13 Other Planetary Systems
The New Science of Distant Worlds

LEARNING GOALS

13.1 Detecting Extrasolar Planets
- Why is it so difficult to detect planets around other stars?
- How do we detect planets around other stars?

13.2 The Nature of Extrasolar Planets
- What have we learned about extrasolar planets?
- How do extrasolar planets compare with planets in our solar system?

13.3 The Formation of Other Solar Systems
- Can we explain the surprising orbits of many extrasolar planets?
- Do we need to modify our theory of solar system formation?

13.4 Finding More New Worlds
- How will we search for Earth-like planets?
A little more than a decade ago, all of planetary science was based solely on the study of our own solar system. Then, beginning in 1995, a dramatic change occurred as scientists began to detect planets around other stars. More than 250 such planets were already known by 2007, and new discoveries are coming rapidly. We are even beginning to learn about the characteristics of these distant worlds.

The discovery of planets around other stars represents a triumph of modern technology. It also has profound philosophical implications. Knowing that planets are common makes it seem more likely that we might someday find life elsewhere, perhaps even intelligent life. Moreover, having many more worlds to compare to our own vastly enhances our ability to learn how planets work and may help us better understand our home planet, Earth.

The study of other planetary systems also allows us to test in new settings our nebular theory of solar system formation. If this theory is correct, it should be able to explain the observed properties of other planetary systems as well as it explains our own solar system. In this chapter, we’ll focus our attention on the exciting new science of other planetary systems.

Before we begin, it’s worth noting that these discoveries have further complicated the question of precisely how we define a planet. Recall that the 2005 discovery of the Pluto-like world Eris [Section 12.3] forced astronomers to reconsider the minimum size of a planet, and the International Astronomical Union (IAU) now defines Pluto and Eris as dwarf planets. In much the same way that Pluto and Eris raise the question of a minimum planetary size, extrasolar planets raise the question of a maximum size. As we will see shortly, many of the known extrasolar planets are considerably more massive than Jupiter. But how massive can a planet-like object be before it starts behaving less like a planet and more like a star? In Chapter 16 we will see that objects known as brown dwarves, with masses greater than 13 times Jupiter’s mass but less than 0.08 times the Sun’s mass, are in some ways like large jovian planets and in other ways like tiny stars. As a result, the International Astronomical Union defines 13 Jupiter masses as the upper limit for a planet.

Why is it so difficult to detect planets around other stars?

We’ve known for centuries that other stars are distant suns (see Special Topic, p. 386), making it natural to suspect that they would have their own planetary systems. The nebular theory of solar system formation, well established by the middle of the 20th century, made extrasolar planets seem even more likely. As we discussed in Chapter 8, the nebular theory explains our planetary system as a natural consequence of processes that accompanied the birth of our Sun. If the theory is correct, planets should be common throughout the universe. But are they? Prior to 1995, we lacked conclusive evidence.

Why is it so difficult to detect extrasolar planets? You already know part of the answer, if you think back to the scale model solar system discussed in Chapter 1. Recall that on a 1-to-10-billion scale, the Sun is the size of a grapefruit, Earth is a pinhead orbiting 15 meters away, and Jupiter is a marble orbiting 80 meters away. On the same scale, the distance to the nearest stars is equivalent to the distance across the United States. In other words, seeing an Earth-like planet orbiting the nearest star besides the Sun would be like looking from San Francisco for a pinhead orbiting just 15 meters from a grapefruit in Washington, D.C. Seeing a Jupiter-like planet would be only a little easier.

The scale alone would make the task quite challenging, but it is further complicated by the fact that a Sun-like star would be a billion times as bright as the light reflected from any planets. Because even the best telescopes blur the light from stars at least a little, the glare of scattered starlight would overwhelm the small blips of planetary light.
The first actual detection of extrasolar planet-size objects occurred in 1992, when precise timing measurements revealed the existence of three objects with Earth-like masses orbiting a type of “dead” star known as a pulsar [Section 18.2]. Because pulsars are created when stars die in supernova explosions, these “planets” must be either the charred remains of preexisting planets or, more likely, objects that somehow formed from supernova debris. Either way, they are not planets in the same sense as those that form during star birth; in this chapter, we will focus only on planets orbiting ordinary stars like our Sun.

As recently as the early 1990s, these challenges made even some astronomers think that we were still decades away from finding extrasolar planets. But human ingenuity proved greater than the pessimists had guessed. Thanks to technological advances, clever planet-hunting strategies, and some unexpected differences between our solar system and others, we have begun to discover planets orbiting other stars. Although it is too soon to know for sure, it seems ever more likely that our Milky Way Galaxy is home to billions of planetary systems.

**How do we detect planets around other stars?**

The discovery of extrasolar planets has opened a new era in planetary science. The first discovery—a planet orbiting a star called 51 Pegasi—was made in 1995 by Swiss astronomers Michel Mayor and Didier Queloz, and soon confirmed by a team led by Geoffrey W. Marcy and R. Paul Butler of San Francisco State University. More than 250 other extrasolar planets have been discovered since that time, many of them by these same teams of astronomers.

There are two basic ways in which astronomers can identify extrasolar planets:

1. **Directly:** Pictures or spectra of the planets themselves constitute direct evidence of their existence.
2. **Indirectly:** Precise measurements of stellar properties (such as position, brightness, or spectra) may indirectly reveal the effects of orbiting planets.

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*SPECIAL TOPIC How Did We Learn That Other Stars Are Suns?*

Today we know that stars are other suns—meaning objects that produce enough energy through nuclear fusion to supply light and heat to orbiting planets—but this fact is not obvious from looking at the night sky. After all, the feeble light of stars hardly seems comparable to the majestic light of the Sun. Most ancient observers guessed that stars were much more mundane; typical guesses suggested that they were holes in the celestial sphere or flaming rocks in the sky.

The only way to realize that stars are suns is to know that they are incredibly far away; then, a simple calculation will show that they are actually as bright as or brighter than the Sun [Section 15.1]. The first person to make reasonably accurate estimates of the distances to stars was Christiaan Huygens (1629–1695). By assuming that other stars are indeed suns, as some earlier astronomers had guessed, Huygens successfully estimated stellar distances. The late Carl Sagan eloquently described the technique:

> Huygens drilled small holes in a brass plate, held the plate up to the Sun and asked himself which hole seemed as bright as he remembered the bright star Sirius to have been the night before. The hole was effectively the apparent size of the Sun. So Sirius, he reasoned, must be 28,000 times farther from us than the Sun, or about half a light-year away. It is hard to remember just how bright a star is many hours after you look at it, but Huygens remembered very well. If he had known that Sirius was intrinsically brighter than the Sun, he would have come up with a much better estimate of the right answer: Sirius is 8.6 light-years away.*

Huygens could not actually prove that stars are suns, since his method was based on the assumption that they are. However, his results explained a fact known since ancient times: Stellar parallax is undetectable to the naked eye [Section 2.4]. Recall that the lack of detectable parallax led many Greeks to conclude that Earth must be stationary at the center of the universe, but this lack also has an alternate explanation: Stars are incredibly far away. Even with his original estimate that Sirius was only half a light-year away, Huygens knew that its parallax would have been far too small to observe by naked eye or with the telescopes available at the time. Huygens thereby “closed the loop” on the ancient mystery of the nature of stars, showing that their appearance and lack of parallax made perfect sense if they were very distant suns. This new knowledge apparently made a great impression on Huygens, as you can see from his quotation on the top of p. 385.

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Direct detection is preferable, because it can tell us far more about the planet’s properties. However, current telescopes are not quite up to the challenge of direct detection, at least for planets around ordinary stars. As a result, nearly all extrasolar planets discovered to date have been found by indirect techniques. Let’s now explore detection techniques in a little more detail.

**Gravitational Tugs** To date, nearly all extrasolar planets have been detected by observing the gravitational tugs they exert on the stars they orbit. This type of detection is indirect because we discover the planets by observing their stars without actually seeing the planets themselves.

Although we usually think of a star as remaining still while planets orbit around it, that is only approximately correct. In reality, all the objects in a star system, including the star itself, orbit the system’s “balance point,” or center of mass [Section 4.4]. To understand how this fact allows us to discover extrasolar planets, imagine the viewpoint of extraterrestrial astronomers observing our solar system from afar.

Let’s start by considering only the influence of Jupiter, which exerts a much stronger gravitational tug on the Sun than the rest of the planets combined. The center of mass between the Sun and Jupiter lies just outside the Sun’s visible surface (Figure 13.1), so what we usually think of as Jupiter’s 12-year orbit around the Sun is really a 12-year orbit around the center of mass; we generally don’t notice this fact because the center of mass is so close to the Sun itself. In addition, because the Sun and Jupiter are always on opposite sides of the center of mass (otherwise it wouldn’t be a “center”), the Sun must orbit this point with the same 12-year period as Jupiter. The Sun’s orbit traces out only a very small circle (or ellipse) with each 12-year period, because the Sun’s average orbital distance is barely larger than its own radius. Nevertheless, with sufficiently precise measurements, extraterrestrial astronomers could detect this orbital movement of the Sun. They could thereby deduce the existence of Jupiter, even without having observed Jupiter itself. They could even determine Jupiter’s mass from the Sun’s orbital characteristics: A more massive planet at the same distance would pull the center of mass farther from the Sun’s center, giving the Sun a larger orbit and a faster orbital speed around the center of mass.

**SEE IT FOR YOURSELF**

To see how a small planet can make a big star wobble, find a pencil and tape a heavier object (such as a set of keys) to one end and a lighter object (perhaps a small stack of coins) to the other end. Tie a string (or piece of floss) at the balance point—the center of mass—so the pencil is horizontal, then tap the lighter object into “orbit” around the heavier object. What does the heavier object do, and why? How does how your setup correspond to a planet orbiting a star? You can experiment further with objects of different weights or shorter pencils; try to explain the differences you see.

Now let’s add in the effects of Saturn, which exerts the second greatest gravitational tug on the Sun. Saturn takes 29.5 years to orbit the Sun, so by itself it would cause the Sun to orbit its mutual center of mass every 29.5 years. However, because Saturn’s influence is secondary to that of Jupiter, this 29.5-year period appears as a small added effect on top of the Sun’s 12-year orbit around its center of mass with Jupiter. In other words, every 12 years the Sun would return to nearly the same orbital position around its center of mass with Jupiter, but the precise point of return would move around with Saturn’s 29.5-year period. By measuring this motion carefully from afar, an extraterrestrial astronomer could deduce the existence and masses of both Jupiter and Saturn after a few decades of observing.

The other planets also exert gravitational tugs on the Sun, which further affect the Sun’s orbital motion around the solar system’s center of mass (Figure 13.2). These extra effects become increasingly difficult to measure in practice, but extremely precise observations would allow an extraterrestrial astronomer to discover all the planets in our solar system. If we turn this idea around, you’ll realize that it means we can search for planets in other star systems by carefully watching for the tiny orbital motion of a star around the center of mass of its star system.

Two techniques allow us to observe the small orbital motion of a star caused by the gravitational tugs of planets. (1) The **astrometric technique** uses very precise measurements of stellar positions in the sky (astrometry means “measurement of the stars”) to look for the stellar motion caused by orbiting planets. (2) The **Doppler technique** can detect orbital motion through changing Doppler shifts...
in a star’s spectrum [Section 5.5]; a star’s orbital motion will produce alternating blueshifts as the star moves toward us in its orbit and redshifts as it moves away. Each technique has advantages and limitations.

