Others cannot be explained by these theories and require a hypothesis of collisions—“catastrophes”—within the early solar system.

Catastrophes may well have played a part in the formation of the solar system, as in the formation of our Moon (Section 6-5), but it was a fairly minor part, involving relatively few objects. The overall formation of the system in which we live was evolutionary in nature. Nonetheless, the origin of the solar system is poorly understood. Pieces continue to fall into place, but we still have much to learn.

7-7 Planetary Systems Around Other Stars

Is the existence of our planetary system unusual, or is it common for stars to have planets? Until recently, it has been very difficult to answer this question. Direct observation of extrasolar planets (or exoplanets) is necessarily based on light reflected by these objects (or weak infrared light emitted by their cool surfaces); however, planets are very small, and the light emitted from their companion star overwhelms their light. For example, our Sun is 10 billion times brighter than Earth at visible wavelengths. However, in the infrared, the brightness of the star is reduced while the brightness of a planet peaks, allowing us to detect a planet more easily in the infrared. In most cases, we have to use indirect methods to search for exoplanets. Different categories of evidence can help answer the question we asked. We examine each category in turn.

- Direct observation/Infrared companion. The first direct image of an exoplanet was obtained in April 2004 using adaptive optics at ESO’s VLT (Figure 7-14a). The planet, five times as massive as Jupiter, orbits a brown dwarf about 230 light-years from the Sun in the direction of the constellation Hydra. This system is only about 8 million years old, making the planet hotter and brighter than similar objects orbiting much older stars like our Sun and thus easier to detect.

In March 2005, scientists using the Spitzer Space Telescope measured directly the infrared radiation from two previously detected (using the transit method, described later) Jupiter-like planets orbiting Sun-like stars. When the planet dips behind the star, the star’s infrared light is measured and then subtracted from the total infrared light of both the planet and star; this corresponds to the planet’s own infrared radiation and allows a measurement of the planet’s temperature. The planets (HD209458b and TrES-1) orbit their stars with periods of about 3 days, at distances of about 0.04 AU, and have temperatures of about 1100 K. Spitzer has also detected the presence of dust grains or-
biting a number of brown dwarfs, suggesting that planet formation around these failed stars proceeds along steps similar to those for normal stars.

The star T Tauri has a companion (Figure 7-14b) that emits significant radiation only in the infrared region. The companion has too little mass for it to become a star itself, yet its infrared radiation indicates that it has a high temperature. A possible explanation for this high temperature is that it is a giant planet in the process of formation, with dust and gas still falling into it. If so, this scenario lends support for evolutionary theories of planet formation—at least, for large Jupiter-size planets.

- **Dust disks.** Disks of dust and gas about the size of the solar system have been detected around several stars. The most obvious case is that of β (the Greek letter beta) Pictoris (Figure 7-15a). Studies of the disk around the star at midinfrared wavelengths suggest that it contains fine dust with an icy consistency. The presence of dust, which is usually either blown out of the system or accreted by the star, suggests that it is replenished continually, most likely by collisions among planetesimals orbiting the star in belt-like regions at specific distances (about 6, 16, and 30 AU). The lack of dust between 6 and 16 AU from the star suggests the presence of a planet at about 12 AU from the star. This is a system that is still in the process of forming planets.

Figure 7-15b shows the dust disk around the star AU Microscopii. Dust particles are missing from the inner region, 17 AU in radius, suggesting the presence of a planet. The disk also shows structures (unevenness and clumps) at distances of 25 and 40 AU from the star; they are likely created by the gravitational influence of planets.

In early 2005, the Spitzer Space Telescope detected gaps in the dusty disks around two very young stars. The gaps are empty and sharp edged, suggesting the presence of Jupiter-like planets. These findings support the idea that Jupiter-like planets form faster than previously thought. One of the stars, GM Aurigae, is very similar to our Sun and at a mere 1 million years of age provides us a unique opportunity to understand how our solar system formed.

