21

The Birth of Stars and the Discovery of Planets outside the Solar System

Figure 21.1 Where Stars Are Born. We see a close-up of part of the Carina Nebula taken with the Hubble Space Telescope. This image reveals jets powered by newly forming stars embedded in a great cloud of gas and dust. Parts of the clouds are glowing from the energy of very young stars recently formed within them. (credit: modification of work by NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI))

Chapter Outline

Thinking Ahead

There are countless suns and countless earths all rotating round their suns in exactly the same way as the planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous. . . . The unnumbered worlds in the universe are all similar in form and rank and subject to the same forces and the same laws.
>—Giordano Bruno in *On the Infinite Universe and Worlds* (1584)

Bruno was tried for heresy by the Roman Inquisition and burned at the stake in 1600.

We’ve discussed stars as nuclear furnaces that convert light elements into heavier ones. A star’s nuclear evolution begins when hydrogen is fused into helium, but that can only occur when the core temperature exceeds 10 to 12 million K. Since stars form from cold interstellar material, we must understand how they collapse and eventually reach this “ignition temperature” to explain the birth of stars. Star formation is a continuous process, from the birth of our Galaxy right up to today. We estimate that every year in our Galaxy, on average, three solar masses of interstellar matter are converted into stars. This may sound like a small amount of mass for an object as large as a galaxy, but only three new stars (out of billions in the Galaxy) are formed each year.

Do planets orbit other stars or is ours the only planetary system? In the past few decades, new technology has enabled us to answer that question by revealing nearly 4300 exoplanets in over 3200 planetary systems. Even before planets were detected, astronomers had predicted that planetary systems were likely to be byproducts of the star-formation process. In this chapter, we look at how interstellar matter is transformed into stars and planets.

21.1 Star Formation

Learning Objectives

By the end of this section, you will be able to:

- Identify the sometimes-violent processes by which parts of a molecular cloud collapse to produce stars
- Recognize some of the structures seen in images of molecular clouds like the one in Orion
- Explain how the environment of a molecular cloud enables the formation of stars
- Describe how advancing waves of star formation cause a molecular cloud to evolve

As we begin our exploration of how stars are formed, let’s review some basics about stars discussed in earlier chapters:

- Stable (main-sequence) stars such as our Sun maintain equilibrium by producing energy through nuclear fusion in their cores. The ability to generate energy by fusion defines a star.
- Each second in the Sun, approximately 600 million tons of hydrogen undergo fusion into helium, with about 4 million tons turning into energy in the process. This rate of hydrogen use means that eventually the Sun (and all other stars) will run out of central fuel.
- Stars come with many different masses, ranging from 1/12 solar masses (M_{Sun}) to roughly 100–200 M_{Sun}. There are far more low-mass than high-mass stars.
- The most massive main-sequence stars (spectral type O) are also the most luminous and have the highest surface temperature. The lowest-mass stars on the main sequence (spectral type M or L) are the least luminous and the coolest.
- A galaxy of stars such as the Milky Way contains enormous amounts of gas and dust—enough to make billions of stars like the Sun.

If we want to find stars still in the process of formation, we must look in places that have plenty of the raw material from which stars are assembled. Since stars are made of gas, we focus our attention (and our telescopes) on the dense and cold clouds of gas and dust that dot the Milky Way (see Figure 21.1 and Figure 21.2).

Figure 21.2 Pillars of Dust and Dense Globules in M16. (a) This Hubble Space Telescope image of the central regions of M16 (also known as the Eagle Nebula) shows huge columns of cool gas, (including molecular hydrogen, H2) and dust. These columns are of higher density than the surrounding regions and have resisted evaporation by the ultraviolet radiation from a cluster of hot stars just beyond the upper-right corner of this image. The tallest pillar is about 1 light-year long, and the M16 region is about 7000 light-years away from us. (b) This close-up view of one of the pillars shows some very dense globules, many of which harbor embryonic stars. Astronomers coined the term *evaporating gas globules* (EGGs) for these structures, in part so that they could say we found EGGs inside the Eagle Nebula. It is possible that because these EGGs are exposed to the relentless action of the radiation from nearby hot stars, some may not yet have collected enough material to form a star. (credit a : modification of work by NASA, ESA, and the Hubble Heritage Team (STScI/AURA); credit b: modification of work by NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University))

Molecular Clouds: Stellar Nurseries

As we saw in Between the Stars: Gas and Dust in Space, the most massive reservoirs of interstellar matter—and some of the most massive objects in the Milky Way Galaxy—are the **giant molecular clouds**. These clouds have cold interiors with characteristic temperatures of only 10–20 K; most of their gas atoms are bound into molecules. These clouds turn out to be the birthplaces of most stars in our Galaxy.

The masses of molecular clouds range from a thousand times the mass of the Sun to about 3 million solar masses. Molecular clouds have a complex filamentary structure, similar to cirrus clouds in Earth’s atmosphere, but much less dense. The molecular cloud filaments can be up to 1000 light-years long. Within the clouds are cold, dense regions with typical masses of 50 to 500 times the mass of the Sun; we give these regions the highly technical name *clumps*. Within these clumps, there are even denser, smaller regions called cores. The cores are the embryos of stars. The conditions in these cores—low temperature and high density—are just what is required to make stars. Remember that the essence of the life story of any star is the ongoing competition between two forces: *gravity* and *pressure*. The force of gravity, pulling inward, tries to make a star collapse. Internal pressure produced by the motions of the gas atoms, pushing outward, tries to force the star to expand. When a star is first forming, low temperature (and hence, low pressure) and high density (hence, greater gravitational attraction) both work to give gravity the advantage. In order to form a star—that is, a dense, hot ball of matter capable of starting nuclear reactions deep within—we need a typical core of interstellar atoms and molecules to shrink in radius and increase in density by a factor of nearly 10^{20}. It is the force of gravity that produces this drastic collapse.

The Orion Molecular Cloud

Let’s discuss what happens in regions of star formation by considering a nearby site where stars are forming right now. One of the best-studied stellar nurseries is in the constellation of Orion, The Hunter, about 1500 light-years away (Figure 21.3). The pattern of the hunter is easy to recognize by the conspicuous "belt" of three stars that mark his waist. The Orion molecular cloud is much larger than the star pattern and is truly an impressive structure. In its long dimension, it stretches over a distance of about 100 light-years. The total quantity of molecular gas is about 200,000 times the mass of the Sun. Most of the cloud does not glow with visible light but betrays its presence by the radiation that the dusty gas gives off at infrared and radio wavelengths.

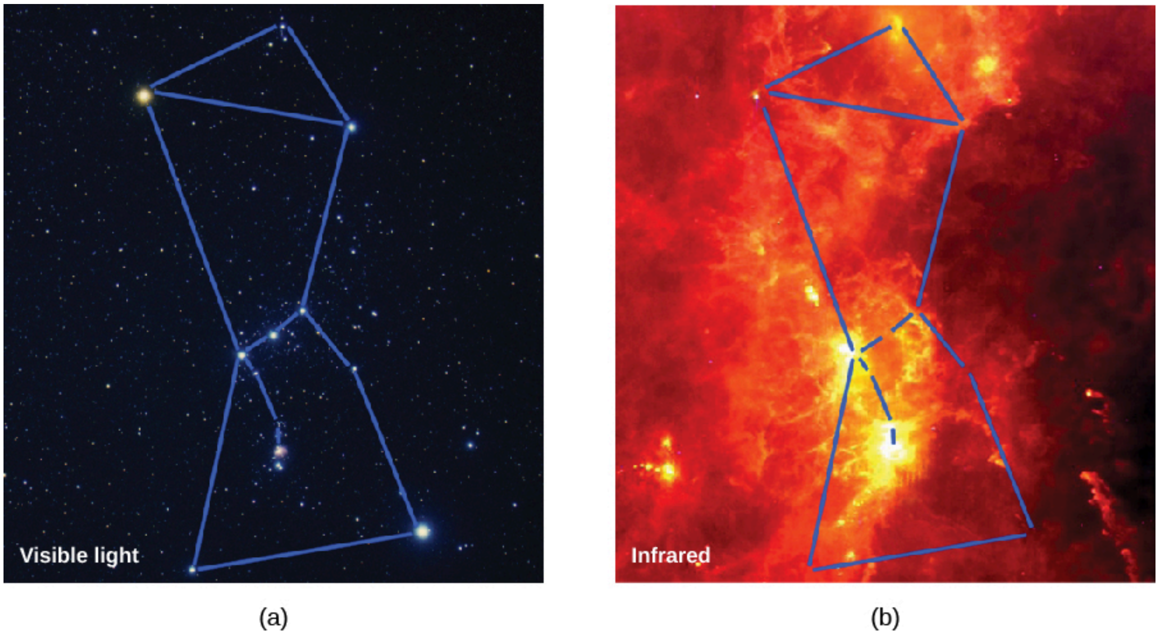


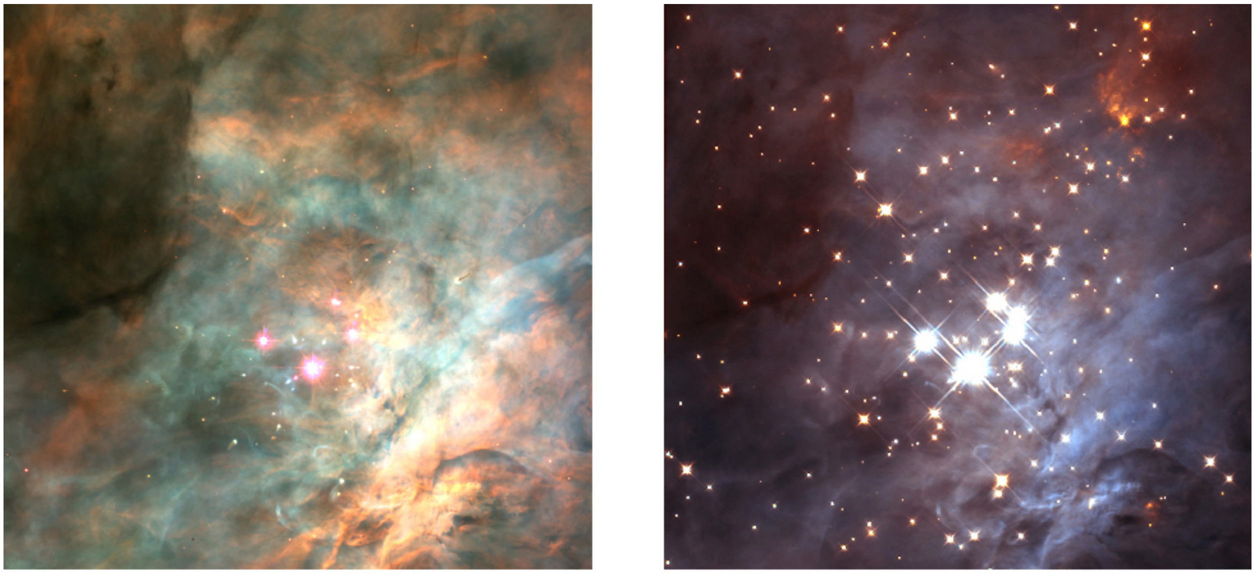
Figure 21.3 Orion in Visible and Infrared. (a) The Orion star group was named after the legendary hunter in Greek mythology. Three stars close together in a link mark Orion's belt. The ancients imagined a sword hanging from the belt; the object at the end of the blue line in this sword is the Orion Nebula. (b) This wide-angle, infrared view of the same area was taken with the Infrared Astronomical Satellite. Heated dust clouds dominate in this false-color image, and many of the stars that stood out on part (a) are now invisible. An exception is the cool, red-giant star Betelgeuse, which can be seen as a yellowish point at the left vertex of the blue triangle (at Orion's left armpit). The large, yellow ring to the right of Betelgeuse is the remnant of an exploded star. The infrared image lets us see how large and full of cooler material the Orion molecular cloud really is. On the visible-light image at left, you see only two colorful regions of interstellar matter—the two, bright yellow splotches at the left end of and below Orion's belt. The lower one is the Orion Nebula and the higher one is the region of the Horsehead Nebula. (credit: modification of work by NASA, visible light: Akira Fujii; infrared: Infrared Astronomical Satellite)

The stars in Orion's belt are typically about 5 million years old, whereas the stars near the middle of the "sword" hanging from Orion's belt are only 300,000 to 1 million years old. The region about halfway down the sword where star formation is still taking place is called the Orion Nebula. About 2200 young stars are found in this region, which is only slightly larger than a dozen light-years in diameter. The Orion Nebula also contains a tight cluster of stars called the Trapezium (Figure 21.5). The brightest Trapezium stars can be seen easily with a small telescope.

(a) (b)

Figure 21.4 Orion Nebula. (a) The Orion Nebula is shown in visible light. (b) With near-infrared radiation, we can see more detail within the dusty nebula since infrared can penetrate dust more easily than can visible light. (credit a: modification of work by Filip Lolić; credit b: modification of work by NASA/JPL-Caltech/T. Megeath (University of Toledo, Ohio))

Compare this with our own solar neighborhood, where the typical spacing between stars is about 3 light-years. Only a small number of stars in the Orion cluster can be seen with visible light, but infrared images—which penetrate the dust better—detect the more than 2000 stars that are part of the group (Figure 21.5).



(a) (b)

Figure 21.5 Central Region of the Orion Nebula. The Orion Nebula harbors some of the youngest stars in the solar neighborhood. At the heart of the nebula is the Trapezium cluster, which includes four very bright stars that provide much of the energy that causes the nebula to glow so brightly. In these images, we see a section of the nebula in (a) visible light and (b) infrared. The four bright stars in the center of the visible-light image are the Trapezium stars. Notice that most of the stars seen in the infrared are completely hidden by dust in the visible-light image. (credit a: modification of work by NASA, C.R. O’Dell and S.K. Wong (Rice University); credit b: modification of work by NASA; K.L. Luhman (Harvard-Smithsonian Center for Astrophysics); and G. Schneider, E. Young, G. Rieke, A. Cotera, H. Chen, M. Rieke, R. Thompson (Steward Observatory, University of Arizona))

Studies of Orion and other star-forming regions show that star formation is not a very efficient process. In the region of the Orion Nebula, about 1% of the material in the cloud has been turned into stars. That is why we still see a substantial amount of gas and dust near the Trapezium stars. The leftover material is eventually heated, either by the radiation and winds from the hot stars that form or by explosions of the most massive stars. (We will see in later chapters that the most massive stars go through their lives very quickly and end by exploding.)

LINK TO LEARNING

Take a journey through the Orion Nebula (https://openstax.org/l/30OriNebula) to view a nice narrated video tour of this region.

Whether gently or explosively, the material in the neighborhood of the new stars is blown away into interstellar space. Older groups or clusters of stars can now be easily observed in visible light because they are no longer shrouded in dust and gas (Figure 21.6).

Figure 21.6 Westerlund 2. This young cluster of stars known as Westerlund 2 formed within the Carina star-forming region about 2 million years ago. Stellar winds and pressure produced by the radiation from the hot stars within the cluster are blowing and sculpting the surrounding gas and dust. The nebula still contains many globules of dust. Stars are continuing to form within the denser globules and pillars of the nebula. This Hubble Space Telescope image includes near-infrared exposures of the star cluster and visible-light observations of the surrounding nebula. Colors in the nebula are dominated by the red glow of hydrogen gas, and blue-green emissions from glowing oxygen. (credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), A. Nota (ESA/STScI), and the Westerlund 2 Science Team)

Although we do not know what initially caused stars to begin forming in Orion, there is good evidence that the first generation of stars triggered the formation of additional stars, which in turn led to the formation of still more stars (Figure 21.7).