**SPECIAL TOPIC**

**The Names of Extrasolar Planets**

The planets in our solar system have familiar names rooted in mythology. Unfortunately, there’s not yet a well-accepted scheme for naming extrasolar planets. Astronomers still generally refer to extrasolar planets by the star they orbit, such as “the planet orbiting the star named . . . ” Worse still, the stars themselves often have confusing or even multiple names, reflecting naming schemes used in star catalogs made by different people at different times in history.

A few hundred of the brightest stars in the sky carry names from ancient times. Many of these names are Arabic—such as Betelgeuse, Algo, and Aldebaran—because of the work of the Arabic scholars of the Middle Ages [Section 3.2]. In the early 1600s, German astronomer Johann Bayer developed a system that gave names to many more stars: Each star gets a name based on its constellation and a Greek letter indicating its ranking in brightness within that constellation. For example, the brightest star in the constellation Andromeda is called Alpha Andromedae, the second brightest is Beta Andromedae, and so on. Bayer’s system worked for only the 24 brightest stars in each constellation, because there are only 24 letters in the Greek alphabet. About a century later, English astronomer John Flamsteed published a more extensive star catalog in which he used numbers once the Greek letters were exhausted. For example, 51 Pegasi gets its name from Flamsteed’s catalog. (Flamsteed’s numbers are based on position within a constellation rather than brightness.)

As more powerful telescopes made it possible to discover more and fainter stars, astronomers developed many new star catalogs. The names we use today usually come from one of these catalogs. For example, the star HD209458 appears as star number 209458 in a catalog compiled by Henry Draper (HD). You may also see stars with numbers preceded by other catalog names, including Gliese, Ross, and Wolf; these catalogs are also named for the astronomers who compiled them. Moreover, because the same star is often listed in several catalogs, a single star can have several different names. Some of the newest planets orbit stars so faint they have not been previously cataloged. They then carry the name of the observing program that discovered them, such as TrES-1 for the first discovery of Trans-Atlantic Exoplanet Survey, or OGLE-TR-132b for the planet orbiting the 132nd object scrutinized by the Optical Gravitational Lensing Experiment.

Objects orbiting other stars usually carry the star name plus a letter denoting their order of discovery around that star. If the second object is another star, a capital B is added to the star name, but a lowercase b is added if it’s a planet. For example, HD209458b is the first planet discovered to be orbiting star number 209458 in the Henry Draper catalog. Upsilon Andromedae d is the third planet discovered to be orbiting the twentieth brightest star (because upsilon is the twentieth letter in the Greek alphabet) in the constellation Andromeda. Many astronomers hope soon to devise a better naming system for these wonderful new worlds.

**The Astrometric Technique**

The astrometric technique has been used for many decades to identify binary star systems, since two orbiting stars will move periodically around their center of mass. The technique works especially well for binary systems in which the two stars are not too close together, because the stellar motions tend to be larger in those cases. In the case of planet searches, however, the expected stellar motion is much more difficult to detect.

For example, from a distance of 10 light-years, a Jupiter-size planet orbiting 5 AU from a Sun-like star would cause its star to move slowly over a side-to-side angular distance of only about 0.003 arcsecond—approximately the width of a hair seen from a distance of 5 kilometers. Remarkably, with careful telescope calibration astronomers can now measure movements this small, and instruments currently under development will be 5 to 10 times more precise. However, two other complications add to the difficulty of the astrometric technique.

The first complication comes from the fact that the farther away a star is, the smaller its side-to-side movement will appear. For example, while Jupiter causes the Sun to move by about 0.003 arcsecond as seen from 10 light-years away, the observed motion is only half as large when seen from 20 light-years away and one-tenth as large when seen from 100 light-years away. The astrometric technique therefore works best for massive planets around relatively nearby stars.

The second complication arises from the time required to detect a star’s motion. It is much easier to detect larger...
movements than smaller ones, and a planet with a larger orbit has a larger effect on its star. To understand why, consider what would happen if Jupiter were moved farther from the Sun. Because the center of mass of the solar system is very nearly at the balance point between the Sun and Jupiter, moving Jupiter outward would also cause the center of mass to move farther from the Sun. With the center of mass located farther from the Sun, the Sun’s orbit around the center of mass—and hence its side-to-side motion as seen from a distance—would be larger, which in principle would make it easier to detect this motion with the astrometric technique. However, Kepler’s third law tells us that a more distant planet takes longer to complete its orbit, which means its star also takes longer to move back and forth. So while the astrometric technique might be useful for detecting this motion, it would take many years of observations. For example, while Jupiter causes the Sun to move around the center of mass with a 12-year period, Neptune’s effects on the Sun show up with the 165-year period of Neptune’s orbit. A century or more of patient observation would be needed to prove that stellar motion was occurring in a 165-year cycle.

As a result of these complications, the astrometric technique has been used to detect only one extrasolar planet through 2007. Nevertheless, as we’ll discuss in Section 13.4, we expect the astrometric technique to be used extensively in the future.

The Doppler Technique The Doppler technique has been used for the vast majority of extrasolar planet discoveries to date (Figure 13.3). The 1995 discovery of a planet orbiting 51 Pegasi came when this star was found to have alternating blueshifts and redshifts corresponding to an orbital speed of 57 meters per second (Figure 13.4a). The 4-day period of the star’s motion is also the orbital period of its planet. We therefore know that the planet lies so close to the star that its “year” lasts only 4 of our days and its surface temperature is probably over 1,000 K (Figure 13.4b). It is therefore an example of what we call a “hot Jupiter,” because it has a Jupiter-like mass but a much higher surface temperature.

Current techniques can measure a star’s velocity to within about 1 meter per second—walking speed—which corresponds to a Doppler wavelength shift of only one part in 300 million. We can therefore find planets that exert a
considerably smaller gravitational tug on their stars than the planet orbiting 51 Pegasi. Moreover, by carefully analyzing Doppler shift data, we can learn about the planet’s orbital characteristics and mass. After all, it is the mass of the planet that causes the star to move around the system’s center of mass, so for a given orbital distance, a more massive planet will cause faster stellar motion.

We can derive an extrasolar planet’s orbital distance using Newton’s version of Kepler’s third law [Section 4.4]. Recall that for a small object like a planet orbiting a much more massive object like a star, this law expresses a relationship between the star’s mass, the planet’s orbital period, and the planet’s average distance (semimajor axis). We generally know the masses of the stars with extrasolar planets (through methods we’ll discuss in Chapter 15), and the Doppler data tell us the orbital period, so we can calculate orbital distance.

We determine orbital shape from the shape of the Doppler data curve. A planet with a perfectly circular orbit travels at a constant speed around its star, so its data curve would be perfectly symmetric. Any asymmetry in the Doppler curve tells us that the planet is moving with varying speed and therefore must have a more eccentric (“stretched out”) elliptical orbit. Figure 13.5 shows four examples of Doppler data for extrasolar planets and what we learn in each case.

![Figure 13.5](image.png)

**Figure 13.5** Sample data showing how measurements of Doppler shifts allow us to learn about extrasolar planets for different types of orbits. The points are data for actual planets whose properties are listed in Appendix E.4. Notice that the data points are repeated for additional cycles to show the patterns.

**THINK ABOUT IT**

Study the four velocity data curves in Figure 13.5. How would each be different if the planet were: (a) closer to its star? (b) more massive? Explain.

In some cases, existing Doppler data are good enough to tell us whether the star has more than one planet. Remember that if two or more planets exert a noticeable gravitational tug on their star, the Doppler data will show the combined effect of these tugs. In 1999, such analysis was used to infer the existence of three planets around the star Upsilon Andromedae, making this the first bona fide, multiple-planet solar system known beyond our own. By 2007, at least 20 other multiple-planet systems had been identified.

The Doppler technique also tells us about planetary masses, though with an important caveat. Remember that Doppler shifts reveal only the part of a star’s motion directed toward or away from us (see Figure 5.23). As a result, a planet whose orbit we view face-on does not cause a Doppler shift in the spectrum of its star, making it impossible to detect the planet with the Doppler technique (Figure 13.6a). We can observe Doppler shifts in a star’s spectrum only if it has a planet orbiting at some angle other than face-on (Figure 13.6b), and the Doppler shift...
The Doppler technique directly tells us a planet’s orbital period. We can then use this period to determine the planet’s orbital distance. If the planet were orbiting a star of exactly the same mass as the Sun, we could find the distance by applying Kepler’s third law in its simplest form: \( p^2 = a^3 \). In fact, many of the planets discovered to date do orbit Sun-like stars, so this law gives a good first estimate of orbital distance. For more precise work, we use Newton’s version of Kepler’s third law (see Mathematical Insight 4.3), which reads:

\[
\frac{p^2}{a^3} = \frac{4\pi^2}{GM}\]

In the case of a planet orbiting a star, \( p \) is the planet’s orbital period, \( a \) is its average orbital distance (semimajor axis), and \( M_1 \) and \( M_2 \) are the masses of the star and planet, respectively. (\( G \) is the gravitational constant; \( G = 6.67 \times 10^{-11} \text{ m}^3/(\text{kg} \times \text{s}^2) \).) Because a star is so much more massive than a planet, the sum \( M_1 + M_2 \) is pretty much just \( M_1 \); that is, we can neglect the mass of the planet compared to the star. With this approximation, we can rearrange the equation to find the orbital distance \( a \):

\[
a \approx \frac{3}{4\pi^2} \frac{GM}{p^2} \]

We will discuss how we determine stellar masses in Chapter 15; for now, we will assume the stellar masses are known so that we can calculate orbital distances of the planets.

**Example:** Doppler measurements show that the planet orbiting 51 Pegasi has an orbital period of 4.23 days; the star’s mass is 1.06 times that of our Sun. What is the planet’s orbital distance?

**Solution:**

**Step 1 Understand:** We are given both the planet’s orbital period and the star’s mass, so we can use Newton’s version of Kepler’s third law to find the planet’s orbital distance. However, to make the units consistent, we need to convert the given stellar mass to kilograms and the given orbital period to seconds; we look up the fact that the Sun’s mass is about \( 2 \times 10^{30} \text{ kg} \).

\[
M_\text{star} = 1.06 \times M_\text{Sun} = 1.06 \times (2 \times 10^{30} \text{ kg}) = 2.12 \times 10^{30} \text{ kg}
\]

\[
p = 4.23 \text{ day} \times \frac{24 \text{ hr}}{1 \text{ day}} \times \frac{3600 \text{ s}}{1 \text{ hr}} = 3.65 \times 10^5 \text{ s}
\]

**Step 2 Solve:** We use these values of the period and mass to find the orbital distance \( a \):

\[
a \approx \frac{3}{4\pi^2} \frac{GM_\text{star}}{p^2} \]

\[
= \frac{3}{4\pi^2} \times \frac{6.67 \times 10^{-11} \text{ m}^3/(\text{kg} \times \text{s}^2) \times 2.12 \times 10^{30} \text{ kg}}{(3.65 \times 10^5 \text{ s})^2}
\]

\[
= 7.81 \times 10^9 \text{ m}
\]

**Step 3 Explain:** We’ve found that the planet orbits its star at a distance of 7.8 billion meters. It’s much easier to interpret this number if we state it as 7.8 million kilometers or, better yet, convert it to astronomical units, remembering that 1 AU is about 150 million kilometers or \( 1.50 \times 10^{11} \text{ m} \):

\[
a = 7.81 \times 10^9 \text{ m} \times \frac{1 \text{ AU}}{1.50 \times 10^{11} \text{ m}} = 0.052 \text{ AU}
\]

We now see that the planet’s orbital distance is only 0.052 AU—small even compared to that of Mercury, which orbits the Sun at 0.39 AU. In fact, comparing the planet’s 7.8-million-kilometer distance to the size of the star itself (presumably close to the 700,000-kilometer radius of our Sun), we estimate that the planet orbits its star at a distance only a little more than 10 times the star’s radius.
tells us the star’s full orbital velocity only if we are viewing the orbit precisely edge-on. A planetary mass that we infer from its star’s Doppler shift therefore will be precise only for a planet in an edge-on orbit. In all other cases, the Doppler shift underestimates the true orbital speed of the star and therefore also leads to an underestimate of the planet’s true mass. As a result, planetary masses inferred from the Doppler technique alone are always minimum possible masses (or “lower limits”) for these planets.