- **Pulsar companion.** In 1992 astronomers reported that they had found variations in the rate of the signals from the pulsar PSR 1257+12 (about 2630 light-years away). Pulsars are stellar remnants that result from supernova explosions and emit beams of radio waves. When these beams sweep past the Earth, we observe them as radio pulses that normally are very constant in their frequency of pulsation. The variations in the frequency of a pulsar can be explained if it has one or more

**Figure 7-15**
(a) This is an infrared photo of β Pictoris, obtained with the ESO ADONIS adaptive optics system (Grenoble Observatory). The star itself has been blocked out, and the disk of particles around it is visible up to 24 AU from the star. β Pictoris is a young star (12 to 20 million years old), 63 light-years away. (b) An infrared image of the dust disk around AU Microscopii obtained with the Keck II Telescope. The blocked out region is 15 AU in radius. The image is about 100 AU wide, but in visible light, the disk extends up to 210 AU from the star. The star is a dim, red star, about 12 million years old, 33 light years away.
more companion objects, such as a planet. We now have a confirmed detection of three planets around this pulsar. Two of these exoplanets have masses about four times that of Earth, while the third is about twice as massive as the Moon. Since 1994, we have another confirmed observation of a planet 2.5 times as massive as Jupiter around pulsar PSR B1620–26 (about 12,400 light-years away). Other observations, which have not been confirmed yet, suggest that planets may be orbiting two other pulsars. As additional pulsars are examined for similar evidence, and if any of these observations are confirmed, we will have more pieces to add to the puzzle of how common are planetary systems.

• Binary systems and visual wobble. As we showed in Chapter 3, gravitationally bound objects revolve around their common center of mass. The case we discussed there was the Earth–Moon system. Among the stars, we observe many cases of binary star systems, in which two stars revolve around one another in this manner. In some cases, only one star of a binary system is visible, but we can deduce the existence of the dimmer star from the motion of the visible one. If we see a star that appears to wiggle in its position or that exhibits an elliptical motion, we can conclude that it is in orbit with another object. This provides us with a possible method of detecting the presence of a large planet in orbit around another star. If we hope to find a planet by such means, we must look at nearby stars, whose motion is easier to observe.

A star named Barnard’s star is the second-closest star to the Sun. In the first half of the 20th century, a back-and-forth motion was reported for this star; however, the motion is very slight and detecting it involved comparing photographs taken over long periods of time. Most astronomers considered the data very suspect, for the photographs were taken under different conditions with instruments that had been changed over the course of the observations; however, measurements of changes in the radial velocity of Barnard’s star agreed with the original conclusions and indicated that the star may indeed have at least one planet of 1.5 times the mass of Jupiter revolving around it at a distance of 4 AU. (Large planets, of course, would cause the star to move more than small ones would.) Measurements on this object are continuing, as even recent observations with the Hubble Space Telescope (HST) have not yet confirmed the existence of any planets around this star.

Detecting the wobble of a star by carefully measuring its position in the sky relative to other stars is not easy (Figure 7-16a). For example, if we were to look at the wobble of our Sun (mainly due to Jupiter) from 30 light-years away, the small circle made by the Sun would appear to be about the size of a quarter seen from a distance of 6000 miles. Measurements made using this direct method must be extremely accurate and must be made over long periods of time to capture the orbital period of the star’s motion. The advantage of this astrometric technique is that it allows us to find the mass of the planet because the star’s motion is detectable in two dimensions.