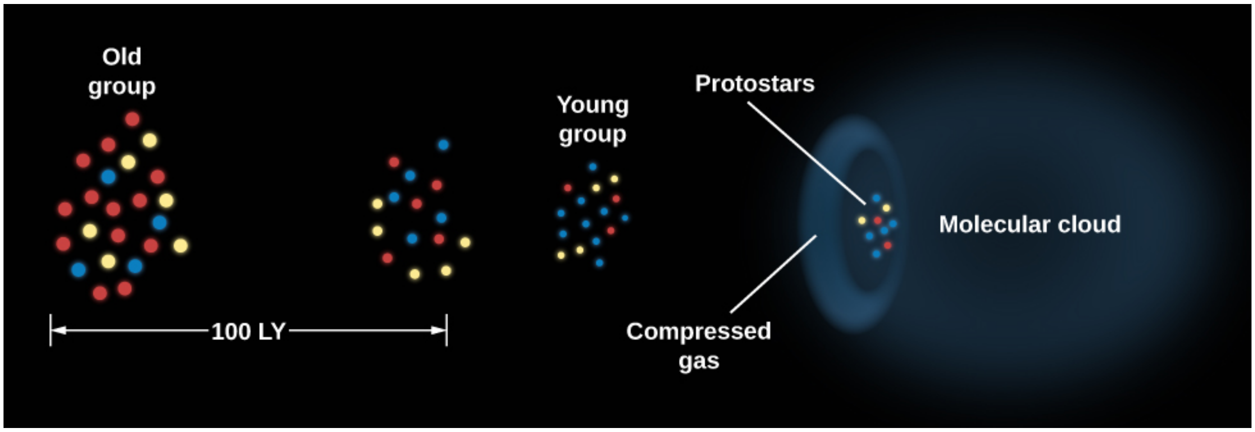


Figure 21.7 Propagating Star Formation. Star formation can move progressively through a molecular cloud. The oldest group of stars lies to the left of the diagram and has expanded because of the motions of individual stars. Eventually, the stars in the group will disperse and no longer be recognizable as a cluster. The youngest group of stars lies to the right, next to the molecular cloud. This group of stars is only 1 to 2 million years old. The pressure of the hot, ionized gas surrounding these stars compresses the material in the nearby edge of the molecular cloud and initiates the gravitational collapse that will lead to the formation of more stars.

The basic idea of triggered star formation is this: when a massive star is formed, it emits a large amount of ultraviolet radiation and ejects high-speed gas in the form of a stellar wind. This injection of energy heats the gas around the stars and causes it to expand. When massive stars exhaust their supply of fuel, they explode, and the energy of the explosion also heats the gas. The hot gases pile into the surrounding cold molecular cloud, compressing the material in it and increasing its density. If this increase in density is large enough, gravity will overcome pressure, and stars will begin to form in the compressed gas. Such a chain reaction—where the brightest and hottest stars of one area become the cause of star formation “next door”—seems to have occurred not only in Orion but also in many other molecular clouds.

There are many molecular clouds that form only (or mainly) low-mass stars. Because low-mass stars do not have strong winds and do not die by exploding, triggered star formation cannot occur in these clouds. There are also stars that form in relative isolation in small cores. Therefore, not all star formation is originally triggered by the death of massive stars. However, there are likely to be other possible triggers, such as spiral density waves and other processes we do not yet understand.

The Birth of a Star

Although regions such as Orion give us clues about how star formation begins, the subsequent stages are still shrouded in mystery (and a lot of dust). There is an enormous difference between the density of a molecular cloud core and the density of the youngest stars that can be detected. Direct observations of this collapse to higher density are nearly impossible for two reasons. First, the dust-shrouded interiors of molecular clouds where stellar births take place cannot be observed with visible light. Second, the timescale for the initial collapse—thousands of years—is very short, astronomically speaking. Since each star spends such a tiny fraction of its life in this stage, relatively few stars are going through the collapse process at any given time. Nevertheless, through a combination of theoretical calculations and the limited observations available, astronomers have pieced together a picture of what the earliest stages of stellar evolution are likely to be.

The first step in the process of creating stars is the formation of dense cores within a clump of gas and dust (Figure 21.8(a)). It is generally thought that all the material for the star comes from the core, the larger structure surrounding the forming star. Eventually, the gravitational force of the infalling gas becomes strong enough to overwhelm the pressure exerted by the cold material that forms the dense cores. The material then undergoes a rapid collapse, and the density of the core increases greatly as a result. During the time a dense core is contracting to become a true star, but before the fusion of protons to produce helium begins, we call the object a **protostar**.

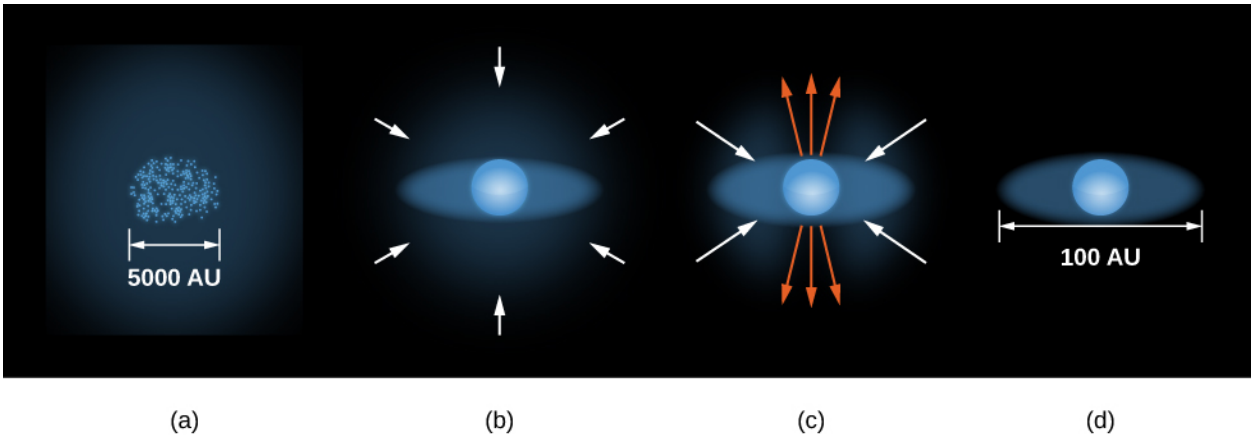


Figure 21.8 Formation of a Star. (a) Dense cores form within a molecular cloud. (b) A protostar with a surrounding disk of material forms at the center of a dense core, accumulating additional material from the molecular cloud through gravitational attraction. (c) A stellar wind breaks out but is confined by the disk to flow out along the two poles of the star. (d) Eventually, this wind sweeps away the cloud material and halts the accumulation of additional material, and a newly formed star, surrounded by a disk, becomes observable. These sketches are not drawn to the same scale. The diameter of a typical envelope that is supplying gas to the newly forming star is about 5000 AU. The typical diameter of the disk is about 100 AU or slightly larger than the diameter of the orbit of Pluto.

The natural turbulence inside a clump tends to give any portion of it some initial spinning motion (even if it is very slow). As a result, each collapsing core is expected to spin. According to the law of conservation of angular momentum (discussed in the chapter on Orbits and Gravity), a rotating body spins more rapidly as it decreases in size. In other words, if the object can turn its material around a smaller circle, it can move that material more quickly—like a figure skater spinning more rapidly as she brings her arms in tight to her body. This is exactly what happens when a core contracts to form a protostar: as it shrinks, its rate of spin increases.

But all directions on a spinning sphere are not created equal. As the protostar rotates, it is much easier for material to fall right onto the poles (which spin most slowly) than onto the equator (where material moves around most rapidly). Therefore, gas and dust falling in toward the protostar’s equator are “held back” by the rotation and form a whirling extended disk around the equator (part b in Figure 21.8). You may have observed this same “equator effect” on the amusement park ride in which you stand with your back to a cylinder that is spun faster and faster. As you spin really fast, you are pushed against the wall so strongly that you cannot possibly fall toward the center of the cylinder. Gas can, however, fall onto the protostar easily from directions away from the star’s equator.

The protostar and disk at this stage are embedded in an envelope of dust and gas from which material is still falling onto the protostar. This dusty envelope blocks visible light, but infrared radiation can get through. As a result, in this phase of its evolution, the protostar itself is emitting infrared radiation and so is observable only in the infrared region of the spectrum. Once almost all of the available material has been accreted and the central protostar has reached nearly its final mass, it is given a special name: it is called a *T Tauri star*, named after one of the best studied and brightest members of this class of stars, which was discovered in the constellation of Taurus. (Astronomers have a tendency to name types of stars after the first example they discover or come to understand. It’s not an elegant system, but it works.) Only stars with masses less than or similar to the mass of the Sun become T Tauri stars. Massive stars do not go through this stage, although they do appear to follow the formation scenario illustrated in Figure 21.8.

Winds and Jets

Recent observations suggest that T Tauri stars may actually be stars in a middle stage between protostars and hydrogen-fusing stars such as the Sun. High-resolution infrared images have revealed jets of material as well as *stellar winds* coming from some T Tauri stars, proof of interaction with their environment. A **stellar wind** consists mainly of protons (hydrogen nuclei) and electrons streaming away from the star at speeds of a few hundred kilometers per second (several hundred thousand miles per hour). When the wind first starts up, the disk of material around the star’s equator blocks the wind in its direction. Where the wind particles *can* escape most effectively is in the direction of the star’s poles.

Astronomers have actually seen evidence of these beams of particles shooting out in opposite directions from the polar regions of newly formed stars. In many cases, these beams point back to the location of a protostar that is still so completely shrouded in dust that we cannot yet see it (Figure 21.9).

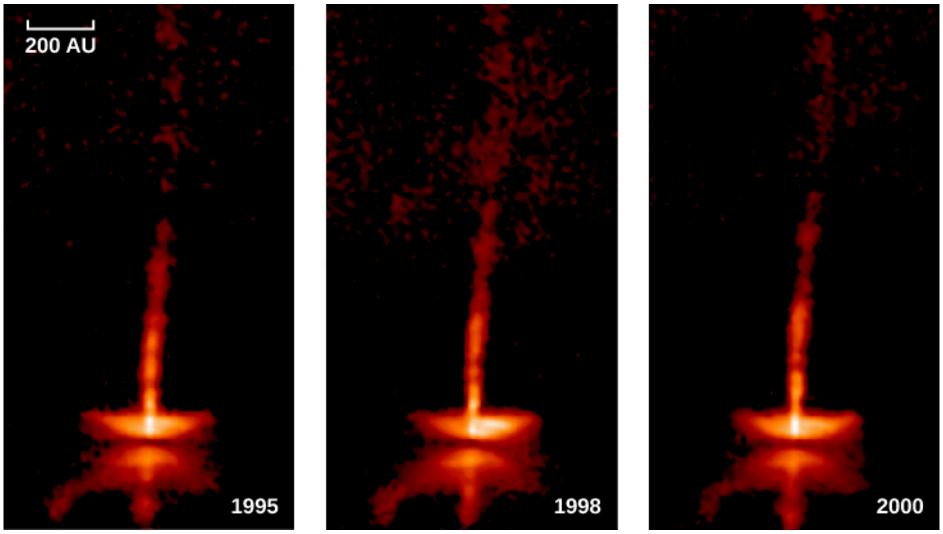


Figure 21.9 Gas Jets Flowing away from a Protostar. Here we see the neighborhood of a protostar, known to us as HH 34 because it is a Herbig-Haro object. The star is about 450 light-years away and only about 1 million years old. Light from the star itself is blocked by a disk, which is larger than 60 billion kilometers in diameter and is seen almost edge-on. Jets are seen emerging perpendicular to the disk. The material in these jets is flowing outward at speeds up to 580,000 kilometers per hour. The series of three images shows changes during a period of 5 years. Every few months, a compact clump of gas is ejected, and its motion outward can be followed. The changes in the brightness of the disk may be due to motions of clouds within the disk that alternately block some of the light and then let it through. This image corresponds to the stage in the life of a protostar shown in part (c) of Figure 21.8. (credit: modification of work by Hubble Space Telescope, NASA, ESA)

On occasion, the jets of high-speed particles streaming away from the protostar collide with a somewhat-denser lump of gas nearby, excite its atoms, and cause them to emit light. These glowing regions, each of which is known as a **Herbig-Haro (HH) object** after the two astronomers who first identified them, allow us to trace the progress of the jet to a distance of a light-year or more from the star that produced it. Figure 21.10 shows two spectacular images of HH objects.

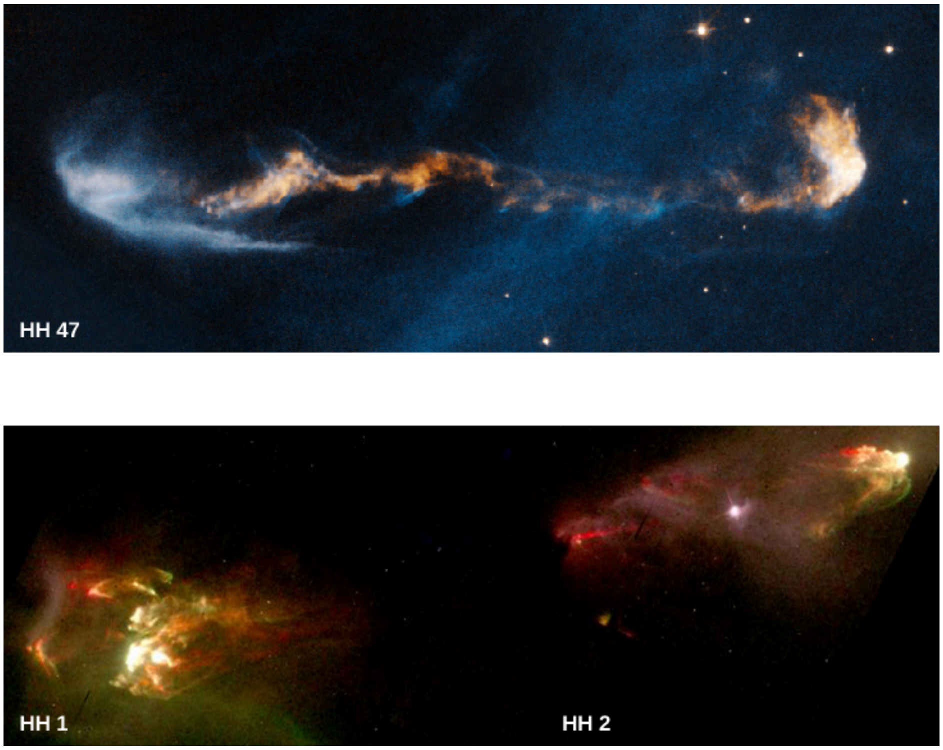


Figure 21.10 Outflows from Protostars. These images were taken with the Hubble Space Telescope and show jets flowing outward from newly formed stars. In the HH47 image, a protostar 1500 light-years away (invisible inside a dust disk at the left edge of the image) produces a very complicated jet. The star may actually be wobbling, perhaps because it has a companion. Light from the star illuminates the white region at the left because light can emerge perpendicular to the disk (just as the jet does). At right, the jet is plowing into existing clumps of interstellar gas, producing a shock wave that resembles an arrowhead. The HH1/2 image shows a double-beam jet emanating from a protostar (hidden in a dust disk in the center) in the constellation of Orion. Tip to tip, these jets are more than 1 light-year long. The bright regions (first identified by Herbig and Haro) are places where the jet is a slamming into a clump of interstellar gas and causing it to glow. (credit “HH 47”: modification of work by NASA, ESA, and P. Hartigan (Rice University); credit “HH 1 and HH 2: modification of work by J. Hester, WFPC2 Team, NASA)

The wind from a forming star will ultimately sweep away the material that remains in the obscuring envelope of dust and gas, leaving behind the naked disk and protostar, which can then be seen with visible light. We should note that at this point, the protostar itself is still contracting slowly and has not yet reached the main-sequence stage on the H–R diagram (a concept introduced in the chapter The Stars: A Celestial Census). The disk can be detected directly when observed at infrared wavelengths or when it is seen silhouetted against a bright background (Figure 21.11).