We can determine a precise mass from the Doppler technique only if we somehow know that we are viewing an edge-on orbit or if we have some way to measure the precise orbital angle. For example, if we also know the planet’s side-to-side motion from the astrometric technique, we can combine this information with the toward and away motions from the Doppler technique to determine the orbital angle. Unfortunately, we rarely have such knowledge, which means that nearly all planetary masses found through the Doppler technique are really minimum masses rather than actual masses. However, statistical calculations based on orbital inclinations show that a planet’s mass will be more than double the minimum mass in fewer than 15% of all cases, and more than ten times the minimum mass in only about 1 out of 200 planetary systems. The minimum masses obtained by the Doppler technique are therefore relatively good estimates in the vast majority of cases.

The Doppler technique is very powerful, but it has limits. In particular, it is best suited to identifying massive planets that orbit relatively close to their star. This limitation arises because gravity weakens with distance, so a planet of a given size pulls harder on its star—making the star move faster—if it is closer. Moreover, it takes a lot less time to observe the periodic Doppler shifts caused by a close-in planet because of the shorter orbital period. For example, it takes only a few weeks of observation to detect a planet with a 4-day period like the one orbiting 51 Pegasi, but it would take 12 years to observe just a single orbital cycle.

**MATHEMATICAL INSIGHT 13.2**

Finding Masses of Extrasolar Planets

We can find the mass of an extrasolar planet by using the law of conservation of momentum [Section 4.3]. Consider a star with a single planet, each orbiting around their common center of mass with the same orbital period. The system as a whole has no momentum relative to this center of mass (which stays in a fixed place between the star and planet), so the planet’s momentum must be equal to the star’s momentum (but in the opposite direction). Remembering that momentum is mass times velocity, we write:

\[ M \text{ star} v \text{ star} = M \text{ planet} v \text{ planet} \]

where \( M \) stands for the mass of the star or planet, and \( v \) stands for the velocity relative to the center of mass. Solving this equation for \( M \text{ planet} \), we find:

\[ M \text{ planet} = \frac{M \text{ star} v \text{ star}}{v \text{ planet}} \]

The Doppler technique gives us a direct measurement of the star’s velocity toward or away from us (\( v \text{ star} \)) and, as discussed earlier, we generally know the star’s mass (\( M \text{ star} \)). We can calculate the planet’s orbital velocity (\( v \text{ planet} \)) from its orbital period and orbital distance; we learn the former directly from the Doppler technique and calculate the latter with the method in Mathematical Insight 13.1. Each time the planet completes an orbit, it must travel a distance of \( 2\pi a \), where \( a \) is the planet’s average orbital distance. (Notice that we are using the formula for circumference of a circle, even though the orbits are generally elliptical.) The time it takes to complete the orbit is the orbital period \( p \). Thus, the planet’s average orbital velocity must be:

\[ v \text{ planet} = \frac{2\pi a \text{ planet}}{p \text{ planet}} \]

You should confirm that substituting this expression for the planet’s velocity into the above equation for mass gives us the following:

\[ M \text{ planet} = \frac{M \text{ star} v \text{ star} p \text{ planet}}{2\pi a \text{ planet}} \]

Remember that with velocity data from the Doppler technique, this formula gives us the minimum mass of the planet.

**Example:** Estimate the mass of the planet orbiting 51 Pegasi.

**Solution:**

**Step 1 Understand:** From Mathematical Insight 13.1, we know the planet’s orbital period \( p = 3.65 \times 10^5 \) s and orbital distance \( a = 7.82 \times 10^9 \) m, and the star’s mass \((M \text{ star} = 2.12 \times 10^{30} \text{ kg})\). As stated earlier in the text, the star’s velocity averages 57 meters per second (see Figure 13.4a). We can therefore use the formula found above to calculate the planet’s mass.

**Step 2 Solve:** We enter the values into the mass formula:

\[
M \text{ planet} = \frac{M \text{ star} v \text{ star} p \text{ planet}}{2\pi a \text{ planet}}
\]

\[
= \frac{(2.12 \times 10^{30} \text{ kg}) \times (57 \text{ m/s}) \times (3.65 \times 10^5 \text{ s})}{2\pi \times (7.82 \times 10^9 \text{ m})}
\]

\[
\approx 9 \times 10^{26} \text{ kg}
\]

**Step 3 Explain:** The minimum mass of the planet is about \( 9 \times 10^{26} \) kilograms. This answer will be more meaningful if we convert it to Jupiter masses. From Appendix E, Jupiter’s mass is \( 1.9 \times 10^{27} \) kilograms, so the planet’s minimum mass is:

\[
M \text{ planet} = 9 \times 10^{26} \text{ kg} \times \frac{1M \text{ Jupiter}}{1.9 \times 10^{27} \text{ kg}} = 0.47M \text{ Jupiter}
\]

The planet orbiting 51 Pegasi has a mass of at least 0.47 Jupiter mass, which is just under half Jupiter’s mass. Remembering that most planets will have actual masses within a factor of about 2 of the minimum mass, we see that the planet probably has a mass quite similar to that of Jupiter.
of a planet with an orbit like that of Jupiter. The Doppler technique also presents a practical difficulty: The extremely precise radial velocity measurements require a relatively large telescope, so only a relatively small number of stars can be studied with this technique.

The limitations of the Doppler technique explain what may at first seem like surprising facts: Most of the extrasolar planets discovered to date orbit closer to their stars than similar planets in our solar system, and we have yet to discover any planets at all with Earth-like masses. Both these facts may simply be selection effects of the Doppler technique; that is, the technique tends to find (or “select”) massive planets in close orbits much more easily than any other type of planet. Planets with masses similar to Earth would have such weak gravitational effects on their stars that we could not use the Doppler technique to find them with current technology, while planets orbiting far from their stars have such long orbital periods that it might take decades of observations to detect them. Thus, the current lack of evidence for Earth-mass planets or jovian-mass planets in distant orbits does not necessarily mean that such planets are rare.

**Transits and Eclipses** A third indirect way of detecting distant planets does not require the observation of gravitational tugs at all. Instead, it relies on searching for slight changes in a star’s brightness caused by a planet passing in front of it or behind it.

If we were to examine a large sample of stars with planets, a small number of them—typically one in several hundred—will by chance be aligned in such a way that one or more of its planets will pass directly between us and the star once each orbit. The result is a transit, in which the planet appears to move across the face of the star. We occasionally witness this effect in our own solar system when Mercury or Venus crosses in front of the Sun (see Figure S1.5). Other star systems are so far away that we cannot actually see a planetary dot set against the face of the star as we can for Mercury or Venus set against the face of the Sun. Nevertheless, a transiting planet will block a little of its star’s light, allowing us not only to detect the planet’s existence but also to calculate the planet’s size in comparison to that of its star (see Mathematical Insight 13.3). Because we usually know the star’s size (through methods we’ll discuss in Chapter 15), transit observations allow us to determine planetary sizes.

Detecting planets through transits requires many repeated observations, because most stars exhibit intrinsic variations in brightness. To be confident that an orbiting planet is responsible for a dip in brightness rather than variability in the star itself, we need to see at least several occurrences of the telltale pattern of dimming that occurs during a transit. If this repeated dimming occurs with a regular period, then it is very likely telling us the orbital period of a transiting planet. We can then calculate the planet’s orbital distance and mass.

**THINK ABOUT IT**

Which of the following types of planet is most likely to cause a transit across its star that we could observe from Earth? (a) a large planet close to its star; (b) a large planet far from its star; (c) a small planet close to its star; or (d) a small planet far from its star. Explain.

The first success of the transit method came during follow-up studies of a planet that had already been discovered with the Doppler technique. The planet, which orbits a star called HD209458, was already known to complete an orbit every 3.5 days. Thus, when astronomers observed the star to undergo dips in brightness every 3.5 days (and at just the times that the Doppler measurements said the planet would be moving across our line of sight), they realized they were observing repeated transits by the planet (Figure 13.7).

This discovery greatly advanced our understanding of the
Transits can also tell us about the composition of a planet’s upper atmosphere or exosphere (Figure 13.8). To see how, consider what happens if a planet like Jupiter passes in front of its star. From a distance, Jupiter looks like a solid disk extending out as far as its cloud tops. During the transit, this “solid” disk blocks all the starlight coming from directly behind it. Now, suppose the Jupiter-like planet also has a low-density upper atmosphere extending above its cloud tops. The gas in this upper atmosphere would absorb starlight at specific wavelengths that depend on its composition. For example, if the planet’s upper atmosphere contained sodium gas, the star’s spectrum would show stronger sodium absorption lines during the transit than at other times. We’d thereby learn that the planet contains sodium in its upper atmosphere.

Planets that pass in front of their stars during a transit can also pass behind their stars, in which case the star blocks the light from the planet. Such an event is called an eclipse (see Figure 13.7), because the star blots out the light from the planet in much the same way that the Moon can blot out the light of our Sun during a total solar eclipse [Section 2.3]. Observing an eclipse is much like observing a transit. In both cases, we measure the total light from the star and planet, searching for a small dip in brightness. Because the star is so much brighter than the planet, the dip in brightness is smaller during an eclipse than a transit. To maximize the effect of the eclipse, astronomers therefore observe at infrared wavelengths, because planets emit most of their own radiation in the form of infrared thermal emission while stars emit more at visible wavelengths. Even so, the total drop in light was only 0.25% when the Spitzer Space Telescope observed an eclipse of the planet orbiting the star HD209458. This small change allowed astronomers to calculate the planet’s total amount of thermal emission and confirm that the planet’s temperature is over 1,100 K. In fact, much as for planets in our own solar system, the infrared brightness can be used to determine how much starlight the planet reflects or absorbs (see Mathematical Insight 10.1), and the crude infrared spectrum can be used to identify gases in the planet’s atmosphere (see Figure 5.14). The first successful observations of this type were announced in 2005, and it is likely that this technique will be improved and applied to more planets by the time you are reading this book.

The method of observing extrasolar planets through transits and eclipses has some unusual strengths and weaknesses. The most obvious weakness is that it can work only for the small fraction of planetary systems whose orbits are oriented edge-on to Earth. A second weakness is that the method is biased in favor of planets with short orbital periods—and hence with orbits close to their stars—both because these planets transit more frequently and because we must observe repeated transits before we can be confident of a discovery. Counterbalancing these weaknesses is a very important strength: With sufficiently precise measurements of stellar brightness, the transit method ought to be able to reveal planets far smaller than is currently possible with the astrometric or Doppler techniques. Indeed, as we’ll discuss in Section 13.4, NASA is currently preparing a mission (called Kepler) specifically intended to search for transits by Earth-size planets.

This planet orbits in 3.5 days. When it is not in front of its star, we see only the spectrum of the star itself.