• Binary systems and Doppler wobble. Another method for detecting the wobble of a star due to the presence of planets around it involves measuring the Doppler shift of the star’s spectrum as it alternately wobbles toward and away from the Earth (Figure 7-16b). Such shifts are tiny because the star’s motion is very slow in its orbit: For example, Jupiter causes the Sun’s speed to vary with an amplitude of 12.5 m/s (or 28 miles/hour); Saturn’s effect is the next largest, with an amplitude of 2.7 m/s (or 6 miles/hour). The current precision achieved by researchers using this radial-velocity technique is 3 m/s, allowing them to find Jupiter-like (but not yet Earth-like) planets orbiting Sun-like stars. The wobble motion of a star can provide a wealth of information about its planetary companion, such as its mass, distance, and orbital period. This method has proven to be very successful. In 1995, astronomers used this method to discover the first planet orbiting a normal, Sun-like star, 51 Pegasi. Since then, many groups of researchers have discovered sev-
eral exoplanets. As of March 2006, about 150 normal stars have been discovered to have planet-like objects (including some stars with orbiting brown dwarfs), and for some of them we detected multiple planets (for a total of about 185). The majority of the exoplanets known so far have been discovered using the Doppler method; the current precision limitations of this method result in a bias toward finding massive, Jupiter-like planets at close distances from their stars (Figure 7-17).

Also, many of these planets have large eccentricities. This is very unlike the planetary orbits in our solar system. The first two Saturn-sized planets were discovered in March 2000, suggesting that as time goes on we should be able to detect even...
smaller planets; this discovery supports our current theory that planets form in a disk of dust and gas by a snowball effect of growth.

Even though this radial-velocity (Doppler) method has proven to be very successful, precise measurements require a large number of spectral lines; because the hottest stars have far fewer spectral features than cooler Sun-like stars, this method cannot be used for the hottest stars. It also does not allow us to find the exact mass of the planet but only a lower limit to it, because the angle at which we observe its orbit is unknown. Finally, finding Earth-like planets in Earth-like orbits with this method is beyond our current capabilities.

- **Stellar occultation.** When one celestial object passes in front of another, we say that an "occultation" occurs. In late 1999 astronomers observed the dimming of star HD209458, caused by its planet passing in front of it (such a passage is called a transit). This confirmed the earlier discovery, made using the Doppler method, that this star has a Jupiter-size planet. The star’s intensity dims by only 1.5% during occultation. This method is very useful in confirming previously discovered planets. An advantage of this method is that it is not sensitive to the planet’s mass; we are looking for the amount of starlight the planet obscures and not the planet’s gravitational pull on its star (Figure 7-16c). It is clear that

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### Table: Some of the exoplanets around normal stars

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass (M_J)</th>
<th>Orbital Semimajor Axis (AU)</th>
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</thead>
<tbody>
<tr>
<td>HD187123</td>
<td>0.53 M_J</td>
<td>0.6 MJ 1.9 M_J 4.2 M_J</td>
</tr>
<tr>
<td>HD209458</td>
<td>0.63 M_J</td>
<td>2.5 M_J 6.0 M_J 3.8 M_J</td>
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<tr>
<td>HD75289</td>
<td>0.45 M_J</td>
<td>1.00 M_J 1.54 M_J</td>
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<td>TauBoo</td>
<td>4.1 M_J</td>
<td>0.76 M_J</td>
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<tr>
<td>51Peg</td>
<td>0.45 M_J</td>
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</tr>
<tr>
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<td>7.0 M_J 3.5 M_J 1.2 M_J 5.1 M_J</td>
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<tr>
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<td>0.88 M_J 1.6 M_J 1.2 M_J 1.00 M_J</td>
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<td>4.2 M_J</td>
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<td>14Her</td>
<td>3.8 M_J</td>
<td>0.99 M_J 1.9 M_J 4.2 M_J</td>
</tr>
</tbody>
</table>

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**Figure 7-17**

Some of the exoplanets around normal stars. Most of these objects are closer to their parent star and more massive than the planets in our solar system. The figure includes the name of the parent star, the mass of the planet (in units of the mass of Jupiter), and the orbital semimajor axis (in AU). Most of the exoplanets known to date were discovered using the Doppler method.
this method can be used only in cases where the Earth lies in or near the orbital
plane of an exoplanet; however, this method is very efficient because within
the field of view of a telescope there are thousands of stars that can be sur-
veyed. In January 2003, astronomers announced the first detection using the
transit method of a Jupiter-sized planet (OGLE-TR-56b) orbiting a normal
star about 5,000 light-years away, in the Sagittarius arm of our Galaxy.