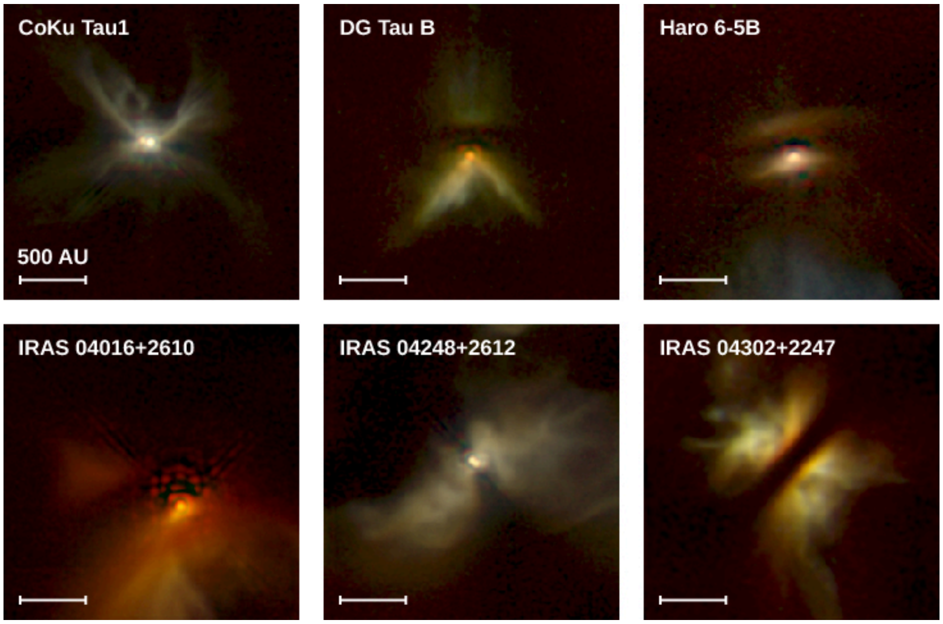


Figure 21.11 Disks around Protostars. These Hubble Space Telescope infrared images show disks around young stars in the constellation of Taurus, in a region about 450 light-years away. In some cases, we can see the central star (or stars—some are binaries). In other cases, the dark, horizontal bands indicate regions where the dust disk is so thick that even infrared radiation from the star embedded within it cannot make its way through. The brightly glowing regions are starlight reflected from the upper and lower surfaces of the disk, which are less dense than the central, dark regions. (Credit: modification of work by D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA)

This description of a protostar surrounded by a rotating disk of gas and dust sounds very much like what happened in our solar system when the Sun and planets formed. Indeed, one of the most important discoveries from the study of star formation in the last decade of the twentieth century was that disks are an inevitable byproduct of the process of creating stars. The next questions that astronomers set out to answer was: will the disks around protostars also form planets? And if so, how often? We will return to these questions later in this chapter.

To keep things simple, we have described the formation of single stars. Many stars, however, are members of binary or triple systems, where several stars are born together. In this case, the stars form in nearly the same way. Widely separated binaries may each have their own disk; close binaries may share a single disk.

21.2 The H–R Diagram and the Study of Stellar Evolution

Learning Objectives

By the end of this section, you will be able to:

- Determine the age of a protostar using an H–R diagram and the protostar’s luminosity and temperature
- Explain the interplay between gravity and pressure, and how the contracting protostar changes its position in the H–R diagram as a result

One of the best ways to summarize all of these details about how a star or protostar changes with time is to use a Hertzsprung-Russell (H–R) diagram. Recall from The Stars: A Celestial Census that, when looking at an H–R diagram, the temperature (the horizontal axis) is plotted increasing toward the left. As a star goes through the stages of its life, its luminosity and temperature change. Thus, its position on the H–R diagram, in which luminosity is plotted against temperature, also changes. As a star ages, we must replot it in different places on the diagram. Therefore, astronomers often speak of a star *moving* on the H–R diagram, or of its evolution tracing out a path on the diagram. In this context, “tracing out a path” has nothing to do with the star’s motion through space; this is just a shorthand way of saying that its temperature and luminosity change as it evolves.

LINK TO LEARNING

Watch an animation (https://openstax.org/l/30aniomelen) of the stars in the Omega Centauri cluster as they rearrange according to luminosity and temperature, forming a Hertzsprung-Russell (H–R) diagram.

To estimate just how much the luminosity and temperature of a star change as it ages, we must resort to calculations. Theorists compute a series of models for a star, with each successive model representing a later point in time. Stars may change for a variety of reasons. Protostars, for example, change in size because they are contracting, and their temperature and luminosity change as they do so. After nuclear fusion begins in the star’s core (see Stars from Adolescence to Old Age), main-sequence stars change because they are using up their nuclear fuel.

Given a model that represents a star at one stage of its evolution, we can calculate what it will be like at a slightly later time. At each step, the model predicts the luminosity and size of the star, and from these values, we can figure out its surface temperature. A series of points on an H–R diagram, calculated in this way, allows us to follow the life changes of a star and hence is called its *evolutionary track*.

Evolutionary Tracks

Let’s now use these ideas to follow the evolution of protostars that are on their way to becoming main-sequence stars. The evolutionary tracks of newly forming stars with a range of stellar masses are shown in Figure 21.12. These young stellar objects are not yet producing energy by nuclear reactions, but they derive energy from gravitational contraction—through the sort of process proposed for the Sun by Helmhotz and Kelvin in this last century (see the chapter on The Sun: A Nuclear Powerhouse).

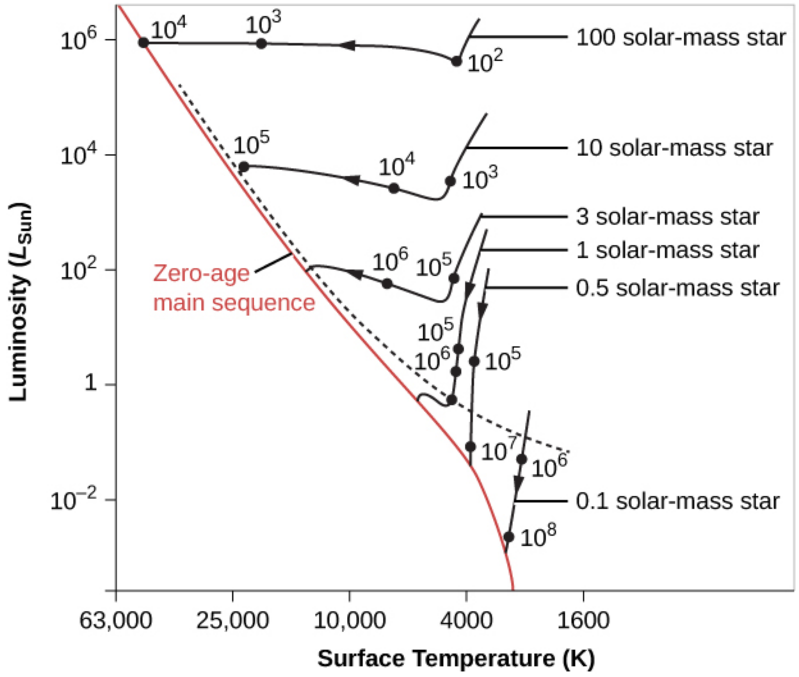


Figure 21.12 Evolutionary Tracks for Contracting Protostars. Tracks are plotted on the H–R diagram to show how stars of different masses change during the early parts of their lives. The number next to each dark point on a track is the rough number of years it takes an embryo star to reach that stage (the numbers are the result of computer models and are therefore not well known). Note that the surface temperature (K) on the horizontal axis increases toward the left. You can see that the more mass a star has, the shorter time it takes to go through each stage. Stars above the dashed line are typically still surrounded by infalling material and are hidden by it.

Initially, a protostar remains fairly cool with a very large radius and a very low density. It is transparent to infrared radiation, and the heat generated by gravitational contraction can be radiated away freely into space. Because heat builds up slowly inside the protostar, the gas pressure remains low, and the outer layers fall almost unhindered toward the center. Thus, the protostar undergoes very rapid collapse, a stage that corresponds to the roughly vertical lines at the right of Figure 21.12. As the star shrinks, its surface area gets smaller, and so its total luminosity decreases. The rapid contraction stops only when the protostar becomes dense and opaque enough to trap the heat released by gravitational contraction.

When the star begins to retain its heat, the contraction becomes much slower, and changes inside the contracting star keep the luminosity of stars like our Sun roughly constant. The surface temperatures start to build up, and the star “moves” to the left in the H–R diagram. Stars first become visible only after the stellar wind described earlier clears away the surrounding dust and gas. This can happen during the rapid-contraction phase for low-mass stars, but high-mass stars remain shrouded in dust until they end their early phase of gravitational contraction (see the dashed line in Figure 21.12).

To help you keep track of the various stages that stars go through in their lives, it can be useful to compare the development of a star to that of a human being. (Clearly, you will not find an exact correspondence, but thinking through the stages in human terms may help you remember some of the ideas we are trying to emphasize.) Protostars might be compared to human embryos—as yet unable to sustain themselves but drawing resources from their environment as they grow. Just as the birth of a child is the moment it is called upon to produce its own energy (through eating and breathing), so astronomers say that a star is born when it is able to sustain itself through nuclear reactions (by making its own energy.)

When the star’s central temperature becomes high enough (about 12 million K) to fuse hydrogen into helium, we say that the star has reached the main sequence (a concept introduced in The Stars: A Celestial Census). It is now a full-fledged star, more or less in equilibrium, and its rate of change slows dramatically. Only the gradual depletion of hydrogen as it is transformed into helium in the core slowly changes the star’s properties.

The mass of a star determines exactly where it falls on the main sequence. As Figure 21.12 shows, massive stars on the main sequence have high temperatures and high luminosities. Low-mass stars have low temperatures and low luminosities.

Objects of extremely low mass never achieve high-enough central temperatures to ignite nuclear reactions. The lower end of the main sequence stops where stars have a mass just barely great enough to sustain nuclear reactions at a sufficient rate to stop gravitational contraction. This critical mass is calculated to be about 0.075 times the mass of the Sun. As we discussed in the chapter on Analyzing Starlight, objects below this critical mass are called either brown dwarfs or planets. At the other extreme, the upper end of the main sequence terminates at the point where the energy radiated by the newly forming massive star becomes so great that it halts the accretion of additional matter. The upper limit of stellar mass is between 100 and 200 solar masses.

Evolutionary Timescales

How long it takes a star to form depends on its mass. The numbers that label the points on each track in Figure 21.12 are the times, in years, required for the embryo stars to reach the stages we have been discussing. Stars of masses much higher than the Sun’s reach the main sequence in a few thousand to a million years. The Sun required millions of years before it was born. Tens of millions of years are required for stars of lower mass to evolve to the lower main sequence. (We will see that this turns out to be a general principle: massive stars go through *all* stages of evolution faster than low-mass stars do.)

We will take up the subsequent stages in the life of a star in Stars from Adolescence to Old Age, examining what happens after stars arrive in the main sequence and begin a “prolonged adolescence” and “adulthood” of fusing hydrogen to form helium. But now we want to examine the connection between the formation of stars and planets.

21.3 Evidence That Planets Form around Other Stars

Learning Objectives

By the end of this section, you will be able to:

- Trace the evolution of dust surrounding a protostar, leading to the development of rocky planets and gas giants
- Estimate the timescale for growth of planets using observations of the disks surrounding young stars
- Evaluate evidence for planets around forming stars based on the structures seen in images of the circumstellar dust disks

Having developed on a planet and finding it essential to our existence, we have a special interest in how planets fit into the story of star formation. Yet planets outside the solar system are extremely difficult to detect. Recall that we see planets in our own system only because they reflect sunlight and are close by. When we look to the other stars, we find that the amount of light a planet reflects is a depressingly tiny fraction of the light its star gives off. Furthermore, from a distance, planets are lost in the glare of their much-brighter parent stars.

Disks around Protostars: Planetary Systems in Formation

It is a lot easier to detect the spread-out raw material from which planets might be assembled than to detect planets after they are fully formed. From our study of the solar system, we understand that planets form by the gathering together of gas and dust particles in orbit around a newly created star. Each dust particle is heated by the young protostar and radiates in the infrared region of the spectrum. Before any planets form, we can detect such radiation from all of the spread-out individual dust particles that are destined to become parts of planets. We can also detect the silhouette of the disk if it blocks bright light coming from a source behind it (Figure 21.13).

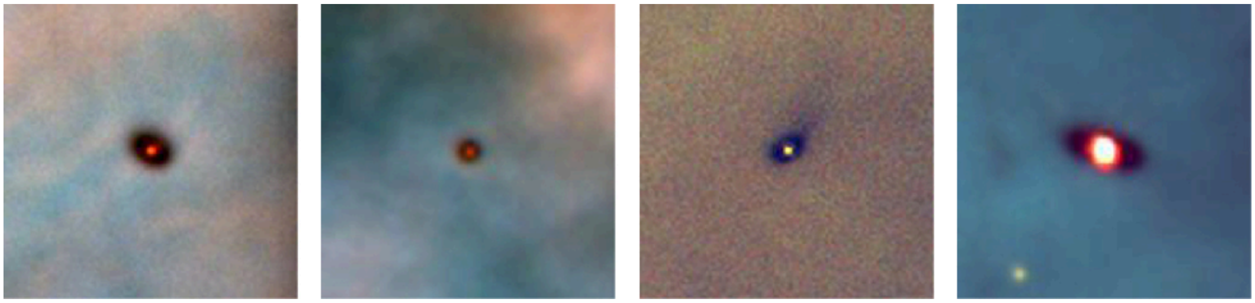


Figure 21.13 Disks around Protostars. These Hubble Space Telescope images show four disks around young stars in the Orion Nebula. The dark, dusty disks are seen silhouetted against the bright backdrop of the glowing gas in the nebula. The size of each image is about 30 times the diameter of our planetary system; this means the disks we see here range in size from two to eight times the orbit of Pluto. The red glow at the center of each disk is a young star, no more than a million years old. These images correspond to the stage in the life of a protostar shown in part (d) of Figure 21.8. (credit: modification of work by Mark McCaughrean (Max-Planck-Institute for Astronomy), C. Robert O'Dell (Rice University), and NASA)

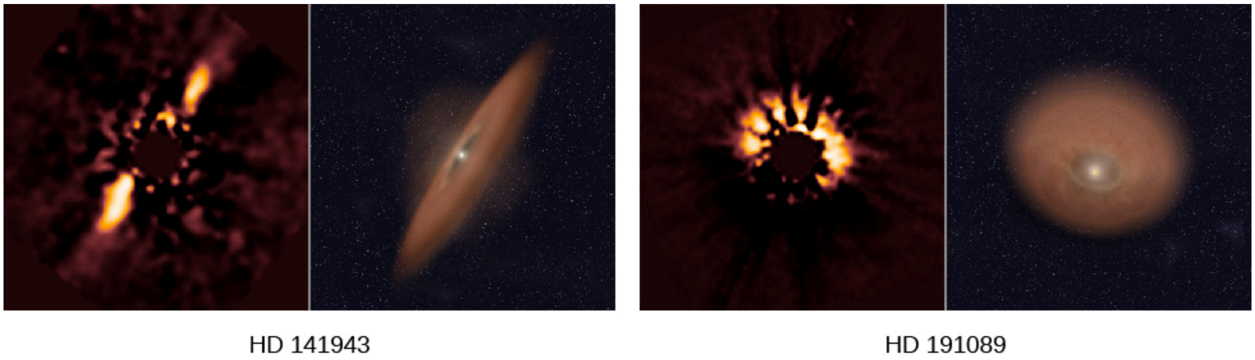
Once the dust particles gather together and form a few planets (and maybe some moons), the overwhelming majority of the dust is hidden in the interiors of the planets where we cannot see it. All we can now detect is the radiation from the outside surfaces, which cover a drastically smaller area than the huge, dusty disk from which they formed. The amount of infrared radiation is therefore greatest before the dust particles combine into planets. For this reason, our search for planets begins with a search for infrared radiation from the material required to make them.