The star appears 1.7% dimmer when the planet passes in front of it, so we can figure out the planet’s size compared to the star.

The planet’s upper atmosphere absorbs additional light at wavelengths that depend on its composition.

The sodium lines are deeper when the planet is in front of the star, telling us that the planet’s atmosphere contains sodium.

Absorption line depths are exaggerated for clarity.

**Figure 13.8** This diagram shows how transit observations can give us information about the composition of an extrasolar planet’s extended upper atmosphere or exosphere.
Perhaps the most interesting aspect of the transit method is that it can work with both large and small telescopes. With a large telescope, searches for transits can successfully monitor stars at much greater distances than is possible with the astrometric or Doppler techniques. At the opposite extreme, a telescope as small as 4 inches in diameter has been used to discover an extrasolar planet, and it’s relatively easy to confirm for yourself some of the transits that have already been detected. What was once considered impossible can now be assigned as homework (see Problem 54 at the end of the chapter).

**Direct Detection** The indirect planet-hunting techniques we have discussed so far have started a revolution in planetary science by demonstrating that our solar system is just one of many planetary systems. However, these indirect techniques tell us relatively little about the planets themselves, aside from their orbital properties and sometimes their masses and radii. To learn more about their nature, we need to observe the planets themselves, obtaining images of their surfaces or spectra of their atmospheres.

Unfortunately, we cannot yet obtain images or spectra of planets around Sun-like stars, primarily because of the incredible glare of the stars themselves. However, in at least one case as of early 2007, astronomers have observed a possible planet around a much fainter star. The “star” is actually a type of object known as a brown dwarf (Section 16.3); brown dwarfs have masses between those of very large planets and those of very small stars, and they emit very little visible light. The “candidate planet” has been photographed in the infrared by both the European Southern Observatory’s Very Large Telescope (see the photo that opens this chapter) and the Hubble Space Telescope (Figure 13.9). The infrared emission from the brown dwarf itself was subtracted from the Hubble photo, allowing us to see the candidate planet more clearly. The infrared data tell us that the object is cooler than the brown dwarf it orbits, though its temperature is still above 1,000 K. The Very Large Telescope used adaptive optics to “unblur” effects of Earth’s atmosphere (Section 6.3), thereby obtaining picture quality comparable to that of Hubble, though still not nearly sharp enough to see any detail on the object. The Very Large Telescope was also able to obtain an infrared spectrum of the candidate planet. The spectrum showed evidence of water molecules, which could be a sign of jovian nature (because water is a common molecule in jovian planet atmospheres), but it’s still possible the object is a brown dwarf.

**Other Planet-Hunting Strategies** The astonishing success of recent efforts to find extrasolar planets has led astronomers to think of many other possible ways of enhancing the search. One example is a project known as the Optical Gravitational Lensing Experiment (OGLE), a large survey of thousands of distant stars. Although it was not originally designed with planet detection in mind, OGLE has already detected several planets by observing transits. It has also succeeded in detecting at least one by gravitational lensing, an effect that occurs when one object’s gravity bends or brightens the light of a more distant object directly behind it [Sections S3.5, 22.2]. While this method has led to the detection of the smallest planet so far (and could in principle allow the detection of planets as small as Earth), the special alignment of objects necessary for lensing will never repeat, so there’s no opportunity for follow-up observations.

Planets can also reveal themselves through their gravitational effects on the disks of dust that surround many stars or through thermal emission from impacts of accreting planetesimals. If a planet is present within a dust disk, it can exert small gravitational tugs on dust particles that produce gaps, waves, or ripples in the disk. Such is the case for the star Beta Pictoris, which is surrounded by a dust disk with ripples indicating that it also has one or more planets. The impact technique relies on looking for the thermal emission generated by the enormous heat that must accompany large impacts in young planetary systems. Other astronomers are searching for the special kinds of emission known to come from the magnetospheres of our jovian planets. As we learn more about extrasolar planets, new search methods are sure to arise. The two-page Cosmic Context spread in Figure 13.10 summarizes the major planet detection techniques.

**Detecting Extrasolar Planets Tutorial, Lessons 1–3**

### 13.2 The Nature of Extrasolar Planets

The mere existence of planets around other stars has changed our perception of our place in the universe, because it shows that our planetary system is not unique. In addition, these extrasolar planets provide us with two
The search for planets around other stars is one of the fastest growing and most exciting areas of astronomy. Although it has been only a little more than a decade since the first discoveries, known extrasolar planets already number well above 250. This figure summarizes major techniques that astronomers use to search for and study extrasolar planets.

1. **Gravitational Tugs**: We can detect a planet by observing the small orbital motion of its star as both the star and its planet orbit their mutual center of mass. The star’s orbital period is the same as that of its planet, and the star’s orbital speed depends on the planet’s distance and mass. Any additional planets around the star will produce additional features in the star’s orbital motion.

   Jupiter actually orbits the center of mass every 12 years, but appears to orbit the Sun because the center of mass is so close to the Sun.

   The Sun also orbits the center of mass every 12 years.

   Not to scale!

1a. **The Doppler Technique**: As a star moves alternately toward and away from us around the center of mass, we can detect its motion by observing alternating Doppler shifts in the star’s spectrum: a blueshift as the star approaches and a redshift as it recedes. This technique has revealed the vast majority of known extrasolar planets.

   Current Doppler shift measurements can detect an orbital velocity as small as 1 meter per second—walking speed.

   The change in the Sun’s apparent position, if seen from a distance of 10 light years, would be similar to the angular width of a human hair at a distance of 5 kilometers.

1b. **The Astrometric Technique**: A star’s orbit around the center of mass leads to tiny changes in the star’s position in the sky. As we improve our ability to measure these tiny changes, we should discover many more extrasolar planets.
2 Transits and Eclipses: If a planet's orbital plane happens to lie along our line of sight, the planet will transit in front of its star once each orbit, while being eclipsed behind its star half an orbit later. The amount of starlight blocked by the transiting planet can tell us the planet's size, and changes in the spectrum can tell us about the planet's atmosphere.

We observe a transit when the planet passes in front of the star. When the planet passes behind the star, we say it is eclipsed by the star.

3 Direct Detection: In principle, the best way to learn about an extrasolar planet is to observe directly either the visible starlight it reflects or the infrared light that it emits. Our technology is only beginning to reach the point where direct detection is possible, but someday we will be able to study both images and spectra of distant planets.
opportunities for expanding our understanding of planets and how they form.

First, the nature of the individual planets themselves gives us an opportunity to learn more about the range of possible planets. For example, the planets of our own system come in two basic types: terrestrial and jovian. Studies of extrasolar planets may tell us whether these are the only two categories of planet or whether there are others that we do not see in our own solar system.

Second, studying the arrangements of other planetary systems can tell us whether the layout of our solar system is common or rare, thereby shedding light on whether the nebular theory really does explain the origin of our solar system as neatly as we have presumed. For example, in our solar system the terrestrial planets are all located close to the Sun and the jovian planets are much farther away—an observation that the nebular theory successfully explains. Can the nebular theory explain the layouts of other solar systems equally well? In this section, we’ll discuss what we have learned to date about the orbits, masses, sizes, and compositions of extrasolar planets. We’ll then be prepared to turn our attention in the next section to the questions of how other planetary systems compare to our own and how differences may have arisen.

What have we learned about extrasolar planets?

The number of known extrasolar planets is now large enough that we can begin to search for patterns, trends, and groupings that might give us insight into how these planets compare to the planets of our own solar system. Before we go into detail, let’s summarize the planetary properties that we can learn with current detection techniques:

- **Orbital period**: All three indirect techniques that we discussed (astrometric, Doppler, and transits) tell us the orbital period of detected planets.
- **Orbital distance**: Once we know orbital period, we can calculate orbital distance by using Newton’s version of Kepler’s third law (see Mathematical Insight 13.1).
- **Orbital shape**: We need data spanning an entire orbit to determine whether the orbit is a circle or a more eccentric ellipse. The astrometric and Doppler techniques can provide the needed data, but transits alone cannot.
- **Mass**: We can determine an extrasolar planet’s mass from its orbital period, the mass of its star, and the speed at which it makes its star orbit their mutual center of mass (see Mathematical Insight 13.2). In principle, we can learn a star’s full orbital speed with the astrometric technique, while the Doppler technique tells us only a minimum mass for the planet unless we also know the orbital inclination. We cannot learn mass from transits alone.
- **Size (radius)**: We can learn a planet’s size only by observing transits. The dip in the star’s brightness during a transit tells us the fraction of its light blocked by the planet, which allows us to calculate the planet’s radius (see Mathematical Insight 13.3).
- **Density**: We can calculate a planet’s average density from its size and mass. Because we get size only from transits, we can determine density only for planets that are jovian in nature. Transits provide this information in a simple geometric fashion.

While the masses of most known extrasolar planets are Jupiter-like, we also need to know sizes to be confident these planets really are jovian in nature. Transits provide this information in a simple geometric fashion.

The technique relies on measuring the fraction of the star’s light that the planet blocks during a transit. From a distance, the star and planet must look like circular disks (though we generally cannot resolve the disks with our telescopes), so we can use the formula for the area of a circle \( \pi r^2 \) to determine the sizes of these disks. We generally know the approximate radius of the host star (from methods we’ll discuss in Chapter 15), so the fractional drop in the star’s light during a transit is:

\[
\text{fraction of light blocked} \approx \frac{\text{area of planet’s disk}}{\text{area of star’s disk}} = \frac{\pi r_{\text{planet}}^2}{\pi r_{\text{star}}^2} = \frac{r_{\text{planet}}^2}{r_{\text{star}}^2}
\]

We can rearrange the equation to solve for the planet’s radius \( r_{\text{planet}} \); you should confirm that the formula becomes:

\[
r_{\text{planet}} \approx r_{\text{star}} \times \sqrt{\text{fraction of light blocked}}
\]

**Example**: What is the radius of the planet orbiting the star HD209458? The star’s radius is about 800,000 kilometers (1.15\( r_{\text{Jup}} \)), and during a transit the planet blocks 1.7% of the star’s light (see Figure 13.7b).

**Solution**:

**Step 1 Understand**: The fraction of the star’s light that is blocked during a transit is 1.7% = 0.017. We now have all the information needed to use the above equation for the planet’s radius.

**Step 2 Solve**: Plugging the numbers into the equation, we find:

\[
r_{\text{planet}} \approx r_{\text{star}} \times \sqrt{\text{fraction of light blocked}}
\]

\[
= 800,000 \text{ km} \times \sqrt{0.017}
\]

\[
\approx 100,000 \text{ km}
\]

**Step 3 Explain**: The planet’s radius is close to 100,000 kilometers. From Appendix E, Jupiter’s radius is about 71,500 kilometers. So the planet’s radius is about 100,000/71,500 \( \approx 1.4 \) times that of Jupiter. In other words, the planet is about 40% larger than Jupiter in radius.
produce transits and for which we also have mass data from the astrometric or Doppler techniques.

- **Composition**: We learn composition from spectra. Transits can provide limited information about the composition of a planet’s upper atmosphere if the star shows absorption during the transit that is not present at other times. Eclipses can also provide limited spectral information. More detailed information about composition requires spectra from direct detections.

We are now ready to see what we’ve learned about the extrasolar planets discovered to date. (See Appendix E.4 for detailed data.)

**Orbits** Much as Johannes Kepler first appreciated the true layout of our own solar system [Section 3.3], we can now step back and see the layout of many other solar systems. Figure 13.11a shows the orbits of known extrasolar planets superimposed on each other, as if they were all orbiting a single star; the dots indicate the minimum masses of the planets found through the Doppler technique.