NASA’s Kepler Mission, scheduled for launch in June 2008, will use a space
borne telescope to search for Earth-like (or even smaller) exoplanets using the
transit method. Because a planet transits its star in a periodic fashion, all tran-
sits produced by the same planet last the same amount of time (the orbital pe-
riod) and result in the same drop in the star’s brightness; from such
observations we can determine the size of the orbit and the size of the planet.
From the orbital size and the star’s temperature (which can be found from spec-
troscopy), we can calculate the planet’s characteristic temperature and thus
find out if the planet is in principle habitable. The 0.95-meter diameter tele-
scope has a 105-square degrees field of view and can continuously monitor the
brightnesses of more than 100,000 stars at the same time.

• **Gravitational Microlensing.** When a massive object passes between the observer and
a distant source of light (say a star), the gravity of the object will bend the light
according to the general theory of relativity. The massive object plays the role of a
lens, causing the source to appear to slowly brighten to a few times its usual in-
tensity over a period of time. For the case of a star and its planet(s), their individ-
ual gravitational fields act as a lens magnifying the light of a distant background
star (Figure 7-20d). This method can only be used when the star and its planet(s)
pass almost directly between the observer and the background star. Both stars
and Earth are moving relative to each other during the microlensing event,
which lasts for a few days or weeks. Even though these events cannot be re-
peated, this method can be used to find how common Earth-like planets are in
our Galaxy because it allows for such planets to be discovered with available
technology. In early 2006, astronomers discovered a small, icy planet with a mass
only five times that of Earth using this technique.

All of the methods described previously are currently used from the ground, and
in the future, they will also be used from space. Astronomers are also exploring addi-
tional methods. For example, spectroscopy can be used to detect elements expected to
be present in the atmospheres of planets such as water vapor and sodium. Indeed, us-
ing the *HST*, astronomers detected atomic sodium in the atmosphere of HD209458b.
Spectra also show the presence of molecules of methyl formate (a product of alcohol
and formaldehyde, commonly used as an insecticide) in the dust clouds in our Galaxy;
the average ratio between such molecules to hydrogen molecules is about 1 to a bil-
lion, but a typical dust cloud would still contain about $10^{27}$ gallons of the chemical
condensed into liquid form. We do not yet know what role this and other molecules
play in the formation of stars and planets. The *Spitzer Space Telescope* has detected signif-
ificant amounts of icy dusty particles coated with carbon dioxide, water, and methanol,
in the dusty disks around young stars in the constellation Taurus. Such materials may
be the building blocks for comets. Finally, organic gases such as acetylene and hydro-
gen cyanide were detected in the disk around the young star IRS46. In the presence
of water, these gases form amino acids and adenine, one of the four chemical bases of
DNA. Such gases are found in our solar system, on comets, and in the atmospheres of
the Jovian planets and Saturn’s moon Titan.

**The Formation of Planetary Systems**

In Section 7-6 we discussed the *core-accretion model* of planetary formation: Planets
start as small chunks of rock, dust, and debris and grow through a series of collisions
among planetesimals and accretion of dust and gas from the disk. In this model,
Jupiter-like planets form if their rocky core is more massive than a few Earth masses, but it takes tens of millions of years for such cores to grow. This contradicts the observed lifetimes of the accretion disks, which tend to evaporate as a result of the stellar wind or influences from nearby stars in only a few millions of years. A substantial gas reservoir is needed to complete the formation of a Jupiter-like planet, whereas Earth-like planets can continue growing in a gas-free environment.