A disk of gas and dust appears to be an essential part of star formation. Observations show that nearly all very young protostars have disks and that the disks range in size from 10 to 1000 AU. (For comparison, the average diameter of the orbit of Pluto, which can be considered the rough size of our own planetary system, is 80 AU, whereas the outer diameter of the Kuiper belt of smaller icy bodies is about 100 AU.) The mass contained in these disks is typically 1–10% of the mass of our own Sun, which is more than the mass of all the planets in our solar system put together. Such observations already demonstrate that a large fraction of stars begin their lives with enough material in the right place to form a planetary system.

The Timing of Planet Formation and Growth

We can use observations of how the disks change with time to estimate how long it takes for planets to form. If we measure the temperature and luminosity of a protostar, then, as we saw, we can place it in an H–R diagram like the one shown in Figure 21.12. By comparing the real star with our models of how protostars should evolve with time, we can estimate its age. We can then look at how the disks we observe change with the ages of the stars that they surround.

What such observations show is that if a protostar is less than about 1 to 3 million years old, its disk extends all the way from very close to the surface of the star out to tens or hundreds of AU away. In older protostars, we find disks with outer parts that still contain large amounts of dust, but the inner regions have lost most of their dust. In these objects, the disk looks like a donut, with the protostar centered in its hole. The inner, dense parts of most disks have disappeared by the time the stars are 10 million years old (Figure 21.14).



HD 141943

HD 191089

Figure 21.14 Protoplanetary Disks around Two Stars. The left view of each star shows infrared observations by the Hubble Space Telescope of their protoplanetary disks. The central star is much brighter than the surrounding disk, so the instrument includes a coronagraph, which has a small shield that blocks the light of the central star but allows the surrounding disk to be imaged. The right image of each star shows models of the disks based on the observations. The star HD 141943 has an age of about 17 million years, while HD 191089 is about 12 million years old. (credit: modification of work by NASA, ESA, R. Soummer and M. Perrin (STScI), L. Pueyo (STScI/Johns Hopkins University), C. Chen and D. Golimowski (STScI), J.B. Hagan (STScI/Purdue University), T. Mittal (University of California, Berkeley/Johns Hopkins University), E. Choquet, M. Moerchen, and M. N'Diaye (STScI), A. Rajan (Arizona State University), S. Wolff (STScI/Purdue University), J. Debes and D. Hines (STScI), and G. Schneider (Steward Observatory/University of Arizona))

Calculations show that the formation of one or more planets could produce such a donut-like distribution of dust. Suppose a planet forms a few AU away from the protostar, presumably due to the gathering together of matter from the disk. As the planet grows in mass, the process clears out a dust-free region in its immediate neighborhood. Calculations also show that any small dust particles and gas that were initially located in the region between the protostar and the planet, and that are not swept up by the planet, will then fall onto the star very quickly in about 50,000 years.

Matter lying outside the planet's orbit, in contrast, is prevented from moving into the hole by the gravitational forces exerted by the planet. (We saw something similar in Saturn's rings, where the action of the shepherd moons keeps the material near the edge of the rings from spreading out.) If the formation of a planet is indeed what produces and sustains holes in the disks that surround very young stars, then planets must form in 3 to 30 million years. This is a short period compared with the lifetimes of most stars and shows that the formation of planets may be a quick byproduct of the birth of stars.

Calculations show that *accretion* can drive the rapid growth of planets—small, dust-grain-size particles orbiting in the disk collide and stick together, with the larger collections growing more rapidly as they attract and capture smaller ones. Once these clumps grow to about 10 centimeters in size or so, they enter a perilous stage in their development. At that size, unless they can grow to larger than about 100 meters in diameter, they are subject to drag forces produced by friction with the gas in the disk—and their orbits can rapidly decay, plunging them into the host star. Therefore, these bodies must rapidly grow to nearly 1 kilometer in size in diameter to avoid a fiery fate. At this stage, they are considered planetesimals (the small chunks of solid matter—ice and dust particles—that you learned about in Other Worlds: An Introduction to the Solar System). Once they survive to those sizes, the largest survivors will continue to grow by accreting smaller planetesimals; ultimately, this process results in a few large planets.

If the growing planets reach a mass bigger than about 10 times the mass of Earth, their gravity is strong enough to capture and hold on to hydrogen gas that remains in the disk. At that point, they will grow in mass and radius rapidly, reaching giant planet dimensions. However, to do so requires that the rapidly evolving central star hasn't yet driven away the gas in the disk with its increasingly vigorous wind (see the earlier section on Star Formation). From observations, we see that the disk can be blown away within 10 million years, so growth of a giant planet must also be a very fast process, astronomically speaking.

Debris Disks and Shepherd Planets

The dust around newly formed stars is gradually either incorporated into the growing planets in the newly forming planetary system or ejected through gravitational interactions with the planets into space. The dust will disappear after about 30 million years unless the disk is continually supplied with new material. Local comets and asteroids are the most likely sources of new dust. As the planet-size bodies grow, they stir up the orbits of smaller objects in the area. These small bodies collide at high speeds, shatter, and produce tiny particles of silicate dust and ices that can keep the disk supplied with the debris from these collisions.

Over several hundred million years, the comets and asteroids will gradually be reduced in number, the frequency of collisions will go down, and the supply of fresh dust will diminish. Remember that the heavy bombardment in the early solar system ended when the Sun was only about 500 million years old. Observations show that the dusty "debris disks" around stars also become largely undetectable by the time the stars reach an age of 400 to 500 million years. It is likely, however, that some small amount of cometary material will remain in orbit, much like our Kuiper belt, a flattened disk of comets outside the orbit of Neptune.

In a young planetary system, even if we cannot see the planets directly, the planets can concentrate the dust particles into clumps and arcs that are much larger than the planets themselves and more easily imaged. This is similar to how the tiny moons of Saturn shepherd the particles in the rings and produce large arcs and structures in Saturn's rings.

Debris disks—many with just such clumps and arcs—have now been found around many stars, such as HL Tau, located about 450 light-years from Earth in the constellation Taurus (Figure 21.15). In some stars, the brightness of the rings varies with position; around other stars, there are bright arcs and gaps in the rings. The brightness indicates the relative concentration of dust, since what we are seeing is infrared (heat radiation) from the dust particles in the rings. More dust means more radiation.

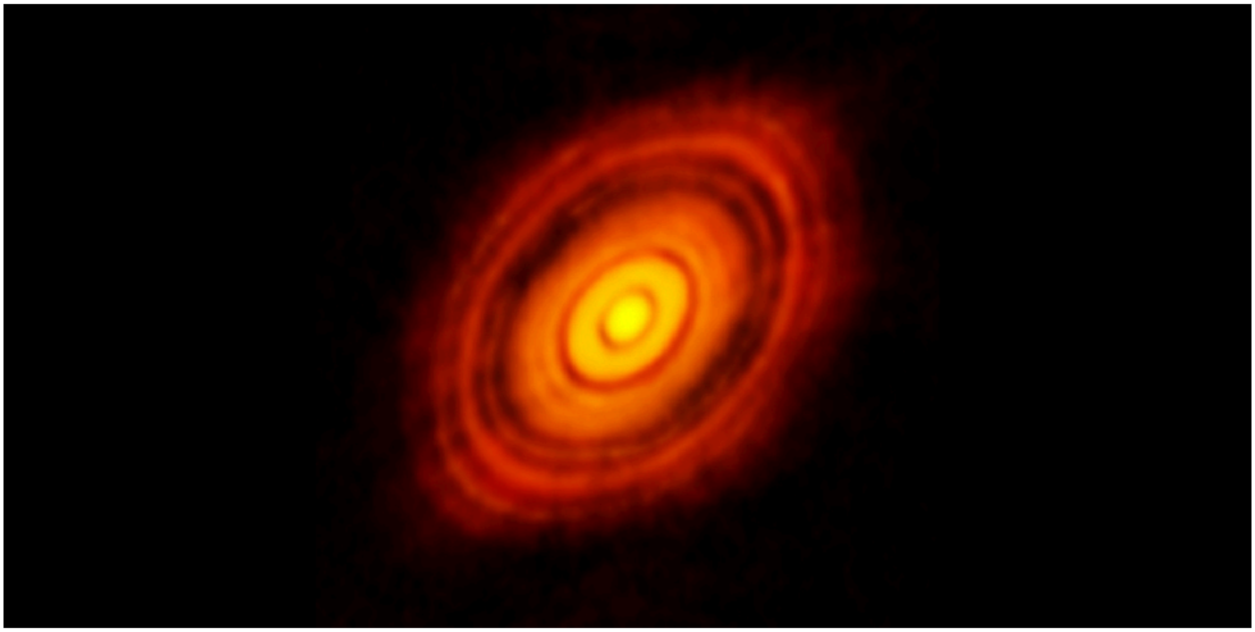


Figure 21.15 Dust Ring around a Young Star. This image was made by ALMA (the Atacama Large Millimeter/Submillimeter Array) at a wavelength of 1.3 millimeters and shows the young star HL Tau and its protoplanetary disk. It reveals multiple rings and gaps that indicate the presence of emerging planets, which are sweeping their orbits clear of dust and gas. (credit: modification of work by ALMA (ESO/NAOJ/NRAO))

LINK TO LEARNING

Watch a short video clip (https://openstax.org/l/30vidNRAOdir) of the director of NRAO (National Radio Astronomy Observatory) describing the high-resolution observations of the young star HL Tau. While you're there, watch an artist's animation of a protoplanetary disk to see newly formed planets traveling around a host (parent) star.

21.4 Planets beyond the Solar System: Search and Discovery

Learning Objectives

By the end of this section, you will be able to:

- Describe the orbital motion of planets in our solar system using Kepler's laws
- Compare the indirect and direct observational techniques for exoplanet detection

For centuries, astronomers have dreamed of finding planets around other stars, including other planets like Earth. Direct observations of such distant planets are very difficult, however. You might compare a planet orbiting a star to a mosquito flying around one of those giant spotlights at a shopping center opening. From close up, you might spot the mosquito. But imagine viewing the scene from some distance away—say, from an airplane. You could see the spotlight just fine, but what are your chances of catching the mosquito in that light? Instead of making direct images, astronomers have relied on indirect observations and have now succeeded in detecting a multitude of planets around other stars.

In 1995, after decades of effort, we found the first such **exoplanet** (a planet outside our solar system) orbiting a main-sequence star, and today we know that most stars form with planets. This is an example of how persistence and new methods of observation advance the knowledge of humanity. By studying exoplanets, astronomers hope to better understand our solar system in context of the rest of the universe. For instance, how does the arrangement of our solar system compare to planetary systems in the rest of the universe?

What do exoplanets tell us about the process of planet formation? And how does knowing the frequency of exoplanets influence our estimates of whether there is life elsewhere?

Searching for Orbital Motion

Most exoplanet detections are made using techniques where we observe the *effect* that the planet exerts on the host star. For example, the gravitational tug of an unseen planet will cause a small wobble in the host star. Or, if its orbit is properly aligned, a planet will periodically cross in front of the star, causing the brightness of the star to dim.

To understand how a planet can move its host star, consider a single Jupiter-like planet. Both the planet and the star actually revolve about their *common center of mass*. Remember that gravity is a mutual attraction. The star and the planet each exert a force on the other, and we can find a stable point, the center of mass, between them about which both objects move. The smaller the mass of a body in such a system, the larger its orbit. A massive star barely swings around the center of mass, while a low-mass planet makes a much larger "tour."

Suppose the planet is like Jupiter and has a mass about one-thousandth that of its star; in this case, the size of the star's orbit is one-thousandth the size of the planet's. To get a sense of how difficult observing such motion might be, let's see how hard Jupiter would be to detect in this way from the distance of a nearby star. Consider an alien astronomer trying to observe our own system from Alpha Centauri, the closest star system to our own (about 4.3 light-years away). There are two ways this astronomer could try to detect the orbital motion of the Sun. One way would be to look for changes in the Sun's position on the sky. The second would be to use the Doppler effect to look for changes in its velocity. Let's discuss each of these in turn.

The diameter of Jupiter's apparent orbit viewed from Alpha Centauri is 10 seconds of arc, and that of the Sun's orbit is 0.010 seconds of arc. (Remember, 1 second of arc is 1/3600 degree.) If they could measure the apparent position of the Sun (which is bright and easy to detect) to sufficient precision, they would describe an orbit of diameter 0.010 seconds of arc with a period equal to that of Jupiter, which is 12 years.

In other words, if they watched the Sun for 12 years, they would see it wiggle back and forth in the sky by this minuscule fraction of a degree. From the observed motion and the period of the "wiggle," they could deduce the mass of Jupiter and its distance using Kepler's laws. (To refresh your memory about these laws, see the chapter on Orbits and Gravity.)

Measuring positions in the sky this accurately is extremely difficult, and so far, astronomers have not made any confirmed detections of planets using this technique. However, we have been successful in using spectrometers to measure the changing velocity of stars with planets around them.

As the star and planet orbit each other, part of their motion will be in our line of sight (toward us or away from us). Such motion can be measured using the *Doppler effect* and the star's spectrum. As the star moves back and forth in orbit around the system's center of mass in response to the gravitational tug of an orbiting planet, the lines in its spectrum will shift back and forth.

Let's again consider the example of the Sun. Its *radial velocity* (motion toward or away from us) changes by about 13 meters per second with a period of 12 years because of the gravitational pull of Jupiter. This corresponds to about 30 miles per hour, roughly the speed at which many of us drive around town. Detecting motion at this level in a star's spectrum presents an enormous technical challenge, but several groups of astronomers around the world, using specialized spectrographs designed for this purpose, have succeeded. Note that the change in speed does not depend on the distance of the star from the observer. Using the Doppler effect to detect planets will work at any distance, as long as the star is bright enough to provide a good spectrum and a large telescope is available to make the observations (Figure 21.16).

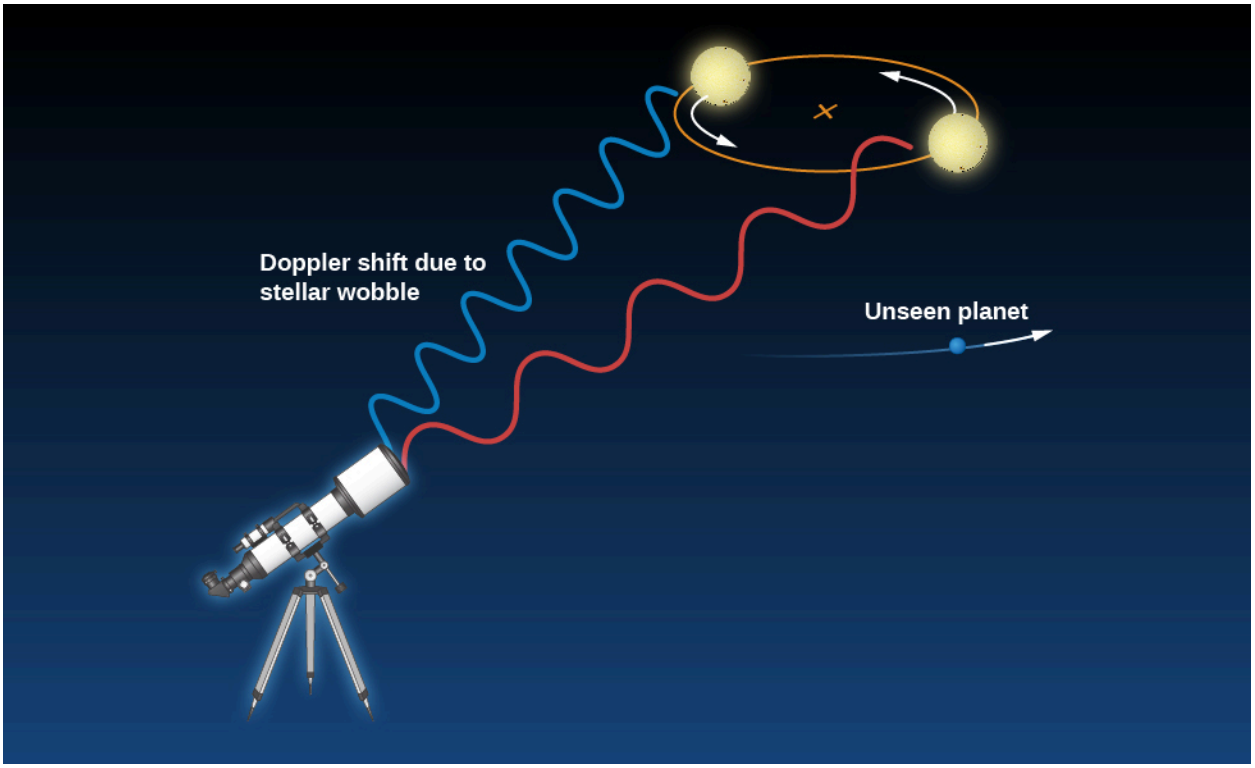


Figure 21.16 Doppler Method of Detecting Planets. The motion of a star around a common center of mass with an orbiting planet can be detected by measuring the changing speed of the star. When the star is moving away from us, the lines in its spectrum show a tiny redshift; when it is moving toward us, they show a tiny blueshift. The change in color (wavelength) has been exaggerated here for illustrative purposes. In reality, the Doppler shifts we measure are extremely small and require sophisticated equipment to be detected.