Despite the crowding of the orbits when viewed this way, at least two important facts should jump out at you. First, notice that only a handful of these planets have orbits that take them beyond about 5 AU, which is Jupiter’s distance from our Sun. Most of the planets orbit very close to their host star. Second, notice that many of the orbits are clearly elliptical, rather than nearly circular like the orbits of planets in our own solar system. These facts are even easier to see if we display the same information on a graph (Figure 13.11b). Look first at the green squares representing the planets in our own solar system; notice that they are located at the distances you should expect and all but Mercury have very small eccentricity, meaning nearly circular orbits. Now look at the red dots representing extrasolar planets. Quite a few of these planets orbit their stars more closely than Mercury orbits the Sun, and none are located as far from their stars as the jovian planets of our solar system. Many also have large orbital eccentricities, telling us that their elliptical orbits have very stretched-out shapes. As we’ll see shortly, both facts provide important clues about the nature of these extrasolar planets.

**THINK ABOUT IT**

Should we be surprised that we haven’t found many planets orbiting as far from their stars as Saturn, Uranus, and Neptune orbit the Sun? Why or why not?

At least 20 stars have so far been found to contain two or more planets, and one system has four known planets (Figure 13.12). This is not surprising, since our own solar system and our understanding of planet formation suggest that any star with planets is likely to have multiple planets. We will probably find many more multiple-planet systems as observations improve. However, one fact about these
other planetary systems is surprising. Already, we’ve found at least five systems that seem to have planets in orbital resonances [Section 11.2] with each other. For example, four systems have one planet that orbits in exactly half the time as another planet. In our own solar system we’ve seen the importance of orbital resonances in sculpting planetary rings, stirring up the asteroid belt, and even affecting the orbits of Jupiter’s moons. As we’ll discuss shortly, orbital resonances may also have profound influences on extrasolar planets.

**Masses** Look again at Figure 13.11. The sizes of the dots indicate the approximate minimum masses of these planets; they are lower limits because nearly all have been found with the Doppler technique. The mass data are easy to see if we display them as a bar chart (Figure 13.13). We see clearly that the planets we’ve detected in other star systems are generally quite massive. Most are more massive than Jupiter, and only a few are less massive than Uranus and Neptune. The smallest detected as of late 2007 is five times as massive as Earth (which has a mass of about 0.003 Jupiter mass). If we go by mass alone, it seems likely that most of the known extrasolar planets are jovian in nature.

Should we be surprised by the scarcity of planets with masses like those expected for terrestrial worlds? Not yet. Remember that nearly all these planets have been found indirectly by looking for the gravitational tugs they exert on their stars. Massive planets exert much greater gravitational tugs and are therefore much easier to detect. As we discussed earlier, the abundance of very massive planets among these early discoveries is probably a “selection effect” arising because current planet-finding techniques detect massive planets far more easily than lower-mass planets.

**Sizes and Densities** The masses of the known extrasolar planets suggest they are jovian in nature, but mass alone cannot rule out the possibility of “supersize” terrestrial planets—that is, very massive planets made of metal or rock. To check whether the planets are jovian in nature, we also need to know their sizes, from which we can calculate their densities. If their sizes and densities are consistent with those of the jovian planets in our solar system, then we’d have good reason to think that they really are jovian in nature.

Unfortunately, we lack size data for the vast majority of known extrasolar planets, because they have only been detected by the Doppler technique and their orbits are not oriented to produce transits. However, in the relatively few cases for which we have size data from transits, the sizes and densities do indeed seem consistent with what we expect for jovian planets.

The first planet for which we obtained size data (the planet orbiting the star HD209458) has a mass of about 0.63 Jupiter mass and a radius of about 1.43 Jupiter radii. In other words, it is somewhat larger than Jupiter in size but smaller than Jupiter in mass, with an average density about 2/3 that of Jupiter. This low density is only partially surprising. The planet orbits very close to its star, with an average orbital distance of 0.047 AU (only 12% of Mercury’s distance from the Sun), so we expect the planet to be quite hot. The high temperature should cause its atmosphere to be “puffed up,” giving the planet a lower average density than Jupiter, although we cannot yet explain why its density is quite as low as it is. We currently have size and density information for several other extrasolar planets (see Appendix E.4), and in all but one case they are also larger and

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**Figure 13.12** This diagram shows the orbital distances and approximate masses of the planets in the first 20 multiple-planet systems discovered. The four highlighted systems are the ones with the best data to show planets in orbital resonances. For example, the “3:1” for 55 Cnc indicates that the inner of the two indicated planets completes exactly three orbits while the outer planet completes two orbits. When reading orbital periods from the graph, be sure to notice that the axis is exponential, so that each tick mark represents a period 10 times longer than the previous one.

**Figure 13.13** This bar chart shows the number of planets in different mass categories for 196 extrasolar planets with known minimum masses. Notice that the axis uses an exponential scale so that the wide range of masses can all fit on the graph.
lower in density than Jupiter. The one known exception is a planet orbiting the star HD149026. This planet appears to have a Saturn-like mass and a Neptune-like density of about 1.5 g/cm³ (about twice the density of Saturn). Astronomers presume that it contains a proportion of dense materials—rock, metal, and hydrogen compounds—more like that of Neptune than Saturn, despite its Saturn-like mass.

**Compositions** We have even less data about the compositions of extrasolar planets. Nevertheless, the available data support the idea that these planets are jovian in nature.

Our first data about an extrasolar planet’s composition came from the same transiting planet for which we first measured size. During the transits of HD209458, the Hubble Space Telescope detected absorption by hydrogen and sodium that is not present at other times (see Figure 13.8). From the amount of this absorption, astronomers concluded that the planet has an extended upper atmosphere containing abundant hydrogen—just as we should expect for a jovian planet—and a trace of sodium. The next case of composition information came from the “candidate planet” shown in Figure 13.9 and the photo that opens this chapter. As noted earlier, this object’s spectrum suggests the presence of atmospheric water, consistent with what we find in the jovian planets of our own solar system.

**How do extrasolar planets compare with planets in our solar system?**

Despite the limited data on extrasolar planets, we are already starting to answer key questions about other planetary systems. One key question is, do planets in other star systems fit the same terrestrial and jovian categories as the planets in our solar system? So far, the tentative answer seems to be “yes.”

We have not yet found a reason to doubt that most known extrasolar planets are similar in nature to the jovian planets of our solar system. Although in most cases the only evidence for this claim comes from planetary mass, the few cases for which we also have data on size, density, or composition lend strong support. Because these few cases are essentially a random sample of the full set of high-mass extrasolar planets, the fact that they all support a jovian nature makes it seem likely that most or all of these extrasolar planets are jovian.

The only major surprise among these high-mass extrasolar planets is that many of them orbit quite close to their stars or have highly elliptical orbits, while all the jovian planets of our solar system orbit far from the Sun in nearly circular orbits. In other words, like the planet orbiting 51 Pegasi (see Figure 13.4), many of the known extrasolar planets are “hot Jupiters” with Jupiter-like masses but with orbits so close to their stars that they have much higher temperatures. In the next section we’ll discuss how these planets came to have these surprising orbits, but first let’s look at how the extra heat affects them.

Assuming we are correct about the nature of the hot Jupiters, we can use models to predict their appearance and characteristics. We simply ask how Jupiter would be different if it were located very close to the Sun. The models show that, if Jupiter orbited just 0.05 AU from the Sun (1% of its actual distance), the additional solar heat would make it about 50% larger in radius and therefore much lower in density. This is qualitatively consistent with what we have found for the transiting planets for which we have size and density data, although in several cases these planets seem to be even more puffed up than the models can currently explain.

What would the hot Jupiter look like? It would probably have clouds much like the real Jupiter but of a different type. Recall that Jupiter has multiple cloud layers made from droplets or ice flakes of compounds such as ammonia, methane, and water (see Figure 11.7). The temperature on the hot Jupiter would be far too high for these gases to condense. However, other ingredients still may be able to condense at high altitudes, including some materials that we don’t usually associate with clouds. The models suggest that a hot Jupiter with a temperature above about 1,000 K would have clouds of “rock dust” containing common minerals.

The hot Jupiter would probably also have a striped appearance much like that of the real Jupiter. In fact, the stripes could be visible even on the night side, because the planet’s high temperatures would make it glow. The stripes should be present because the atmospheric circulation of a hot Jupiter should still be driven by the same basic principles that apply to terrestrial and jovian planets in our solar system [Sections 10.2, 11.1]. Because the hot Jupiter is so close to its star, intense starlight will warm one side of the planet. As long as the planet rotates relatively rapidly, the rotation and heat input should create patterns of planet-circling winds much like those on Jupiter. We expect all hot Jupiters to rotate fairly rapidly, because they orbit so close to their stars that strong tidal forces have almost certainly locked them into synchronous rotation. That is, they always show the same face to their stars, just as the Moon always shows the same face to Earth [Section 4.5], and their rotational periods equal their orbital periods of a few days. Figure 13.14
Composed primarily of hydrogen and helium
5 AU from the Sun
Orbit takes 12 Earth years
Cloud top temperatures = 130 K
Clouds of various hydrogen compounds
Radius = 1 Jupiter radius
Mass = 1 Jupiter mass
Average density = 1.33 g/cm³
Moons, rings, magnetosphere

Composed primarily of hydrogen and helium
As close as 0.03 AU to their stars
Orbit as short as 1.2 Earth days
Cloud top temperatures up to 1,300 K
Clouds of “rock dust”
Radius up to 1.3 Jupiter radii
Mass from 0.2 to 2 Jupiter masses
Average density as low as 0.2 g/cm³
Moons, rings, magnetospheres: unknown

**Figure 13.14** A summary of the expected similarities and differences between the real Jupiter and extrasolar “hot Jupiters” orbiting Sun-like stars.

summarizes the similarities and differences expected between the real Jupiter and “hot Jupiters.”

Although we have not yet (as of late 2007) detected any planets as small in mass as Earth, we have found a few planets with masses only a few times that of Earth. While we have no information about the radii or composition of these planets, their masses are much too low for them to be Jupiter-like. They could potentially be small versions of planets like Uranus or Neptune, or alternatively like large versions of Earth (making them what some people call “super-Earths”). Either way, water is probably a major ingredient of these planets.

The planet called Gliese 581c, detected in mid-2007, is particularly interesting. This planet orbits only about 0.07 AU from its star. However, because its star is much cooler and dimmer than our Sun, this orbit places the planet within the habitable zone—the zone of distances from a star in which temperatures should allow for the existence of liquid water on a planet’s surface [Section 24.3]. Thus, if Gliese 581c has water on its surface, it could well prove to be the first world besides Earth known to have surface oceans of liquid water.

**13.3 The Formation of Other Solar Systems**

The discovery of extrasolar planets presents us with an opportunity to test our theory of solar system formation. Can our existing theory explain other planetary systems, or will we have to go back to the drawing board?

As we discussed in Chapter 8, the nebular theory holds that our solar system’s planets formed as a natural consequence of processes that accompanied the formation of our Sun. If the theory is correct, then the same processes should accompany the births of other stars, so the nebular theory clearly predicts the existence of other planetary systems. In that sense, the recent discoveries of extrasolar planets mean the theory has passed a major test, because its most basic prediction has been verified. Some details of the theory also seem supported. For example, the nebular theory says that planet formation begins with condensation of solid particles of rock and ice (see Figure 8.13), which then accrete to larger sizes. We therefore expect that planets should form more easily in a nebula with a higher proportion of rock and ice, and in fact more planets have been found around stars richer in the elements that make these ingredients.