Observations suggest that for Sun-like stars, planetary formation peaks between 1 and 3 million years after the process starts. Infrared and radio data show that planet-forming disks around stars older than about 10 million years are very rare. (It is possible, however, for some stars to have massive dust clouds around them up to hundreds of millions of years after they are formed; such clouds have been observed using the Spitzer Space Telescope and can form from collisions between young, terrestrial-like planets.)

According to a competing model, the disk-instability model, dense regions forming in the disk accrete more material and suddenly collapse to form one or more planets. In this model, giant planets can form in only a few hundreds of years; however, such instabilities require massive disks (more than 10% of the star’s mass), which are not commonly observed.

Many Jupiter-sized exoplanets are observed very close to their parent star. The high temperatures and lack of raw materials at these distances make it unlikely that these planets formed at their current locations. It is possible that planets form at large distances from their star but migrate inward. Because a newly formed planet separates the dust disk around the star into two regions, the protoplanet and the disk’s inner region will lose energy and angular momentum to the outer region of the disk. As a result, the protoplanet will migrate inward toward the star. The protoplanet may finally reach a stable orbit close to the star as a result of tidal interactions with it or because the inner disk region is cleared out by the star’s magnetic field or if the protoplanet manages to accrete the material in the outer disk before it gets destroyed by the star. (In our solar system, the migration of Jupiter lasted a very short time, which allowed Earth to remain in its orbit; as we discuss in Chapter 10, our solar system formed in a cluster of stars that did not allow for a massive accretion disk.) Numerical simulations of planetary migrations show that in most cases protoplanets are trapped into a series of resonances and migrate inward together in less than a million years; this suggests that understanding how giant planets form is still a major challenge.

Observations suggest that the size of the largest planet formed around a star is directly related to the size of the star. That is, super-Earths form in the disks around small, red dwarf stars, Jupiter-like planets form in the disks of Sun-like stars, whereas brown dwarfs may form in the disks of bigger stars. For example, low-mass stars tend to have less massive disks, resulting in smaller amounts of raw material to form planets; in addition, planets form gradually in such disks, allowing the gas in the disk to dissipate before large planets form. Spectroscopic surveys also suggest that there is an almost linear relationship between the likelihood that a planetary system will form around a star and the star’s abundance of heavy elements such as iron, nickel, titanium, silicon, and sodium. Because a star will have the same chemical composition as its surrounding disk of gas and dust, such surveys support the idea that heavier elements coalesce easier, allowing the formation of planetesimals and therefore planetary systems.

Theoretical calculations suggest that it is easier to form small, cold planets than larger ones around low mass stars. Because about two thirds of the stars in our Galaxy are small, red dwarf stars, it is likely that planetary systems with super-Earths are three times as common as systems with Jupiter-like planets.

Current observational data coupled with theoretical work suggest that at least 25% of Sun-like stars have planetary systems; this means that just in our Galaxy there are tens of billions of stars with planetary systems. This does not guarantee, however, that these planetary systems are as stable as our own solar system; planet–planet inter-
actions during the early stages of formation may result in highly eccentric orbits for the planets, as is the case of many of the exoplanets observed so far.

The properties of the exoplanets found so far have defied expectations and are forcing us to reexamine our ideas of how planets form. Infrared observations of the Orion Nebula suggest that what we once thought to be an obstacle in forming a planet, namely ultraviolet radiation from a nearby star, may actually promote the formation of planets; such radiation can remove the gas from a disk, allowing large dust grains to grow and slowly form planetesimals. Our own solar system was formed in an Orion-like environment, as we learned from the study of primitive materials in meteorites. Theoretical work suggests that planetary systems can form around binary stars in much the same way that they form around single stars like our Sun. Finally, computer simulations suggest that we need to consider not only the role of collisions between embryonic planets but also the role of close encounters between them; tidal interactions between such objects can have dramatic effects, such as melting, stripping material away, decompressing, and of course annihilating the smaller object.