The first successful use of the Doppler effect to find a planet around another star was in 1995. Michel Mayor and Didier Queloz of the Geneva Observatory (Figure 21.17) used this technique to find a planet orbiting a star resembling our Sun called 51 Pegasi, about 40 light-years away. (The star can be found in the sky near the great square of Pegasus, the flying horse of Greek mythology, one of the easiest-to-find star patterns.) To everyone’s surprise, the planet takes a mere 4.2 days to orbit around the star. (Remember that Mercury, the innermost planet in our solar system, takes 88 days to go once around the Sun, so 4.2 days seems fantastically short.)

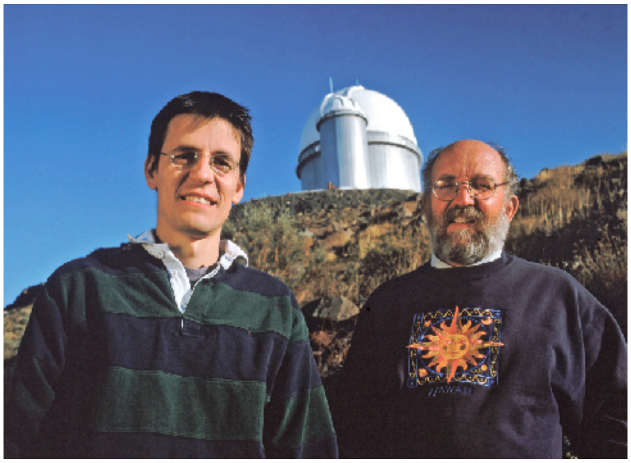


Figure 21.17 Planet Discoverers. In 1995, Didier Queloz and Michel Mayor of the Geneva Observatory were the first to discover a planet around a regular star (51 Pegasi), for which they received the 2019 Nobel Prize in physics. They are seen here at an observatory in Chile where they are continuing their planet hunting. (credit: Weinstein/Ciel et Espace Photos)

Mayor and Queloz's findings mean the planet must be very close to 51 Pegasi, circling it about 7 million kilometers away (Figure 21.18). At that distance, the energy of the star should heat the planet's surface to a temperature of a few thousand degrees Celsius (a bit hot for future tourism). From its motion, astronomers calculate that it has at least half the mass of Jupiter[1], making it clearly a jovian and not a terrestrial-type planet.

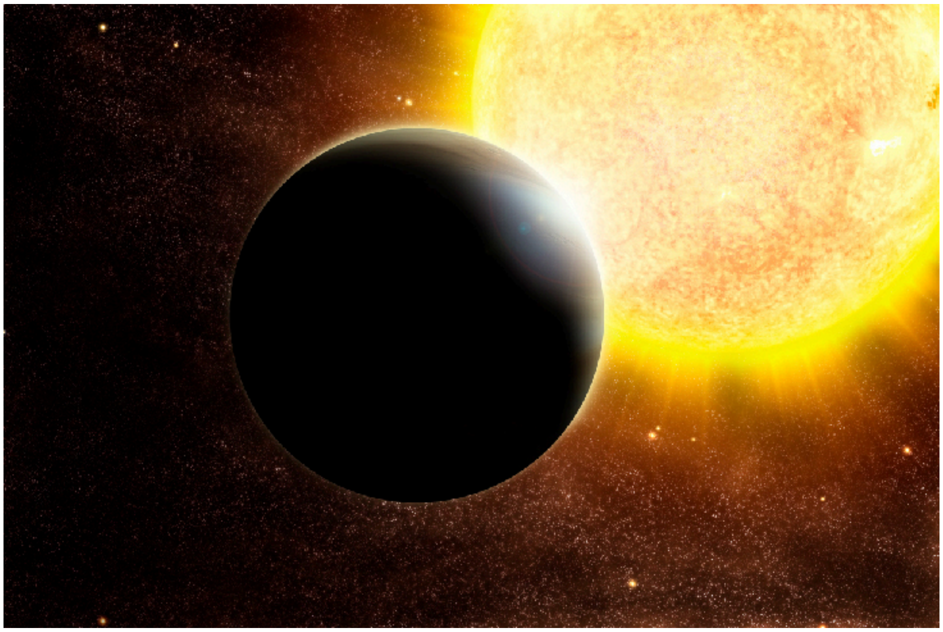


Figure 21.18 Hot Jupiter. Artist Greg Bacon painted this impression of a hot, Jupiter-type planet orbiting close to a sunlike star. The artist shows bands on the planet like Jupiter, but we only estimate the mass of most hot, Jupiter-type planets from the Doppler method and don't know what conditions on the planet are like. (credit: ESO)

Since that initial planet discovery, the rate of progress has been breathtaking. Almost a thousand giant planets have been discovered using the Doppler technique. Many of these giant planets are orbiting close to their stars—astronomers have called these *hot Jupiters*.

The existence of giant planets so close to their stars was a surprise, and these discoveries have forced us to rethink our ideas about how planetary systems form. But for now, bear in mind that the Doppler-shift method—which relies on the pull of a planet making its star "wiggle" back and forth around the center of mass—is most effective at finding planets that are both close to their stars and massive. These planets cause the biggest "wiggles" in the motion of their stars and the biggest Doppler shifts in the spectrum. Plus, they will be found sooner, since astronomers like to monitor the star for at least one full orbit (and perhaps more) and hot Jupiters take the shortest time to complete their orbit.

So if such planets exist, we would expect to be finding this type first. Scientists call this a *selection effect*—where our technique of discovery selects certain kinds of objects as "easy finds." As an example of a selection effect in everyday life, imagine you decide you are ready for a new romantic relationship in your life. To begin with, you only attend social events on campus, all of which require a student ID to get in. Your selection of possible partners will then be limited to students at your college. That may not give you as diverse a group to choose from as you want. In the same way, when we first used the Doppler technique, it selected massive planets close to their stars as the most likely discoveries. As we spend longer times watching target stars and as our ability to measure smaller Doppler shifts improves, this technique can reveal more distant and less massive planets too.

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[1] The Doppler method only allows us to find the minimum mass of a planet. To determine the exact mass using the Doppler shift and Kepler's laws, we must also have the angle at which the planet's orbit is oriented to our view—something we don't have any independent way of knowing in most cases. Still, if the minimum mass is half of Jupiter's, the actual mass can only be larger than that, and we are sure that we are dealing with a jovian planet.

LINK TO LEARNING

View a series of animations (https://openstax.org/l/30keplawsolarani) demonstrating solar system motion and Kepler's laws, and select animation 1 (Kepler's laws) from the dropdown playlist. To view an animation demonstrating the radial velocity curve for an exoplanet, select animation 29 (radial velocity curve for an exoplanet) and animation 30 (radial velocity curve for an exoplanet—elliptical orbit) from the dropdown playlist.

Transiting Planets

The second method for indirect detection of exoplanets is based not on the motion of the star but on its brightness. When the orbital plane of the planet is tilted or inclined so that it is viewed edge-on, we will see the planet cross in front of the star once per orbit, causing the star to dim slightly; this event is known as **transit**. Figure 21.19 shows a sketch of the transit at three time steps: (1) out of transit, (2) the start of transit, and (3) full transit, along with a sketch of the light curve, which shows the drop in the brightness of the host star. The amount of light blocked—the depth of the transit—depends on the area of the planet (its size) compared to the star. If we can determine the size of the star, the transit method tells us the size of the planet.

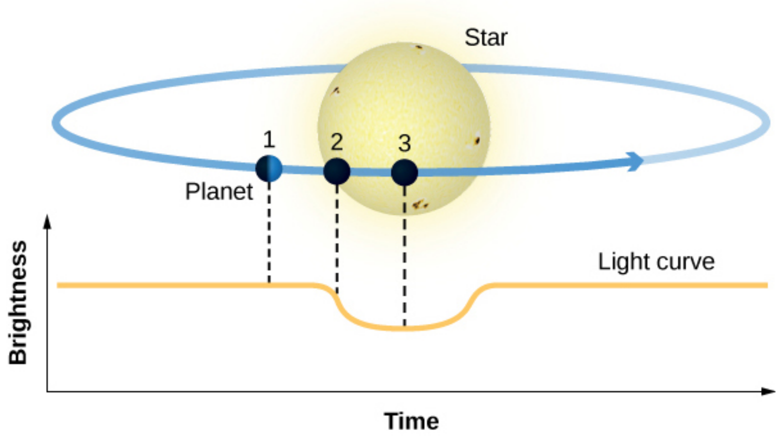

Figure 21.19 Planet Transits. As the planet transits, it blocks out some of the light from the star, causing a temporary dimming in the brightness of the star. The top figure shows three moments during the transit event and the bottom panel shows the corresponding light curve: (1) out of transit, (2) transit ingress, and (3) the full drop in brightness.

The interval between successive transits is the length of the year for that planet, which can be used (again using Kepler's laws) to find its distance from the star. Larger planets like Jupiter block out more starlight than small earthlike planets, making transits by giant planets easier to detect, even from ground-based observatories. But by going into space, above the distorting effects of Earth's atmosphere, the transit technique has been extended to exoplanets as small as Mars.

EXAMPLE 21.1

Transit Depth

In a transit, the planet's circular disk blocks the light of the star's circular disk. The area of a circle is πR^2. The amount of light the planet blocks, called the transit depth, is then given by

$$\frac{\pi R^2{}_{\text{planet}}}{\pi R^2{}_{\text{star}}} = \frac{R^2{}_{\text{planet}}}{R^2{}_{\text{star}}} = \left(\frac{R_{\text{planet}}}{R_{\text{star}}}\right)^2$$

Now calculate the transit depth for a star the size of the Sun with a gas giant planet the size of Jupiter.

Solution

The radius of Jupiter is 71,400 km, while the radius of the Sun is 695,700 km. Substituting into the equation, we get $\left(\frac{R_{\text{planet}}}{R_{\text{star}}}\right)^2 = \left(\frac{71{,}400 \text{ km}}{695{,}700 \text{ km}}\right)^2 = 0.01$ or 1%, which can easily be detected with the instruments on board the Kepler spacecraft.

Check Your Learning

What is the transit depth for a star half the size of the Sun with a much smaller planet, like the size of Earth?

Answer:

The radius of Earth is 6371 km. Therefore,

$$\left(\frac{R_{\text{planet}}}{R_{\text{star}}}\right)^2 = \left(\frac{6371 \text{ km}}{695{,}700/2 \text{ km}}\right)^2 = \left(\frac{6371 \text{ km}}{347{,}850 \text{ km}}\right)^2 = 0.0003$$, or significantly less than 1%.

The Doppler method allows us to estimate the mass of a planet. If the same object can be studied by both the Doppler and transit techniques, we can measure both the mass and the size of the exoplanet. This is a powerful combination that can be used to derive the average density (mass/volume) of the planet. In 1999, using measurements from ground-based telescopes, the first transiting planet was detected orbiting the star HD 209458. The planet transits its parent star for about 3 hours every 3.5 days as we view it from Earth. Doppler measurements showed that the planet around HD 209458 has about 70% the mass of Jupiter, but its radius is about 35% larger than Jupiter's. This was the first case where we could determine what an exoplanet was made of—with that mass and radius, HD 209458 must be a gas and liquid world like Jupiter or Saturn.

It is even possible to learn something about the planet's atmosphere. When the planet passes in front of HD 209458, the atoms in the planet's atmosphere absorb starlight. Observations of this absorption were first made at the wavelengths of yellow sodium lines and showed that the atmosphere of the planet contains sodium; now, other elements can be measured as well.

LINK TO LEARNING

Try a transit simulator (https://openstax.org/l/30transimul) that demonstrates how a planet passing in front of its parent star can lead to the planet's detection. Follow the instructions to run the animation on your computer.

Transiting planets reveal such a wealth of information that the French Space Agency (CNES) and the European Space Agency (ESA) launched the CoRoT space telescope in 2007 to detect transiting exoplanets. CoRoT discovered 32 transiting exoplanets, including the first transiting planet with a size and density similar to Earth. In 2012, the spacecraft suffered an onboard computer failure, ending the mission. Meanwhile, NASA built a much more powerful transit observatory called Kepler.

In 2009, NASA launched the Kepler space telescope, dedicated to the discovery of transiting exoplanets. This spacecraft stared continuously at more than 150,000 stars in a small patch of sky near the constellation of Cygnus—just above the plane of our Milky Way Galaxy (Figure 21.20). Kepler's cameras and ability to measure small changes in brightness very precisely enabled the discovery of thousands of exoplanets, including many multi-planet systems. The spacecraft required three reaction wheels—a type of wheel used to help control slight rotation of the spacecraft—to stabilize the pointing of the telescope and monitor the brightness of the same group of stars over and over again. Kepler was launched with four reaction wheels (one a spare), but by

May 2013, two wheels had failed and the telescope could no longer be accurately pointed toward the target area. Kepler had been designed to operate for 4 years, and ironically, the pointing failure occurred exactly 4 years and 1 day after it began observing.

However, this failure did not end the mission. The Kepler telescope continued to observe for two more years, looking for short-period transits in different parts of the sky. We discuss the Kepler results in the next section Exoplanets Everywhere: What We Are Learning. A new NASA mission called TESS (Transiting Exoplanet Survey Satellite) is now carrying out a transit survey of the nearer (and therefore brighter) stars all over the sky. TESS completed its first planned survey of the sky in August 2020 and reported 66 exoplanet discoveries and almost 2100 candidates that need further observations to confirm.