Nevertheless, extrasolar planets have already presented at least one significant challenge to our theory. According to the nebular theory, jovian planets form as gravity pulls in gas around large, icy planetesimals that accrete in a spinning disk of material around a young star. The theory therefore predicts that jovian planets should form only in the cold outer regions of star systems (because it must be cold for ice to condense), and that these planets should be born with nearly circular orbits (matching the orderly, circular motion of the spinning disk). Massive extrasolar planets...
with close-in or highly elliptical orbits present a direct challenge to these ideas.

Can we explain the surprising orbits of many extrasolar planets?

The nature of science demands that we question the validity of a theory whenever it is challenged by any observation or experiment [Section 3.4]. If the theory cannot explain the new observations, then we must revise or discard it. The surprising orbits of many known extrasolar planets have indeed caused scientists to reexamine the nebular theory of solar system formation.

Questioning began almost immediately upon the discovery of the first extrasolar planets. The close-in orbits of these massive planets made scientists wonder whether something might be fundamentally wrong with the nebular theory. For example, is it possible for jovian planets to form very close to a star? Astronomers addressed this question by studying many possible models of planet formation and reexamining the entire basis of the nebular theory. Several years of such reexamination did not turn up any good reasons to discard the basic theory. While it’s still possible that a major flaw has gone undetected, it seems more likely that the basic outline of the nebular theory is correct. Scientists therefore suspect that extrasolar jovian planets were indeed born with circular orbits far from their stars, and that those that now have close-in or eccentric orbits underwent some sort of “planetary migration” or suffered gravitational interactions with other massive objects.

Planetary Migration. If the hot Jupiters formed in the outer regions of their star systems and then migrated inward, how did these planetary migrations occur? You might think that drag within the solar nebula could cause planets to migrate, much as atmospheric drag can cause satellites in low-Earth orbit to lose orbital energy and eventually plunge into the atmosphere; however, calculations show this drag effect to be negligible. A more likely scenario is that waves propagating through a gaseous disk lead to migration (Figure 13.15). The gravity of a planet moving through a disk can create waves that propagate through the disk, causing material to bunch up as the waves pass by. This “bunched up” matter (in the wave peaks) then exerts a gravitational pull back on the planet that reduces its orbital energy, causing the planet to migrate inward toward its star.

Computer models confirm that waves in a nebula can cause young planets to spiral slowly toward their star. In our own solar system, this migration is not thought to have played a significant role because the solar wind cleared out the gas before it could have much effect. But planets may form earlier in some other solar systems, allowing time for jovian planets to migrate substantially inward. In a few cases, the planets may form so early that they end up spiraling inward.

Figure 13.15 This figure shows a simulation of waves created by a planet embedded in a dusty disk of material surrounding its star.

Encounters and Resonances. Migration may explain the close-in orbits, but why do so many extrasolar planets have highly eccentric orbits? One hypothesis links both migration and eccentric orbits to close gravitational encounters [Section 4.5] between young jovian planets forming in the outer regions of a disk. A close gravitational encounter between two massive planets can send one planet out of the star system entirely while the other is flung inward into a highly elliptical orbit. Alternatively, a jovian planet could migrate inward as a result of multiple close encounters with much smaller planetesimals. Astronomers suspect that this type of migration affected the jovian planets in our own solar system. Recall that the Oort cloud is thought to consist of comets that were ejected outward by gravitational encounters with the jovian planets [Section 12.2]. In that case, the law of conservation of energy demands that the jovian planets must have migrated inward, losing the same amount of orbital energy that the comets gained.

Gravitational interactions can also affect orbits through resonances. Recall that Jupiter’s moons Io, Europa, and Ganymede share orbital resonances that cause their orbits to be more elliptical than they would be otherwise (see Figure 11.20b). Models show that similar resonances between massive jovian planets could make their orbits more eccentric, explaining why some extrasolar planets that orbit at Jupiter-like distances have surprisingly high eccentricities. Other kinds of resonances could lead to planetary migration or ejection of a planet from its system altogether. Alternatively, planetary migration might force two planets
into a resonance that they did not have originally. The fact that we’ve already discovered orbital resonances in several multiple-planet systems (see Figure 13.12) lends support to the idea that resonances play an important role in many planetary systems.

Do we need to modify our theory of solar system formation?

We began this section by asking whether the nebular theory of solar system formation can still hold up in light of our discoveries of planets around other stars. As we’ve seen, it probably can—provided that we allow for planets undergoing orbital changes after their births.

The bottom line is that discoveries of extrasolar planets have shown us that the nebular theory was incomplete. It explained the formation of planets and the simple layout of a solar system such as ours. However, it needs new features—such as planetary migration and gravitational encounters or resonances—to explain the differing layouts of other solar systems. A much wider range of solar system arrangements now seems possible than we had guessed before the discovery of extrasolar planets.

Given the fact that we have not yet found any other planetary system with a layout like our own, it’s natural to wonder whether our own solar system is the unusual one. Could it be that the neat layout of our solar system is the result of some sort of extreme cosmic luck, and that most or all other planetary systems undergo far greater changes after their planets are born? First impressions from the current data might seem to support this idea, but a more careful look shows that we cannot yet draw such a conclusion.

Among the thousands of Sun-like stars that astronomers have so far examined in search of extrasolar planets, only about 1 in 10 show evidence of planets around them. While this could mean that planetary systems are relatively rare, a more likely hypothesis is that planets are present but more difficult to detect in the other 9 in 10 systems. Remember that with current technology it is easiest to find massive planets in close-in orbits. Many of the stars without detected planets could still have jovian planets orbiting at large distances—just as in our own solar system—in which case solar systems like ours might be quite common. In essence, we have been hunting for planets with “elephant traps”—and we have been catching elephants. The more common systems with smaller planets may simply be beyond the grasp of our current traps. As time goes on and technology improves, we may begin to find more systems like our own.

If solar systems like our own turn out to be common, then the real challenge will be to explain precisely how and under what conditions a system ends up like the “unusual” ones discovered to date. This challenge has led planetary scientists to look more closely at the question of exactly how the planets in our own solar system would have interacted with one another when the solar system was young. These studies are only in preliminary stages at present, but they are already causing some scientists to wonder whether migration and gravitational interactions were more important in our solar system than previously thought. It may be that all planetary systems experience these processes to some extent, but that in most cases they stop before jovian planets end up with close-in or eccentric orbits.

The question of which types of planetary systems are unusual has profound implications for the way we view our place in the universe. If solar systems like ours are common, then it seems reasonable to imagine that Earth-like planets—and perhaps life and civilizations—might also be common. But if our solar system is a rarity or even unique, then Earth might be the lone inhabited planet in our galaxy or even the universe. We’ll discuss this important issue in more depth in Chapter 24; for now, we’ll turn our attention to plans for gathering the data needed to learn whether planets like ours are rare or common.

13.4 Finding More New Worlds

We have entered a new era in planetary science, one in which our understanding of planetary processes can be based on far more planets than just those of our own solar system. Although our current knowledge of extrasolar planets and their planetary systems is still quite limited, ingenious new observing techniques, dedicated observatories, and ambitious space telescopes should broaden our understanding dramatically in the coming years and decades.

In this section we’ll focus on the more dramatic improvements that space missions and new ground-based methods will provide. These techniques will not only permit the discovery of Earth-like planets (if they exist), but will also give us the ability to map and study planets around other stars in far greater detail than we can now.

How will we search for Earth-like planets?

There’s probably no bigger question in planetary science than whether Earth-like planets exist around other stars. NASA’s Spitzer Space Telescope has already seen the infrared glow from dust created by the collisions of rocky planetesimals in other accreting solar systems, and the nebular theory makes it seem inevitable that terrestrial planets should form around other stars. We therefore have good reason to think that Earth-like planets should be out there; but are they? When you consider that the smallest known extrasolar planets are still several times as massive as Earth, you might be tempted to think that discovery of Earth-size planets is still decades away. However, missions currently in preparation should be capable of such discoveries. If all goes well, within just 5 to 10 years we will have surveyed tens of thousands of star systems and learned the definitive answer to the question of whether Earth-size planets are rare or common. Let’s examine a few of the future missions that should help us answer age-old questions about our place in the universe.
Transit Missions: Kepler and COROT  As we discussed in Section 13.1, we should in principle be able to detect planets the size of Earth or even smaller by searching for transits—the slight dips in stellar brightness that occur when a planet passes in front of its star. The search for transits by Earth-size planets poses three major technological challenges. First, the dips in brightness caused by Earth-size planets will be very small and will therefore require extraordinarily precise measurement. For example, viewed from afar, a transit of Earth across the Sun would dim the Sun’s light by only about 0.008%—not quite one part in 10,000. Second, because stars can vary in brightness for reasons besides transits, we can be confident that we’ve detected a planet only if the characteristic dimming of a transit repeats with a regular period. For planets with sizes and orbital periods like those of the terrestrial worlds in our solar system, this means searching for transits that last no more than a few hours and recur anywhere from every couple of months to every couple of years. Clearly, we are likely to miss the transits unless we continuously monitor stars both day and night year-round. Third, only a tiny fraction of planetary systems will by chance have an orientation that would allow us to see a transit by an Earth-size planet in an Earth-like orbit. We therefore must monitor thousands of stars to have a reasonable expectation of just a few successes.

All three challenges should be met by a NASA mission called Kepler, tentatively scheduled for launch in early 2009 (Figure 13.16). Kepler, which will orbit around the Sun rather than Earth (so that Earth will not get in the way of its observations), is a telescope that will stare continuously in the direction of the constellation Cygnus for 4 years. Its field of view is wide enough to monitor about 100,000 stars, measuring their brightnesses about every 15 minutes. Its cameras are sensitive enough to detect transits of Earth-size planets around Sun-like stars and transits of planets as small as Mercury around somewhat dimmer stars. If our solar system is typical with its two Earth-size planets (Venus and Earth), calculations show that Kepler should detect about 50 such planets during its 4 years of observations. It should be even more successful at detecting larger planets that block more of their star’s light and should therefore greatly add to our current collection of known extrasolar planets.

Meanwhile, the European Space Agency’s COROT mission is already searching for transits and found its first planet just a few months after its launch in late 2006. Although COROT was not expected to be sensitive enough to detect planets as small as Earth, its early performance is better than expected, giving scientists hope that it may indeed be able to observe transits of a few Earth-size worlds.

**THINK ABOUT IT**

Find the current status of the Kepler and COROT missions. Is Kepler still on track for launch in 2009, or already launched? What is the smallest planet discovered by either mission so far? Do you think the search for Earth-size planets is important?

Astrometric Missions: GAIA and SIM  Recall from Section 13.1 that the astrometric technique can in principle be used to find the slight side-to-side motions of stars in our sky caused by the gravitational tugs of orbiting planets. To date, this technique has not yielded many planetary discoveries, primarily because current telescopes cannot measure stellar positions with sufficient accuracy. For example, if you look back at Figure 13.2, you’ll see that from 30 light-years away, we’d need position measurements accurate to less than a milliarcsecond (a thousandth of an arcsecond) to notice the effects of Jupiter or Saturn on the Sun’s position.

The only way to achieve higher astrometric precision is through interferometry [Section 6.4], in which two or more telescopes work together to obtain the angular resolution of a much larger telescope. Astronomers are making rapid progress in adapting interferometry to ground-based infrared and visible-light telescopes. For example, the twin Keck telescopes on Mauna Kea may soon be capable of detecting at least some planets by using the astrometric technique.