It is too early for us to draw any conclusions based on the newly discovered exoplanets. After all, the recent discoveries seem to suggest two contradictory ideas. On one hand, we now know that planets are more plentiful than we once thought, and therefore, it is more likely that Earth-like planets exist where life could develop. On the other hand, life on Earth could be unique, as all planetary systems discovered so far are not suitable for life. We do not yet have the ability to detect Earth-like objects, and the few discovered objects may be exceptions to the general rules of planetary formation. There is no doubt that in the next few decades we will discover many more exoplanets as our telescopes and instruments allow us to make even more precise observations. A planned space-borne interferometer (such as ESA’s Darwin mission) might be able to detect other Earths as early as the next decade, and it should be able to use spectroscopy to determine the chemical composition of their atmospheres or surfaces, looking for any signatures of life on them.

During the 4th century BC, Aristotle argued in favor of the uniqueness of our planet, as it was at the center of the universe. Another great philosopher at the time, Epicurus, argued that the universe must be infinite and therefore must contain an infinite number of other worlds. For about 2400 years we have been trying to answer the question of whether our solar system is truly unique. We are getting very close.
unlikely, this in itself is not an argument against such a scenario in the case of the solar system. If there is any possibility at all that a catastrophic event can cause a planetary system, it could well have happened here; however, there is now clear evidence that evolutionary development of planetary systems is common, and it lends support for hypotheses that postulate that this is what occurred in our own system.

In the next three chapters we examine each of the planets in more detail and look at the lesser objects within the solar system—comets, meteoroids, and asteroids.

### Study Guide

1. Which planet is most massive?
   - A. Mercury.
   - B. Mars.
   - C. Earth.
   - D. Jupiter.
   - E. Saturn.

2. The only object whose orbit is more eccentric than Mercury’s is
   - A. Saturn.
   - B. Earth.
   - C. Pluto.
   - D. Venus.
   - E. Neptune.

3. Whether a planet or moon has an atmosphere depends on the planet’s (or moon’s)
   - A. orbital speed.
   - B. temperature.
   - C. escape velocity.
   - D. [Both A and C above.]
   - E. [Both B and C above.]

4. Which planet has its plane of rotation tilted most with respect to its plane of revolution?
   - A. Uranus.
   - B. Earth.
   - C. Venus.
   - D. Mars.
   - E. Mercury.

5. Venus might be called Earth’s sister planet because it is similar to the Earth in
   - A. size.
   - B. mass.
   - C. rotation period.
   - D. [Both A and B above.]
   - E. [Both A and C above.]

6. Saturn is one of the ______ planets.
   - A. Jovian
   - B. inner
   - C. inferior
   - D. minor

7. Which of the following statements is true of all of the planets?
   - A. They rotate on their axes and revolve around the Sun.
   - B. They rotate in the same direction.
   - C. They have at least one moon.
   - D. Their axes point toward Polaris.
   - E. [More than one of the above is true of all of the planets.]

8. Saturn’s density is
   - A. less than that of Jupiter.
   - B. more than that of Jupiter.
   - C. similar to the Earth’s.
   - D. greater than that of Earth.
   - E. [Two of the above.]

9. Which of the following choices lists the four planets from smallest to largest?
   - A. Mars, Mercury, Earth, Uranus
   - B. Mercury, Uranus, Mars, Earth
   - C. Uranus, Mercury, Mars, Earth
   - D. Mars, Mercury, Earth, Uranus
   - E. [None of the above.]

10. Compared to Jovian planets, terrestrial planets have a
    - A. more rocky composition.
    - B. lower density.
    - C. more rapid rotation.
    - D. larger size.
    - E. [More than one of the above.]

11. Which of the following statements is true of Jovian planets?
    - A. They have low average densities compared to terrestrial planets.
    - B. Their orbits are closer to the Sun than the asteroids’ orbits.
    - C. They have craters in old surfaces.
    - D. They have smaller diameters than terrestrial planets do.
    - E. They have fewer satellites than terrestrial planets do.