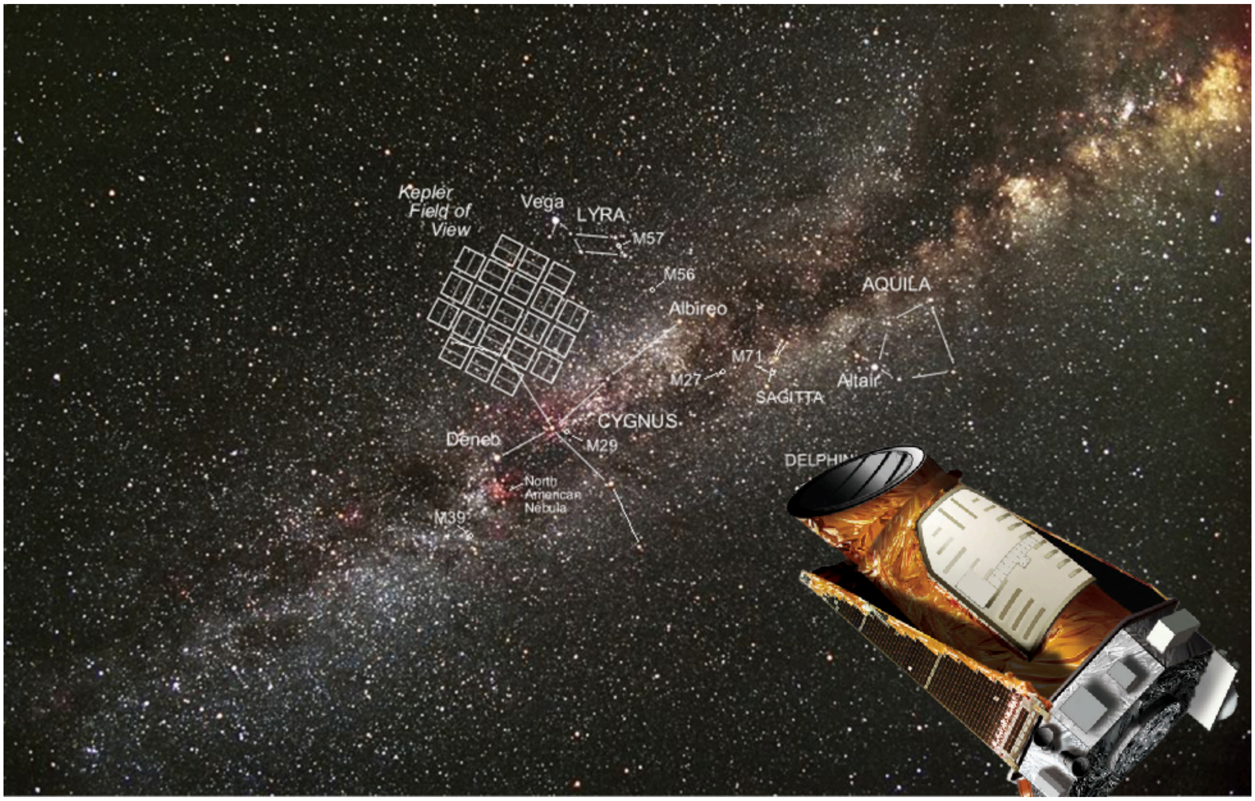

Figure 21.20 Kepler's Field of View. The boxes show the region where the Kepler spacecraft cameras took images of over 150,000 stars regularly, to find transiting planets. (credit "field of view": modification of work by NASA/Kepler mission; credit "spacecraft": modification of work by NASA/Kepler mission/Wendy Stenzel)

What do we mean, exactly, by "discovery" of transiting exoplanets? A single transit shows up as a very slight drop in the brightness of the star, lasting several hours. However, astronomers must be on guard against other factors that might produce a false transit, especially when working at the limit of precision of the telescope. We must wait for a second transit of similar depth. But when another transit is observed, we don't initially know whether it might be due to another planet in a different orbit. The "discovery" occurs only when a third transit is found with similar depth and the same spacing in time as the first pair.

Computers normally conduct the analysis, which involves searching for tiny, periodic dips in the light from each star, extending over 4 years of observation. But the Kepler mission also has a program in which non-astronomers—citizen scientists—can examine the data. These dedicated volunteers have found several transits that were missed by the computer analyses, showing that the human eye and brain sometimes recognize unusual events that a computer was not programmed to look for.

Measuring three or four evenly spaced transits is normally enough to "discover" an exoplanet. But in a new field like exoplanet research, we would like to find further independent verification. The strongest confirmation happens when ground-based telescopes are also able to detect a Doppler shift with the same period as the transits. However, this is generally not possible for Earth-size planets. One of the most convincing ways to verify that a dip in brightness is due to a planet is to find more planets orbiting the same star—a *planetary system*. Multi-planet systems also provide alternative ways to estimate the masses of the planets, as we will discuss in the next section.

The selection effects (or biases) in the Kepler data are similar to those in Doppler observations. Large planets are easier to find than small ones, and short-period planets are easier than long-period planets. If we require three transits to establish the presence of a planet, we are of course limited to discovering planets with orbital periods less than one-third of the observing interval. Thus, it was only in its fourth and final year of operation that Kepler was able to find planets with orbits like Earth's that require 1 year to go around their star.

Direct Detection

The best possible evidence for an earthlike planet elsewhere would be an image. After all, "seeing is believing" is a very human prejudice. But imaging a distant planet is a formidable challenge indeed. Suppose, for example, you were a great distance away and wished to detect reflected light from Earth. Earth intercepts and reflects less than one billionth of the Sun's radiation, so its apparent brightness in visible light is less than one billionth that of the Sun. Compounding the challenge of detecting such a faint speck of light, the planet is swamped by the blaze of radiation from its parent star.

Even today, the best telescope mirrors' optics have slight imperfections that prevent the star's light from coming into focus in a completely sharp point.

Direct imaging works best for young gas giant planets that emit infrared light and reside at large separations from their host stars. Young giant planets emit more infrared light because they have more internal energy, stored from the process of planet formation. Even then, clever techniques must be employed to subtract out the light from the host star. In 2008, three such young planets were discovered orbiting HR 8799, a star in the constellation of Pegasus (Figure 21.21). Two years later, a fourth planet was detected closer to the star. Additional planets may reside even closer to HR 8799, but if they exist, they are currently lost in the glare of the star.

Since then, a number of planets around other stars have been found using direct imaging. However, one challenge is to tell whether the objects we are seeing are indeed planets or if they are brown dwarfs (failed stars) in orbit around a star.

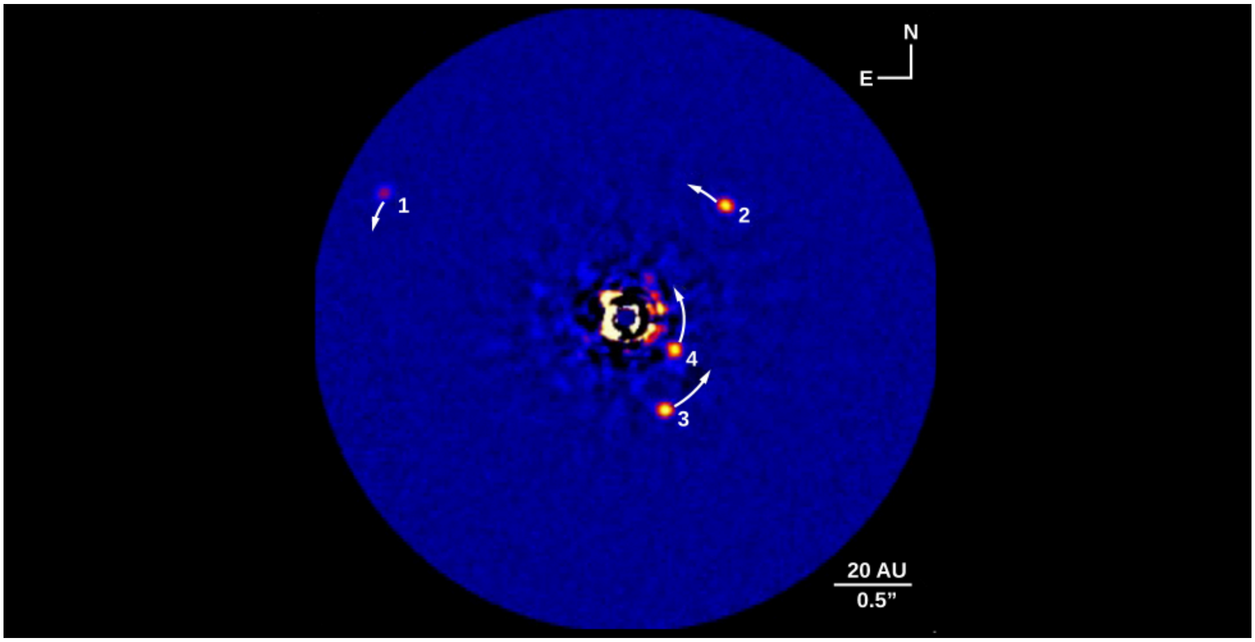

Figure 21.21 Exoplanets around HR 8799. This image shows Keck telescope observations of four directly imaged planets orbiting

HR 8799. A size scale for the system gives the distance in AU (remember that one astronomical unit is the distance between Earth and the Sun.) (credit: modification of work by Ben Zuckerman)

Direct imaging is an important technique for characterizing an exoplanet. The brightness of the planet can be measured at different wavelengths. These observations provide an estimate for the temperature of the planet’s atmosphere; in the case of HR 8799 planet 1, the color suggests the presence of thick clouds. Spectra can also be obtained from the faint light to analyze the atmospheric constituents. A spectrum of HR 8799 planet 1 indicates a hydrogen-rich atmosphere, while the closer planet 4 shows evidence for methane in the atmosphere.

Another way to overcome the blurring effect of Earth’s atmosphere is to observe from space. Infrared may be the optimal wavelength range in which to observe because planets get brighter in the infrared while stars like our Sun get fainter, thereby making it easier to detect a planet against the glare of its star. Special optical techniques can be used to suppress the light from the central star and make it easier to see the planet itself. However, even if we go into space, it will be difficult to obtain images of Earth-size planets.

21.5 Exoplanets Everywhere: What We Are Learning

Learning Objectives

By the end of this section, you will be able to:

- Explain what we have learned from our discovery of exoplanets
- Identify which kind of exoplanets appear to be the most common in the Galaxy
- Discuss the kinds of planetary systems we are finding around other stars

Before the discovery of exoplanets, most astronomers expected that other planetary systems would be much like our own—planets following roughly circular orbits, with the most massive planets several AU from their parent star. Such systems do exist in large numbers, but many exoplanets and planetary systems are very different from those in our solar system. Another surprise is the existence of whole classes of exoplanets that we simply don’t have in our solar system: planets with masses between the mass of Earth and Neptune, and planets that are several times more massive than Jupiter.

Kepler Results

The Kepler telescope has been responsible for the discovery of most exoplanets, especially at smaller sizes, as illustrated in Figure 21.22, where the Kepler discoveries are plotted in yellow. You can see the wide range of sizes, including planets substantially larger than Jupiter and smaller than Earth. The absence of Kepler-discovered exoplanets with orbital periods longer than a few hundred days is a consequence of the 4-year lifetime of the mission. (Remember that three evenly spaced transits must be observed to register a discovery.) At the smaller sizes, the absence of planets much smaller than one earth radius is due to the difficulty of detecting transits by very small planets. In effect, the “discovery space” for Kepler was limited to planets with orbital periods less than 400 days and sizes larger than Mars.

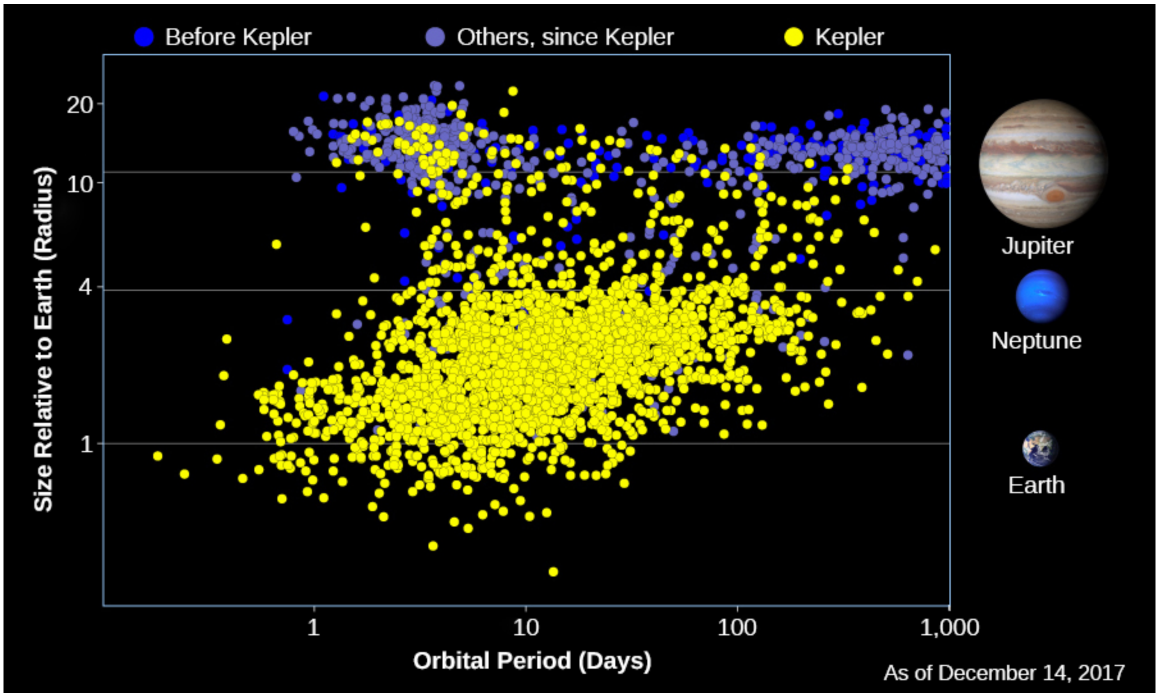

Figure 21.22 Exoplanet Discoveries through 2017. The vertical axis shows the radius of each planet compared to Earth. Horizontal lines show the size of Earth, Neptune, and Jupiter. The horizontal axis shows the time each planet takes to make one orbit (and is given in Earth days). Recall that Mercury takes 88 days and Earth takes a little more than 365 days to orbit the Sun. The yellow dots show planets discovered by the Kepler mission using transits, and the blue dots are the discoveries by other projects and techniques. When this graph was made, astronomers had discovered just over 3,500 exoplanets; as of the start of 2022, that number has risen to roughly 5,000. (credit: modification of work by NASA/Ames Research Center/Jessie Dotson and Wendy Stenzel)

One of the primary objectives of the Kepler mission was to find out how many stars hosted planets and especially to estimate the frequency of earthlike planets. Although Kepler looked at only a very tiny fraction of the stars in the Galaxy, the sample size was large enough to draw some interesting conclusions. While the observations apply only to the stars observed by Kepler, those stars are reasonably representative, and so astronomers can extrapolate to the entire Galaxy.

Figure 21.23 shows that the Kepler discoveries include many rocky, Earth-size planets, far more than Jupiter-size gas planets. This immediately tells us that the initial Doppler discovery of many hot Jupiters was a biased sample, in effect, finding the odd planetary systems because they were the easiest to detect. However, there is one huge difference between this observed size distribution and that of planets in our solar system. The most common planets have radii between 1.4 and 2.8 that of Earth, sizes for which we have no examples in the solar system. These have been nicknamed **super-Earths**, while the other large group with sizes between 2.8 and 4 that of Earth are often called **mini-Neptunes**.