Interferometry should be even more successful from space. The European Space Agency’s GAIA mission, slated for launch in 2011, has the ambitious goal of performing astrometric observations of a billion stars in our galaxy with an accuracy of 10 microarcseconds. (A microarcsecond is one-millionth of an arcsecond.) GAIA will also be capable of planetary transit detections. Scientists are optimistic that it will discover thousands of new worlds.

On the American side, NASA has spent many years developing plans for the Space Interferometry Mission (SIM). Although cuts to NASA’s budget have placed this mission on hold, scientists still hope that either SIM or a similar mission will enable us to conduct astrometric surveys in the future.
A mission can be launched within the next decade or two. According to the existing plans, SIM would be capable of measuring stellar positions to a precision of just 1 microarcsecond—10 times better than GAIA’s precision and good enough to detect stellar motion caused by Earth-size planets around the nearest few dozen stars and motion due to Jupiter-size planets orbiting stars as far as 3,000 light-years away. SIM would also serve as a test bed for a new technology, called nulling interferometry, designed to cancel (or “null”) the light from a star so that we can more easily see its orbiting planets.

**Direct Detection: TPF and Darwin**  Although Kepler and other missions described above should answer the question of whether Earth-size planets are common, they will still fall short of answering the more profound question of whether any of these planets are Earth-like. To answer this question, we need images and spectra of distant terrestrial worlds, so that we can learn whether they are geologically dead like Mercury and the Moon, frozen like Mars or overheated like Venus, or “just right” like Earth.

NASA and the European Space Agency have begun planning missions that could obtain the necessary images and spectra. Current concepts for NASA’s Terrestrial Planet Finder (TPF) and the European Darwin mission both envision multiple space telescopes flying in formation as interferometers (Figure 13.17); an alternate concept has also recently been proposed, in which a dark screen would fly a few thousand kilometers from a single telescope, so that the screen could block starlight without blocking the light of orbiting planets. However, the same budget cuts that have halted work on SIM have also placed TPF on hold, and the European budget situation is only marginally better for Darwin. Nevertheless, if we take a long-term view, it seems reasonable to hope that within our lifetimes we will see the first crude images of Earth-size planets around other stars, and spectra of these worlds will allow us to search for signs of life-sustaining atmospheres and possibly of life itself.

**THINK ABOUT IT**

How do you think the discovery of other Earth-like planets would change our view of our place in the universe? Defend your opinions.

**THE BIG PICTURE**

Putting Chapter 13 into Perspective

With what we have learned in this chapter and the previous chapter, we now have a complete “big picture” view of how the terrestrial worlds started out so similar yet ended up so different. As you continue your studies, keep in mind the following important ideas:

- With the discoveries of more than 250 extrasolar planets already in hand, we now know that planetary systems are common in the universe, although we do not yet know whether most are similar to or different from our own.
- The discovery of other planetary systems has inaugurated a new era in planetary science, one in which we have far more individual worlds to study and in which we can put our theory of solar system formation to the test.
- Because nearly all detections to date have been made with indirect techniques, we do not yet know much about the planets we have discovered. However, mass estimates combined with limited information about
size and composition suggest that we have so far discovered planets similar in nature to the jovian planets of our solar system.

- It is too soon to know if Earth-like planets are rare or common, but new technologies should help us answer this fundamental question within most of our lifetimes.

SUMMARY OF KEY CONCEPTS

13.1 Detecting Extrasolar Planets

- Why is it so difficult to detect planets around other stars? The great distances to stars and the fact that typical stars are a billion times brighter than the light reflected from any of their planets make it very difficult to detect extrasolar planets.

- How do we detect planets around other stars? Nearly all known extrasolar planets have been discovered indirectly. We can look for a planet's gravitational effect on its star through the astrometric technique, which looks for small shifts in stellar position, or the Doppler technique, which looks for the back-and-forth motion of stars revealed by Doppler shifts. We can also search for transits and eclipses in which a system becomes slightly dimmer as a planet passes in front of or behind its star. The Doppler technique has yielded the vast majority of extrasolar planet discoveries to date.

13.2 The Nature of Extrasolar Planets

- What have we learned about extrasolar planets? The known extrasolar planets are all much more massive than Earth. Many of them orbit surprisingly close to their stars and have large orbital eccentricities. We have limited information about sizes and compositions, but these data are consistent with the idea that the planets are jovian in nature.

How do extrasolar planets compare with planets in our solar system? The known planets are probably jovian in nature. The planets that orbit close to their stars are called “hot Jupiters” because they must have very high temperatures that puff them up in size and give them a lower density than Jupiter.

13.3 The Formation of Other Solar Systems

- Can we explain the surprising orbits of many extrasolar planets? Jovian planets with close-in and eccentric orbits probably were born on orbits similar to those of the jovian planets in our solar system. Several different effects could later have changed their orbits: planetary migration induced by waves in the gaseous disk from which they formed, gravitational encounters with other objects, or resonances with other massive planets.

- Do we need to modify our theory of solar system formation? Our basic theory of solar system formation seems to be sound, but we have had to modify it to allow for orbital change of the type thought to have occurred with the “hot Jupiters” or planets on very eccentric orbits.

13.4 Finding More New Worlds

- How will we search for Earth-like planets? The first systematic attempt will be made by searching for transits with the Kepler mission. Later missions may use interferometry or other techniques to detect such planets directly.
Review Questions

Short-Answer Questions Based on the Reading

1. Why are extrasolar planets hard to detect directly?
2. What are the three major methods used to detect extrasolar planets indirectly?
3. Explain why a planet can cause its star to move slightly in the sky.
4. How does the astrometric technique work? Why hasn’t it been very successful in discovering planets to date?
5. How does the Doppler technique work? Explain how it can tell us a planet’s orbital period, orbital distance, and orbital eccentricity.
6. Why does the Doppler technique generally allow us to determine only minimum planetary masses rather than actual planetary masses? Should we expect these minimum masses to be close to the actual masses? Explain.
7. How does the transit technique work? Could we use this method to find planets around all stars that have them? Why or why not?
8. Have any planets been detected directly? Explain.
9. Briefly summarize the planetary properties we can in principle measure with current techniques, and state which techniques allow us to measure each of these properties.
10. How do the orbits of known extrasolar planets differ from those of jovian planets in our solar system? Why are these orbits surprising?
11. What data suggest that many extrasolar planets are similar in nature to the jovian planets in our solar system?
12. What do we mean by a “hot Jupiter”? How should we expect a hot Jupiter to compare to the real planet Jupiter?
13. Many extrasolar jovian planets orbit surprisingly close to their stars. How might they have ended up in these orbits?
14. Many extrasolar jovian planets have high orbital eccentricities. How might they have ended up with such eccentric orbits?
15. Based on current data, does it seem likely that our solar system has a particularly unusual layout? Explain.
16. Briefly describe how the Kepler mission will search for evidence of Earth-size planets.
17. How would the SIM and GAIA missions aid our search for extrasolar planets?
18. What technologies offer the hope of determining whether Earth-like planets exist around other stars?

Test Your Understanding

Answers to Odd-Numbered Problems in Back of the Book

Does It Make Sense?

Decide whether the statement makes sense (or is clearly true) or does not make sense (or is clearly false). Explain clearly; not all these have definitive answers, so your explanation is more important than your chosen answer.

19. An extraterrestrial astronomer surveying our solar system with the Doppler technique could discover the existence of Jupiter within a few days of observation.
20. The fact that we have not yet discovered an Earth-mass planet tells us that such planets must be very rare.
21. Within the next few years, astronomers expect to confirm all the planet detections made with the Doppler technique by observing transits of these same planets.
22. Although “hot Jupiters” are unlikely places to find life, they could be orbited by moons that would have pleasant, Earth-like temperatures.
23. Before the discovery of planetary migration, scientists were unable to explain how Saturn could have gotten into its current orbit.
24. It’s the year 2011: Astronomers have successfully photographed an Earth-size planet, showing that it has oceans and continents.
25. It’s the year 2025: Astronomers have just announced that they have obtained a spectrum showing the presence of oxygen in the atmosphere of an Earth-size planet.
26. It’s the year 2040: Scientists announce that our first spacecraft to reach an extrasolar planet is now orbiting a planet around a star located near the center of the Milky Way Galaxy.
27. An extrasolar planet is discovered with an orbital period of only 3 days.
28. Later this year, scientists use the Doppler technique to identify a planet whose mass is equal to Earth’s mass.
29. Astronomers announce that all the Doppler technique discoveries of extrasolar planets made to date are actually more massive brown dwarfs, and we had thought they were less massive only because we didn’t realize that they have nearly face-on orbits.
30. The number of known extrasolar planets increases from around 250 in 2007 to more than 1,000 by the year 2015.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

31. What method has detected the most extrasolar planets so far? (a) the transit method (b) Hubble images (c) the Doppler technique
32. Most extrasolar planets discovered so far probably resemble (a) terrestrial planets. (b) jovian planets. (c) large icy worlds.
33. How many extrasolar planets have been detected? (a) between 10 and 100 (b) between 100 and 1,000 (c) more than 1,000
34. Which one of the following can the transit method tell us about a planet? (a) its mass (b) its size (c) the eccentricity of its orbit
35. Which method could detect a planet in an orbit that is face-on to the Earth? (a) Doppler technique (b) transits (c) astrometric technique
36. How is the planet orbiting 51 Pegasi different from Jupiter? (a) much closer to its star (b) much longer year (c) much more massive
37. Most known extrasolar planets are more massive than Jupiter because (a) we do not expect smaller planets to exist. (b) current detection methods are more sensitive to larger planets. (c) the Doppler technique usually overestimates planet masses.
38. Which detection method can be used on a backyard telescope with a CCD system? (a) Doppler technique (b) transits (c) astrometric technique
39. What’s the best explanation for the location of “hot Jupiters”? (a) They formed closer to their stars than Jupiter did. (b) They formed farther out like Jupiter but then migrated inward. (c) The strong gravity of their stars pulled them in close.
40. Earth-sized planets orbiting normal stars (a) have already been discovered. (b) should be discovered in the next few years by ground-based telescopes. (c) should be discovered by 2015 by a space telescope.

Process of Science
Examining How Science Works
41. Confirming Observations. After the first few discoveries of extrasolar planets through the Doppler technique, some astronomers hypothesized that the stars’ companions were brown dwarves in nearly face-on orbits, instead of planets with a random distribution of orbits. How did later observations refute this hypothesis? Discuss both later discoveries by the Doppler technique and observations with other techniques.
42. When Is a Theory Wrong? As discussed in this chapter, in its original form the nebular theory of solar system formation does not explain the orbits of many known extrasolar planets, but it can explain them with modifications such as allowing for planetary migration. Does this mean the theory was “wrong” or only “incomplete” before the modifications were made? Explain. Be sure to look back at the discussion in Chapter 3 of the nature of science and scientific theories.
43. Refuting the Theory. Consider the following three hypothetical observations: (1) the discovery of a lone planet that is small and dense like a terrestrial planet but has a Jupiter-like orbit; (2) the discovery of a planetary system in which three terrestrial planets orbit the star beyond the orbital distance of two jovian planets; (3) the discovery that a majority of planetary systems have their jovian planets located nearer to their star than 1 AU and their terrestrial planets located beyond 5 AU. Each of these observations would challenge our current theory of solar system formation, but would any of them shake the very foundations of the theory? Explain clearly for each of the three hypothetical observations.
44. Unanswered Questions. As discussed in this chapter, we are only just beginning to learn about extrasolar planets. Briefly describe one important but unanswered question related to the study of planets around other stars. Then write 2–3 paragraphs in which you discuss how we might answer this question in the future. Be as specific as possible, focusing on the type of evidence necessary to answer the question and how the evidence could be gathered. What are the benefits of finding answers to this question?