12. Most asteroids orbit the Sun
    - A. between Earth and Mars.
    - B. between Mars and Jupiter.
    - C. between Jupiter and Saturn.
    - D. beyond the orbit of Saturn.
    - E. [None of the above. No general statement can be made.]
13. Distances to the planets are measured today by the use of
A. geometry.
B. calculus.
C. spacecraft flybys.
D. analysis of the motion of their moons.
E. radar.

14. The mass of Jupiter was first calculated
A. using its distance from the Sun and its revolution period.
B. using its angular size and distance from the Earth.
C. using data from spacecraft flybys.
D. by analysis of the motion of its moons.
E. [Two of the above.]

15. Which is a longer time on Earth?
A. A sidereal day.
B. A solar day.
C. [Either of the above, depending on the time of year.]
D. [Neither of the above, for they are the same.]

16. At a greater distance from the surface of a planet, the escape velocity from that planet
A. becomes less.
B. remains the same.
C. becomes greater.
D. [Neither of the above, for the behavior of different planets is different in this regard.]

17. At the same temperature, the average speed of hydrogen molecules is _______ than that of oxygen molecules.
A. less than
B. the same as
C. greater than
D. [No general statement can be made.]

18. The escape velocity from the top of Earth’s atmosphere is _______ the escape velocity from the surface of the Moon.
A. less than
B. the same as
C. greater than
D. [No general statement can be made, for the escape velocity depends upon temperature.]

19. Which planet (of those listed) gets closest in distance to the Earth?
A. Jupiter.
B. Mercury.
C. Venus.
D. Saturn.
E. Mars.

20. If planetary systems are caused as proposed by the catastrophe theories, there should be
A. many planetary systems besides ours.
B. few planetary systems besides ours.
C. [Neither of these; the theories would make no predictions in this regard.]

21. Evolutionary theories now account for the slow rotation rate of the Sun by pointing to
A. the slowing effect on the Sun of the solar wind.
B. friction within the gases involved, which would prevent the Sun from rotating fast.
C. the effect of the inner planets on the Sun.
D. the effect of the large planets—particularly Jupiter—on the Sun.
E. the conservation of angular momentum, which predicts a slowly rotating Sun when it formed.

22. Which of the following observations cannot be accounted for by evolutionary theories of solar system formation?
A. All of the planets revolve around the Sun in the same direction that it rotates.
B. All of the planets revolve in nearly the same place.
C. Planets farther from the Sun are farther apart.
D. The outer planets contain more volatile elements than the inner planets do.
E. [All of the above are accounted for by evolutionary theories.]

23. After the evolutionary theory of the formation of the solar system was proposed, it was almost dismissed because it seemingly could not explain
A. planetary masses.
B. planetary distances from the Sun.
C. the existence of comets.
D. why some planets—particularly Jupiter—have a strong magnetic field.
E. the observed rotation rate of the Sun.

24. According to the evolutionary theories of solar system formation, the outer planets contain much more hydrogen and helium than the inner planets because these elements
A. never fell in near the Sun.
B. condensed quickly to liquids and solids and remained far from the Sun.
C. were blown away from the inner solar system by the solar wind.
D. [Both A and B above.]
E. [All of the above.]

25. Astronomers are now reasonably confident that the planets of the solar system
A. formed when a comet pulled material from the Sun.
B. formed when another star passed very close to the Sun.
C. evolved from a rotating disk when the Sun was forming.
D. [None of the above. There is currently no satisfactory explanation for the origin of the planets.]

26. In a previous chapter, we saw that Kepler’s third law relates a planet’s period to its distance from the Sun. This law was expanded by Isaac Newton to include what other quantity?

27. How does the Sun’s mass compare with the total mass of all other objects in the solar system?

28. What is the largest planet, and how does it compare in size and mass with the Earth?

29. What was the first celestial object discovered after Bode’s law was proposed? Did it fit predictions made by the law? (Hint: See the Advancing the Model box on page 193.)