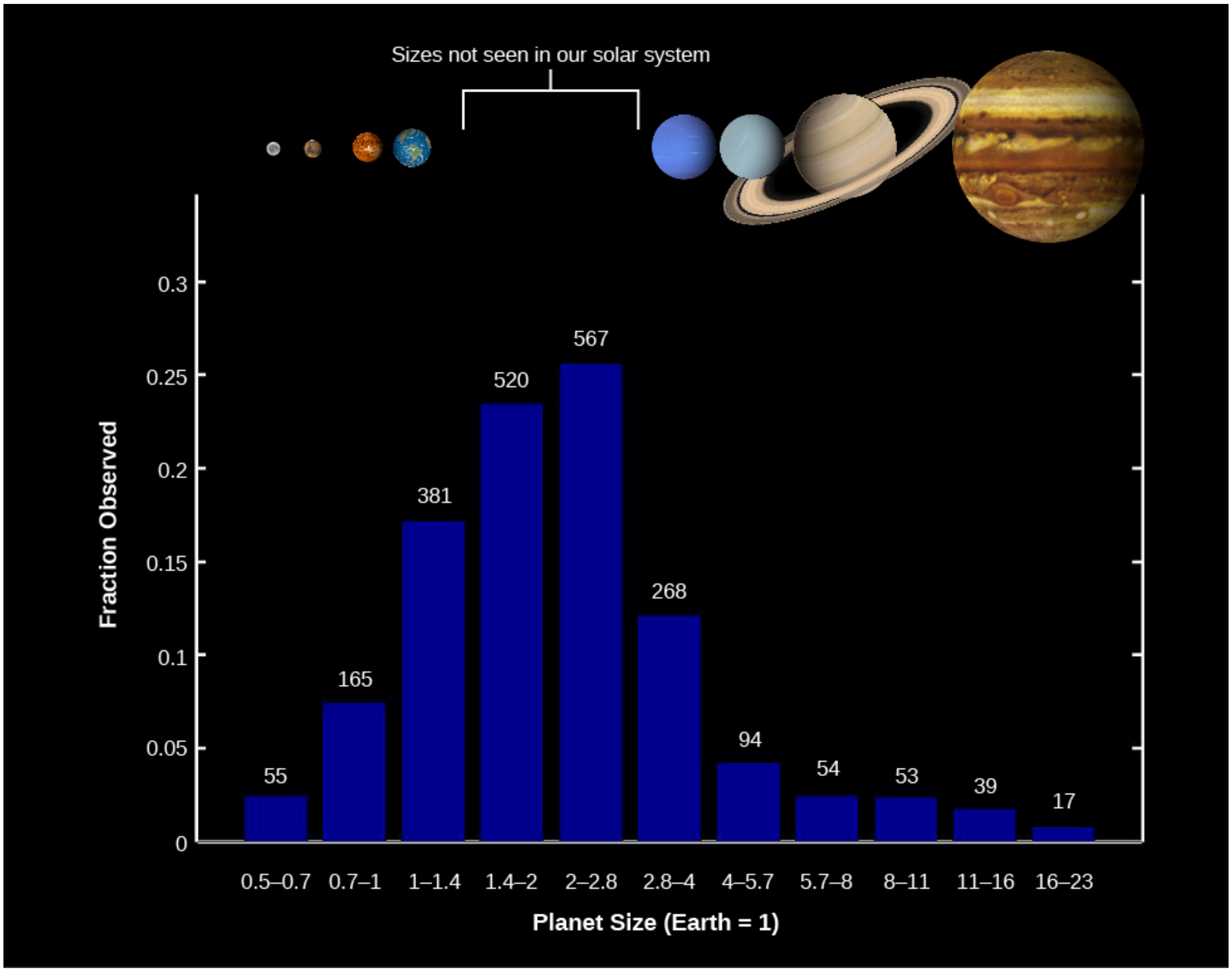

Figure 21.23 Kepler Discoveries. This bar graph shows the number of planets of each size range found among the first 2213 Kepler planet discoveries. Sizes range from half the size of Earth to 20 times that of Earth. On the vertical axis, you can see the fraction that each size range makes up of the total. Note that planets that are between 1.4 and 4 times the size of Earth make up the largest fractions, yet this size range is not represented among the planets in our solar system. (credit: modification of work by NASA/Kepler mission)

What a remarkable discovery it is that the most common types of planets in the Galaxy are completely absent from our solar system and were unknown until Kepler’s survey. However, recall that really small planets were difficult for the Kepler instruments to find. So, to estimate the frequency of Earth-size exoplanets, we need to correct for this sampling bias. The result is the corrected size distribution shown in Figure 21.24. Notice that in this graph, we have also taken the step of showing not the number of Kepler detections but the average number of planets per star for solar-type stars (spectral types F, G, and K).

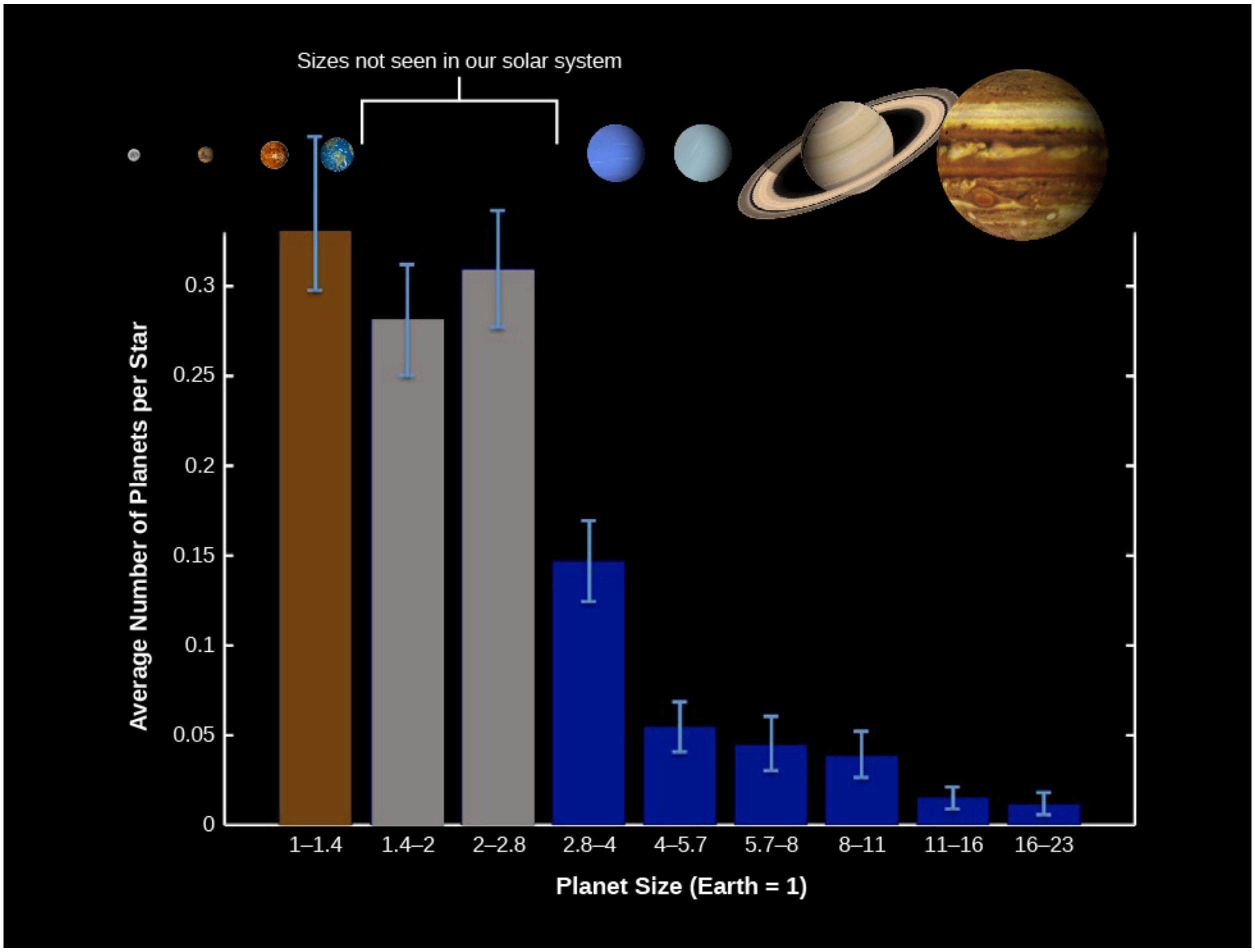

Figure 21.24 Size Distribution of Planets for Stars Similar to the Sun. We show the average number of planets per star in each planet size range. (The average is less than one because some stars will have zero planets of that size range.) This distribution, corrected for biases in the Kepler data, shows that Earth-size planets may actually be the most common type of exoplanets. (credit: modification of work by NASA/Kepler mission)

We see that the most common planet sizes of are those with radii from 1 to 3 times that of Earth—what we have called “Earths” and “super-Earths.” Each group occurs in about one-third to one-quarter of stars. In other words, if we group these sizes together, we can conclude there is nearly one such planet per star! And remember, this census includes primarily planets with orbital periods less than 2 years. We do not yet know how many undiscovered planets might exist at larger distances from their star.

To estimate the number of Earth-size planets in our Galaxy, we need to remember that there are approximately 100 billion stars of spectral types F, G, and K. Therefore, we estimate that there are about 30 billion Earth-size planets in our Galaxy. If we include the super-Earths too, then there could be one hundred billion in the whole Galaxy. This idea—that planets of roughly Earth’s size are so numerous—is surely one of the most important discoveries of modern astronomy.

Planets with Known Densities

For several hundred exoplanets, we have been able to measure both the size of the planet from transit data and its mass from Doppler data, yielding an estimate of its density. Comparing the average density of exoplanets to the density of planets in our solar system helps us understand whether they are rocky or gaseous in nature. This has been particularly important for understanding the structure of the new categories of super-Earths and mini-Neptunes with masses between 3–10 times the mass of Earth. A key observation so far is that planets that are more than 10 times the mass of Earth have substantial gaseous envelopes (like Uranus and Neptune) whereas lower-mass planets are predominately rocky in nature (like the terrestrial planets).

Figure 21.25 compares all the exoplanets that have both mass and radius measurements. The dependence of the radius on planet mass is also shown for a few illustrative cases—hypothetical planets made of pure iron, rock, water, or hydrogen.

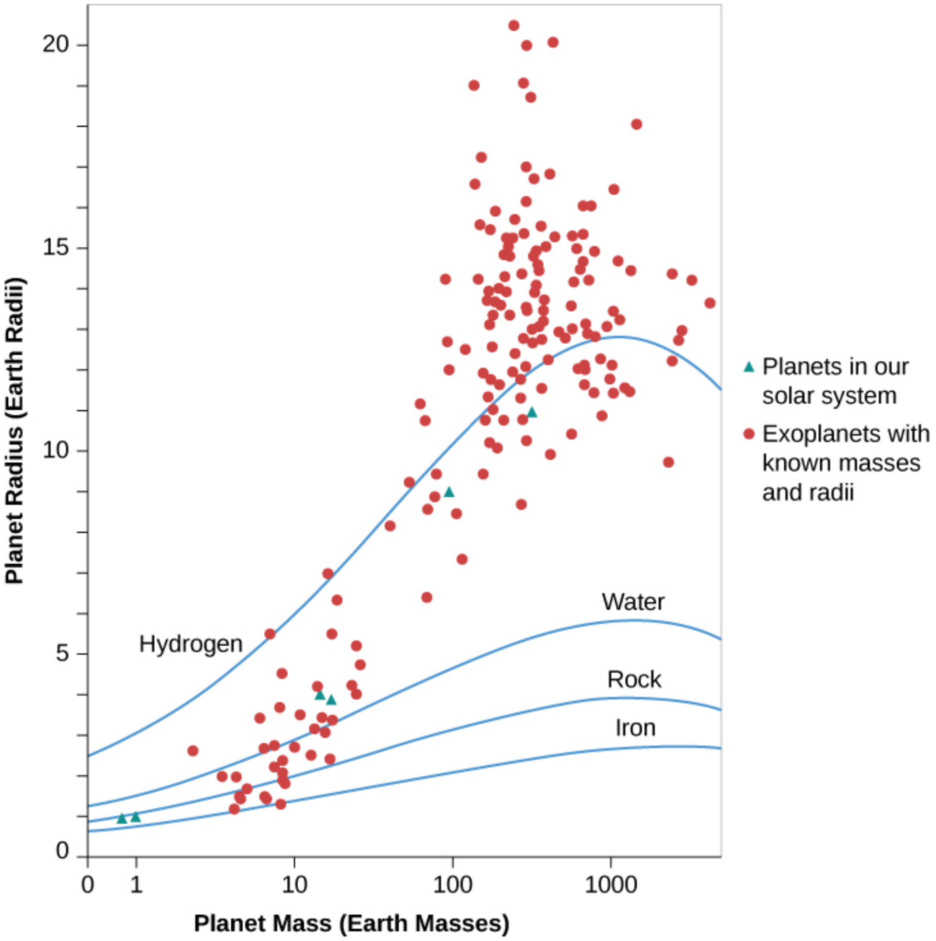

Figure 21.25 Exoplanets with Known Densities. Exoplanets with known masses and radii (red circles) are plotted along with solid lines that show the theoretical size of pure iron, rock, water, and hydrogen planets with increasing mass. Masses are given in multiples of Earth’s mass. (For comparison, Jupiter contains enough mass to make 320 Earths.) The green triangles indicate planets in our solar system.

At lower masses, notice that as the mass of these hypothetical planets increases, the radius also increases. That makes sense—if you were building a model of a planet out of clay, your toy planet would increase in size as you added more clay. However, for the highest mass planets ($M > 1000\ M_{\text{Earth}}$) in Figure 21.25, notice that the radius stops increasing and the planets with greater mass are actually smaller. This occurs because increasing the mass also increases the gravity of the planet, so that compressible materials (even rock is compressible) will become more tightly packed, shrinking the size of the more massive planet.

In reality, planets are not pure compositions like the hypothetical water or iron planet. Earth is composed of a solid iron core, an outer liquid-iron core, a rocky mantle and crust, and a relatively thin atmospheric layer. Exoplanets are similarly likely to be differentiated into compositional layers. The theoretical lines in Figure 21.25 are simply guides that suggest a range of possible compositions.

Astronomers who work on the complex modeling of the interiors of rocky planets make the simplifying assumption that the planet consists of two or three layers. This is not perfect, but it is a reasonable approximation and another good example of how science works. Often, the first step in understanding something new is to narrow down the range of possibilities. This sets the stage for refining and deepening our knowledge. In Figure 21.25, the two green triangles with roughly 1 M_{Earth} and 1 R_{Earth} represent Venus and Earth. Notice that these planets fall between the models for a pure iron and a pure rock planet, consistent with what we would expect for the known mixed-chemical composition of Venus and Earth.

In the case of gaseous planets, the situation is more complex. Hydrogen is the lightest element in the periodic table, yet many of the detected exoplanets in Figure 21.25 with masses greater than 100 M_{Earth} have radii that suggest they are lower in density than a pure hydrogen planet. Hydrogen is the lightest element, so what is happening here? Why do some gas giant planets have inflated radii that are larger than the fictitious pure hydrogen planet? Many of these planets reside in short-period orbits close to the host star where they intercept a significant amount of radiated energy. If this energy is trapped deep in the planet atmosphere, it can cause the planet to expand.

Planets that orbit close to their host stars in slightly eccentric orbits have another source of energy: the star will raise tides in these planets that tend to circularize the orbits. This process also results in tidal dissipation of energy that can inflate the atmosphere. It would be interesting to measure the size of gas giant planets in wider orbits where the planets should be cooler—the expectation is that unless they are very young, these cooler gas giant exoplanets (sometimes called “cold Jupiters”) should not be inflated. But we don’t yet have data on these more distant exoplanets.

Exoplanetary Systems

As we search for exoplanets, we don’t expect to find only one planet per star. Our solar system has eight major planets, half a dozen dwarf planets, and millions of smaller objects orbiting the Sun. The evidence we have of planetary systems in formation also suggest that they are likely to produce multi-planet systems.

The first planetary system was found around the star Upsilon Andromedae in 1999 using the Doppler method, and many others have been found since then. If such exoplanetary system are common, let’s consider which systems we expect to find in the Kepler transit data.

A planet will transit its star only if Earth lies in the plane of the planet’s orbit. If the planets in other systems do not have orbits in the same plane, we are unlikely to see multiple transiting objects. Also, as we have noted before, Kepler was sensitive only to planets with orbital periods less than about 4 years. What we expect from Kepler data, then, is evidence of coplanar planetary systems confined to what would be the realm of the terrestrial planets in our solar system.

By 2022, astronomers gathered data on over 800 such exoplanet systems. Many have only two known planets, but a few have as many as five, and one has eight (the same number of planets as our own solar system). For the most part, these are very compact systems with most of their planets closer to their star than Mercury is to the Sun. The figure below shows one of the largest exoplanet systems: that of the star called Kepler-62 (Figure 21.26). Our solar system is shown to the same scale, for comparison (note that the Kepler-62 planets are drawn with artistic license; we have no detailed images of any exoplanets).