Investigate Further
In-Depth Questions to Increase Your Understanding

Short-Answer/Essay Questions
45. Why So Soon? The detection of extrasolar planets came much sooner than astronomers expected. Was this a result of planets being different than expected, or of technology improving faster? Explain.
46. Why Not Hubble? Of the more than 250 extrasolar planets discovered, only one possible planet has ever been imaged by the Hubble Space Telescope. What limits Hubble’s ability to image planets around other stars, and why was it possible in the case of Figure 13.9?
47. Explaining the Doppler Technique. Explain how the Doppler technique works in terms an elementary school child would understand. It may help to use an analogy to explain the difficulty of direct detection and for the general phenomenon of the Doppler shift.
48. Comparing Methods. What are the advantages and disadvantages of the Doppler and transit techniques? What kinds of planets are easiest to detect in each case? Are there certain planets that each method cannot detect, even if the planets are very large? Explain. What advantages come if a planet can be detected by both methods?
49. No Hot Jupiters Here. How do we think “hot Jupiters” formed? Why didn’t one form in our solar system?
50. Resonances. How may resonances be important in affecting extrasolar planet orbits? How are these effects similar to the effects of resonances in our solar system, and how are they different?
51. Low-Density Planets. Only one planet in our solar system has a density less than 1 g/cm³, but many extrasolar planets do. Explain why in a few sentences. (Hint: Consider the densities of the jovian planets in our solar system, given in Figure 11.1.)
52. A Year on HD209458b. Imagine you’re visiting the planet that orbits the star HD209458, hovering in the upper atmosphere in a suitable spacecraft. What would it be like? What would you see, and how would it look different compared to floating in Jupiter’s atmosphere? Consider factors like local conditions, clouds, how the Sun would appear, and orbital motion.
53. Lots of Big Planets. Many of the extrasolar planets discovered so far are more massive than the most massive planet in our solar system. Does this mean our solar system is unusual? If so, how or why? If not, why not?
54. Detect an Extrasolar Planet for Yourself. Most colleges and many amateur astronomers have the equipment necessary to detect known extrasolar planets using the transit method. All that’s required is a telescope 10 or more inches in diameter, a CCD camera system, and a computer system for data analysis. The basic method is to take exposures of a few minutes duration over a period of several hours around the times of predicted transit, and to compare the brightness of the star being transited relative to other stars in the same CCD frame (Figure 13.7). For complete instructions, see Mastering Astronomy.

Quantitative Problems
Be sure to show all calculations clearly and state your final answers in complete sentences. (Answers to odd-numbered problems in back of the book.)
55. Lost in the Glare. How hard would it be for an alien astronomer to detect the light from planets in our solar system compared to light from the Sun itself? a. Calculate the fraction of the total emitted sunlight that is reflected by Earth. (Hint: Imagine a sphere around the Sun the size of the planet’s orbit (area = \(4\pi r^2\)). What fraction of that area does the disk of a planet (area = \(\pi r_{\text{planet}}^2\)) take up? Earth’s reflectivity is 29%.
b. Would detecting Jupiter be easier or harder than detecting Earth? Comment on whether you think Jupiter’s larger size or greater distance has a stronger effect on its detectability. You may neglect any difference in reflectivity between Earth and Jupiter.

56. **Transit of TrES-1.** The planet orbiting this star has been detected by both the transit and Doppler techniques, so we can calculate its density and get an idea of what kind of planet it is.
   a. Using the method of Mathematical Insight 13.3, calculate the radius of the transiting planet. The planetary transits block 2% of the star’s light. The star TrES-1 has a radius of about 85% of our Sun’s radius.
   b. The mass of the planet is approximately 0.75 times the mass of Jupiter, and Jupiter’s mass is about $1.9 \times 10^{27}$ kilograms. Calculate the average density of the planet. Give your answer in grams per cubic centimeter. Compare this density to the average densities of Saturn (0.7 g/cm$^3$) and Earth (5.5 g/cm$^3$). Is the planet terrestrial or jovian in nature? (Hint: To find the volume of the planet, use the formula for the volume of a sphere: $V = \frac{4}{3}\pi r^3$. Be careful with unit conversions.)

57. **Planet Around 51 Pegasi.** The star 51 Pegasi has about the same mass as our Sun. A planet discovered around it has an orbital period of 4.23 days. The mass of the planet is estimated to be 0.6 times the mass of Jupiter. Use Kepler’s third law to find the planet’s average distance (semimajor axis) from its star. (Hint: Because the mass of 51 Pegasi is about the same as the mass of our Sun, you can use Kepler’s third law in its original form, $p^2 = a^3$ [Section 3.3]. Be sure to convert the period into years before using this equation.)

58. **Identical Planets?** Imagine two planets orbiting a star with orbits edge-on to the Earth. The peak Doppler shift for each is 50 m/s, but one has a period of 3 days and the other has a period of 300 days. Calculate the two minimum masses and say which, if either, is larger. (Hint: See Mathematical Insight 13.2.)

59. **Finding Orbit Sizes.** The Doppler technique allows us to find a planet’s semimajor axis using just the orbital period and the star’s mass (Mathematical Insight 13.1).
   a. Imagine that a new planet is discovered around a 2-solar-mass star that has a period of 5 days. What is its semimajor axis?
   b. Another planet is discovered around a 0.5-solar-mass star with a period of 100 days. What is its semimajor axis?

60. **One Born Every Minute?** It’s possible to make a rough estimate of how often planetary systems form by making some basic assumptions. For example, if you assume that the stars we see have been born at random times over the last 10 billion years, then the rate of star formation is simply the number of stars we see divided by 10 billion years. The fraction of planets with detected extrasolar planets is at least 5%, so this factor can be multiplied in to find the approximate rate of formation of planetary systems.
   a. Using these assumptions, how often does a planetary system form in our galaxy? (Our galaxy contains at least 100 billion stars.)
   b. How often does a planetary system form somewhere in the observable universe, which contains at least 100 billion galaxies?
   c. Write a few sentences describing your reaction to your results. Do you think the calculation is realistic? Are the rates larger or smaller than you expected?

61. **Habitable Planet Around 51 Pegasi?** The star 51 Pegasi is approximately as bright as our Sun and has a planet that orbits at a distance of only 0.052 AU.
   a. Suppose the planet reflects 15% of the incoming sunlight. Using Mathematical Insight 10.1, calculate its “no greenhouse” average temperature. How does this temperature compare to that of Earth?
   b. Repeat part (a), but assume that the planet is covered in bright clouds that reflect 80% of the incoming sunlight.
   c. Based on your answers to parts (a) and (b), do you think it is likely that the conditions on this planet are conducive to life? Explain.

**Discussion Questions**

62. **So What?** What is the significance of the discovery of extrasolar planets, if any? Justify your answer in the context of this book’s discussion of the history of astronomy.

63. **Is It Worth It?** The cost of the Kepler mission is several hundred million dollars. The cost of the Terrestrial Planet Finder mission would likely be several billion dollars. Are these expenses worth it, compared to the results expected? Defend your opinion.

64. **What If?** Consider the possible outcomes of the missions described in Section 13.4. What results would change our perspective on our solar system? On the possibility of life in the universe?
Interactive Tutorials

Tutorial Review of Key Concepts
Use the interactive Tutorial at www.masteringastronomy.com to review key concepts from this chapter.

Detecting Extrasolar Planets Tutorial
Lesson 1 Taking a Picture of a Planet
Lesson 2 Stars’ Wobbles and Properties of Planets
Lesson 3 Planetary Transits

Supplementary Tutorial Exercises
Use the interactive Tutorial Lessons to explore the following questions.

Detecting Extrasolar Planets Tutorial, Lesson 2
1. Using the tool provided, explain how weekly measurements allow us to determine the orbital period of the extrasolar planet.
2. Use the tool to vary the mass of the planet. How does its mass affect the Doppler shifts in its star’s light?
3. Use the tool to vary the orbital radius of the planet. How does the orbital radius affect the Doppler shifts in its star’s light?

Detecting Extrasolar Planets Tutorial, Lesson 3
1. Under what conditions can we view a planetary transit of another star?
2. How does the change in brightness during a transit depend on the planet’s properties?

Exploring the Sky and Solar System
Use the Voyager: SkyGazer CD-ROM accompanying your book to locate the brightest stars known to harbor planets. (These will be the stars in Appendix E.4 named with Greek letters preceding the constellation name.) Are they visible from where you live? At what time of the year and night? Print out a star chart and see if you can find the star in the sky. Bring along the information from the appendix to help you picture the planetary system in the sky.

Movies
Check out the following narrated and animated short documentary available on www.masteringastronomy.com for a helpful review of key ideas covered in this chapter.

Web Projects
1. New Planets. Find the latest information on extrasolar planet discoveries. Create a personal “planet journal,” complete with illustrations as needed, with a page for each of at least three recent discoveries of new planets. On each journal page, note the technique that was used to find the planet, give any information we have about the nature of the planet, and discuss how the planet does or does not fit in with our current understanding of planetary systems.
2. Direct Detections. In this chapter we saw only one example of a direct detection of a possible extrasolar planet. Search for new information on this and any other direct detections now known. Has the detection discussed in this chapter been confirmed (or disavowed) as a planet? Have we made any other direct detections, and if so, how? Summarize your findings with a short written report, including images of the directly detected planets.
3. Extrasolar Planet Mission. Visit the Website for one of the future space missions discussed in this chapter and learn more about the mission design, capabilities, and goals. Write a short report on your findings.
Comparing the terrestrial worlds shows that a planet's size and distance from the Sun are the primary factors that determine how it evolves through time [Chapters 9, 10].

Venus demonstrates the importance of distance from the Sun: If Earth were moved to the orbit of Venus, it would suffer a runaway greenhouse effect and become too hot for life.

Mars shows why size is important: A planet smaller than Earth loses interior heat faster, which can lead to a decline in geological activity and loss of atmospheric gas.

The smallest terrestrial worlds, Mercury and the Moon, became geologically dead long ago. They therefore retain ancient impact craters, which provide a record of how impacts must have affected Earth and other worlds.
2 Jovian planets are gas-rich and far more massive than Earth. They and their ice-rich moons have opened our eyes to the diversity of processes that shape worlds [Chapter 11].

The strong gravity of the jovian planets has shaped the asteroid and Kuiper belts, and flung comets into the distant Oort cloud, ultimately determining how frequently asteroids and comets strike Earth.

Our Moon led us to expect all small objects to be geologically dead . . .

. . . but Europa—along with Io, Titan and other moons—proved that tidal heating or icy composition can lead to geological activity, in some cases with subsurface oceans and perhaps even life.

3 Asteroids and comets may be small bodies in the solar system, but they have played major roles in the development of life on Earth [Chapter 12].

Asteroids or water-rich asteroids from the outer asteroid belt brought Earth the ingredients of its oceans and atmosphere.

Impacts of comets and asteroids have altered the course of life on Earth and may do so again.

4 The discovery of planets around other stars has shown that our solar system is not unique. Studies of other solar systems are teaching us new lessons about how planets form and about the likelihood of finding other Earth-like worlds [Chapter 13].

Current detection techniques are best at finding extrasolar planets similar in mass to Jupiter, but improving technology will soon enable us to detect planets as small as Earth.