30. How do we know the masses of the planets?

31. Distinguish between a sidereal day and a solar day. Which is longer on Earth?
32. The planets’ directions of rotation and revolution have certain features in common. Describe these features. Which planets have an unusual direction of rotation?

33. Name the terrestrial planets and the Jovian planets. Why are the latter called Jovian?

34. In what ways are the terrestrial planets similar to one another but different from the Jovians?

35. How does the eccentricity of the Earth’s orbit compare with that of other planets?

36. How does the Earth compare with the other planets in density?

37. What is meant when we say that the escape velocity from the Earth is 11 kilometers per second?

38. What two factors determine the speed of the molecules of a gas?

39. Explain why hydrogen escapes from the Earth’s atmosphere but carbon dioxide does not.

40. How do evolutionary theories explain the pattern of chemical abundance among the planets?

41. We now have definite evidence that planetary systems exist around other stars. Does this lend support to either the catastrophe or evolutionary theories? If so, which?

42. How do evolutionary theories account for asteroids? The Oort cloud?

43. Describe the evidence that planetary systems exist around other stars.

1. Copernicus did not know the distance from the Earth to the Sun. Yet the text states that he calculated the relative distances to the planets. Explain.

2. How do we measure the distances to the planets today?

3. Is density the same thing as “hardness”? Why do we bother calculating the density of an object when we could just state its mass? (That is, what additional information is gained by calculating its density?)

4. Name the planet that
   A. has the most eccentric orbit.
   B. is largest.
   C. has the least density.
   D. has the most mass.
   E. has the most moons.
   F. has the least atmosphere.

5. If a planet rotates slowly in a retrograde direction (clockwise as seen from above the Sun’s north pole), which will be longer, its sidereal day or its solar day? Explain.

6. Is the escape velocity from Earth the same whether we are considering a point just above the atmosphere or a point higher up? Explain.

7. How do evolutionary theories explain observations 1, 2, and 4 as listed in the section “Evidential Clues from the Data”? How do catastrophe theories explain these observations?

8. Explain the problem the law of conservation of angular momentum presents for evolutionary theories and describe how today’s theory accounts for the observations.

9. Explain in your own words why there is a pattern of changes in the composition of planets as we move from those close to the Sun to those far away.

10. What techniques are used to detect planets that orbit other stars? Name some limitations to these techniques.

11. If we wish to find planets near other stars, why not just use telescopes to look for the planets directly?

1. The eccentricity of Pluto’s orbit is 0.24. Use a drawing of an ellipse to explain what this means quantitatively.

2. If another planet were found beyond Pluto, how far would Bode’s law predict it to be from the Sun (assuming it is the next planet in his scheme)?

3. At a time when Jupiter is 9.0 \times 10^8\text{ kilometers from Earth}, its angular size is 33 seconds of arc. Use these data to calculate the diameter of Jupiter, and then check your answer in Appendix C.

4. Suppose that we bounce a radar signal off of Jupiter. It returns to Earth 100 minutes after being sent. How far away is Jupiter at the time of the measurement?

5. The escape speed of an object from a planet or star of mass \( m \) and radius \( R \) is proportional to \( \sqrt{m/R} \). The escape speed from Earth’s surface is about 11 kilometers/second. Using data from Appendices B and C, find the escape speed from the Sun’s surface and compare your result with that given in Appendix B.

6. Phobos is a small satellite orbiting Mars. The average distance between the two objects (from center to center) is about 9400 kilometers and the orbital period is 0.319 days (see Appendix D). What is the mass of Mars? What assumption did you make to get this answer? As Mars’ radius is 3400 kilometers, what is its average density? What can you say about its chemical composition? You can find information about current explorations of our solar system at NASA’s home page (http://www.nasa.gov).

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