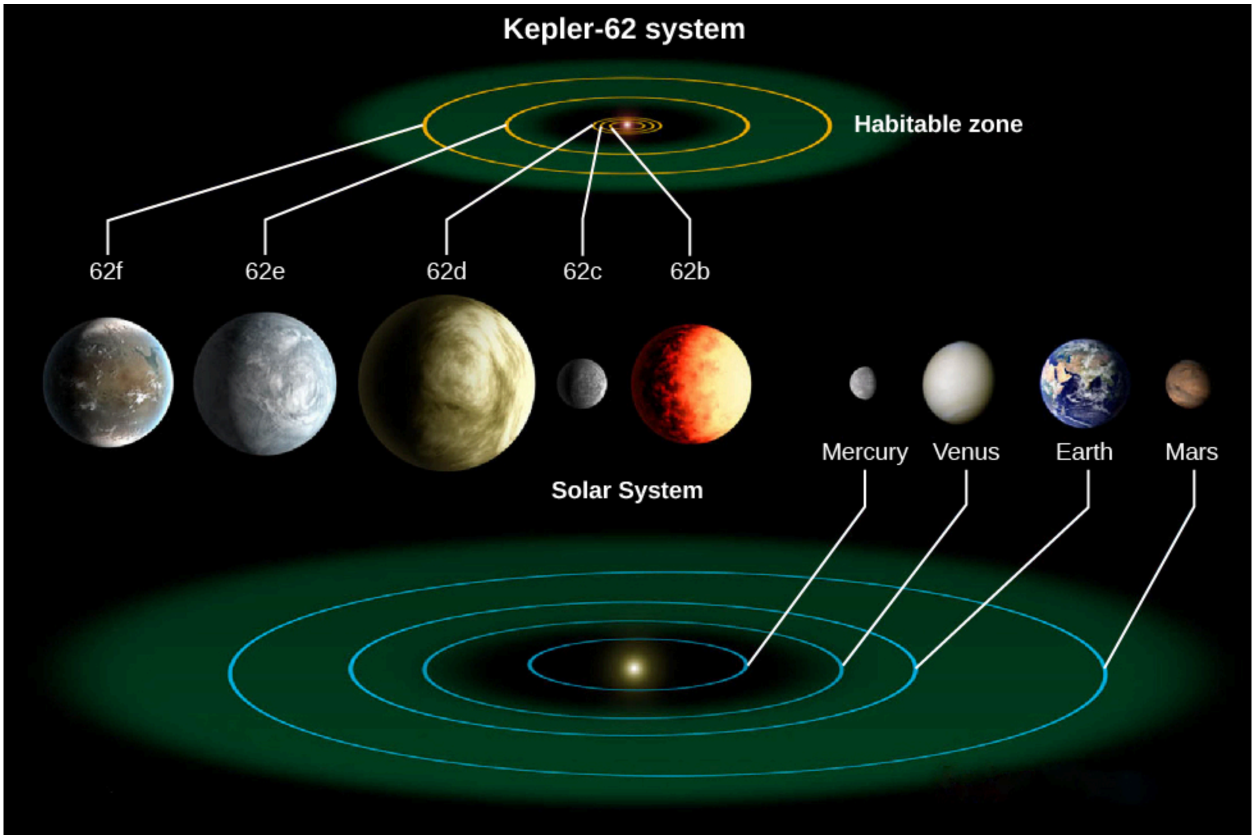

Figure 21.26 Exoplanet System Kepler-62, with the Solar System Shown to the Same Scale. The green areas are the "habitable zones," the range of distance from the star where surface temperatures are likely to be consistent with liquid water. (credit: modification of work by NASA/Ames/JPL-Caltech)

All but one of the planets in the K-62 system are larger than Earth. These are super-Earths, and one of them (62d) is in the size range of a mini-Neptune, where it is likely to be largely gaseous. The smallest planet in this system is about the size of Mars. The three inner planets orbit very close to their star, and only the outer two have orbits larger than Mercury in our system. The green areas represent each star's "habitable zone," which is the distance from the star where we calculate that surface temperatures would be consistent with liquid water. The Kepler-62 habitable zone is much smaller than that of the Sun because the star is intrinsically fainter.

With closely spaced systems like this, the planets can interact gravitationally with each other. The result is that the observed transits occur a few minutes earlier or later than would be predicted from simple orbits. These gravitational interactions have allowed the Kepler scientists to calculate masses for the planets, providing another way to learn about exoplanets.

Kepler has discovered some interesting and unusual planetary systems. For example, most astronomers expected planets to be limited to single stars. But we have found planets orbiting close double stars, so that the planet would see two suns in its sky, like those of the fictional planet Tatooine in the *Star Wars* films. At the opposite extreme, planets can orbit one star of a wide, double-star system without major interference from the second star.

21.6 New Perspectives on Planet Formation

Learning Objectives

By the end of this section, you will be able to:

- Explain how exoplanet discoveries have revised our understanding of planet formation
- Discuss how planetary systems quite different from our solar system might have come about

Traditionally, astronomers have assumed that the planets in our solar system formed at about their current distances from the Sun and have remained there ever since. The first step in the formation of a giant planet is to build up a solid core, which happens when planetesimals collide and stick. Eventually, this core becomes massive enough to begin sweeping up gaseous material in the disk, thereby building the gas giants Jupiter and Saturn.

How to Make a Hot Jupiter

The traditional model for the formation of planets works only if the giant planets are formed far from the central star (about 5–10 AU), where the disk is cold enough to have a fairly high density of solid matter. It cannot explain the hot Jupiters, which are located very close to their stars where any rocky raw material would be completely vaporized. It also cannot explain the elliptical orbits we observe for some exoplanets because the orbit of a protoplanet, whatever its initial shape, will quickly become circular through interactions with the surrounding disk of material and will remain that way as the planet grows by sweeping up additional matter.

So we have two options: either we find a new model for forming planets close to the searing heat of the parent star, or we find a way to change the orbits of planets so that cold Jupiters can travel inward *after* they form. Most research now supports the latter explanation.

Calculations show that if a planet forms while a substantial amount of gas remains in the disk, then some of the planet’s orbital angular momentum can be transferred to the disk. As it loses momentum (through a process that reminds us of the effects of friction), the planet will spiral inward. This process can transport giant planets, initially formed in cold regions of the disk, closer to the central star—thereby producing hot Jupiters. Gravitational interactions between planets in the chaotic early solar system can also cause planets to slingshot inward from large distances. But for this to work, the other planet has to carry away the angular momentum and move to a more distant orbit.

In some cases, we can use the combination of transit plus Doppler measurements to determine whether the planets orbit in the same plane and in the same direction as the star. For the first few cases, things seemed to work just as we anticipated: like the solar system, the gas giant planets orbited in their star’s equatorial plane and in the same direction as the spinning star.

Then, some startling discoveries were made of gas giant planets that orbited at right angles or even in the opposite sense as the spin of the star. How could this happen? Again, there must have been interactions between planets. It’s possible that before the system settled down, two planets came close together, so that one was kicked into an unusual orbit. Or perhaps a passing star perturbed the system after the planets were newly formed.

Forming Planetary Systems

When the Milky Way Galaxy was young, the stars that formed did not contain many heavy elements like iron. Several generations of star formation and star death were required to enrich the interstellar medium for subsequent generations of stars. Since planets seem to form “inside out,” starting with the accretion of the materials that can make the rocky cores with which planets start, astronomers wondered when in the history of the Galaxy, planet formation would turn on.

The star Kepler-444 has shed some light on this question. This is a tightly packed system of five planets—the smallest comparable in size to Mercury and the largest similar in size to Venus. All five planets were detected with the Kepler spacecraft as they transited their parent star. All five planets orbit their host star in less than the time it takes Mercury to complete one orbit about the Sun. Remarkably, the host star Kepler-444 is more than 11 billion years old and formed when the Milky Way was only 2 billion years old. So the heavier elements needed to make rocky planets must have already been available then. This ancient planetary system sets the clock on the beginning of rocky planet formation to be relatively soon after the formation of our Galaxy.

Kepler data demonstrate that while rocky planets inside Mercury’s orbit are missing from our solar system, they are common around other stars, like Kepler-444. When the first systems packed with close-in rocky planets were discovered, we wondered why they were so different from our solar system. When many such systems were discovered, we began to wonder if it was our solar system that was different. This led to speculation that additional rocky planets might once have existed close to the Sun in our solar system.

There is some evidence from the motions in the outer solar system that Jupiter may have migrated inward long ago. If correct, then gravitational perturbations from Jupiter could have dislodged the orbits of close-in rocky planets, causing them to fall into the Sun. Consistent with this picture, astronomers now think that Uranus and Neptune probably did not form at their present distances from the Sun but rather closer to where Jupiter and Saturn are now. The reason for this idea is that density in the disk of matter surrounding the Sun at the time the planets formed was so low outside the orbit of Saturn that it would take several billion years to build up Uranus and Neptune. Yet we saw earlier in the chapter that the disks around protostars survive only a few million years.

Therefore, scientists have developed computer models demonstrating that Uranus and Neptune could have formed near the current locations of Jupiter and Saturn, and then been kicked out to larger distances through gravitational interactions with their neighbors. All these wonderful new observations illustrate how dangerous it can be to draw conclusions about a phenomenon in science (in this case, how planetary systems form and arrange themselves) when you are only working with a single example.

Exoplanets have given rise to a new picture of planetary system formation—one that is much more chaotic than we originally thought. If we think of the planets as being like skaters in a rink, our original model (with only our own solar system as a guide) assumed that the planets behaved like polite skaters, all obeying the rules of the rink and all moving in nearly the same direction, following roughly circular paths. The new picture corresponds more to a roller derby, where the skaters crash into one another, change directions, and sometimes are thrown entirely out of the rink.

Habitable Exoplanets

While thousands of exoplanets have been discovered in the past two decades, every observational technique has fallen short of finding more than a few candidates that resemble Earth (Figure 21.27). Astronomers are not sure exactly what properties would define another Earth. Do we need to find a planet that is *exactly* the same size and mass as Earth? That may be difficult and may not be important from the perspective of habitability. After all, we have no reason to think that life could not have arisen on Earth if our planet had been a little bit smaller or larger. And, remember that how habitable a planet is depends on both its distance from its star and the nature of its atmosphere. The greenhouse effect can make some planets warmer (as it did for Venus and is doing more and more for Earth).

Figure 21.27 Many Earthlike Planets. This painting, commissioned by NASA, conveys the idea that there may be many planets resembling Earth out there as our methods for finding them improve. (credit: NASA/JPL-Caltech/R. Hurt (SSC-Caltech))

We can ask other questions to which we don't yet know the answers. Does this "twin" of Earth need to orbit a solar-type star, or can we consider as candidates the numerous exoplanets orbiting K- and M-class stars? (In the summer of 2016, astronomers reported the discovery of a planet with at least 1.3 times the mass of Earth around the nearest star, Proxima Centauri, which is spectral type M and located 4.2 light years from us.) We have a special interest in finding planets that could support life like ours, in which case, we need to find exoplanets within their star's habitable zone, where surface temperatures are consistent with liquid water on the surface. This is probably the most important characteristic defining an Earth-analog exoplanet.

The search for potentially habitable worlds is one of the prime drivers for exoplanet research in the next decade. Astronomers are beginning to develop realistic plans for new instruments that can even look for signs of life on distant worlds (examining their atmospheres for gases associated with life, for example). If we require telescopes in space to find such worlds, we need to recognize that years are required to plan, build, and launch such space observatories. The discovery of exoplanets and the knowledge that most stars have planetary systems are transforming our thinking about life beyond Earth. We are closer than ever to knowing whether habitable (and inhabited) planets are common. This work lends a new spirit of optimism to the search for life elsewhere, a subject to which we will return in Life in the Universe.

Key Terms

exoplanet	a planet orbiting a star other than our Sun
giant molecular clouds	large, cold interstellar clouds with diameters of dozens of light-years and typical masses of 10^5 solar masses; found in the spiral arms of galaxies, these clouds are where stars form
Herbig-Haro (HH) object	luminous knots of gas in an area of star formation that are set to glow by jets of material from a protostar
mini-Neptune	a planet that is intermediate between the largest terrestrial planet in our solar system (Earth) and the smallest jovian planet (Neptune); generally, mini-Neptunes have sizes between 2.8 and 4 times Earth’s size
protostar	a very young star still in the process of formation, before nuclear fusion begins
stellar wind	the outflow of gas, sometimes at speeds as high as hundreds of kilometers per second, from a star
super-Earth	a planet larger than Earth, generally between 1.4 and 2.8 times the size of our planet
transit	when one astronomical object moves in front of another

Summary

21.1 Star Formation

Most stars form in giant molecular clouds with masses as large as 3×10^6 solar masses. The most well-studied molecular cloud is Orion, where star formation is currently taking place. Molecular clouds typically contain regions of higher density called clumps, which in turn contain several even-denser cores of gas and dust, each of which may become a star. A star can form inside a core if its density is high enough that gravity can overwhelm the internal pressure and cause the gas and dust to collapse. The accumulation of material halts when a protostar develops a strong stellar wind, leading to jets of material being observed coming from the star. These jets of material can collide with the material around the star and produce regions that emit light that are known as Herbig-Haro objects.

21.2 The H–R Diagram and the Study of Stellar Evolution

The evolution of a star can be described in terms of changes in its temperature and luminosity, which can best be followed by plotting them on an H–R diagram. Protostars generate energy (and internal heat) through gravitational contraction that typically continues for millions of years, until the star reaches the main sequence.

21.3 Evidence That Planets Form around Other Stars

Observational evidence shows that most protostars are surrounded by disks with large-enough diameters and enough mass (as much as 10% that of the Sun) to form planets. After a few million years, the inner part of the disk is cleared of dust, and the disk is then shaped like a donut with the protostar centered in the hole—something that can be explained by the formation of planets in that inner zone. Around a few older stars, we see disks formed from the debris produced when small bodies (comets and asteroids) collide with each other. The distribution of material in the rings of debris disks is probably determined by shepherd planets, just as Saturn’s shepherd moons affect the orbits of the material in its rings. Protoplanets that grow to be 10 times the mass of Earth or bigger while there is still considerable gas in their disk can then capture more of that gas and become giant planets like Jupiter in the solar system.

21.4 Planets beyond the Solar System: Search and Discovery

Several observational techniques have successfully detected planets orbiting other stars. These techniques fall into two general categories—direct and indirect detection. The Doppler and transit techniques are our most powerful indirect tools for finding exoplanets. Some planets are also being found by direct imaging.

21.5 Exoplanets Everywhere: What We Are Learning

Although the Kepler mission is finding thousands of new exoplanets, these are limited to orbital periods of less than 400 days and sizes larger than Mars. Still, we can use the Kepler discoveries to extrapolate the distribution of planets in our Galaxy. The data so far imply that planets like Earth are the most common type of planet, and that there may be 100 billion Earth-size planets around Sun-like stars in the Galaxy. More than 800 planetary systems have been discovered around other stars. In many of them, planets are arranged differently than in our solar system.

21.6 New Perspectives on Planet Formation

The ensemble of exoplanets is incredibly diverse and has led to a revision in our understanding of planet formation that includes the possibility of vigorous, chaotic interactions, with planet migration and scattering. It is possible that the solar system is unusual (and not representative) in how its planets are arranged. Many systems seem to have rocky planets farther inward than we do, for example, and some even have "hot Jupiters" very close to their star. Ambitious space experiments should make it possible to image earthlike planets outside the solar system and even to obtain information about their habitability as we search for life elsewhere.

For Further Exploration

Articles

Star Formation

Blaes, O. "A Universe of Disks." *Scientific American* (October 2004): 48. On accretion disks and jets around young stars and black holes.

Croswell, K. "The Dust Belt Next Door [Tau Ceti]." *Scientific American* (January 2015): 24. Short intro to recent observations of planets and a wide dust belt.

Frank, A. "Starmaker: The New Story of Stellar Birth." *Astronomy* (July 1996): 52.

Jayawardhana, R. "Spying on Stellar Nurseries." *Astronomy* (November 1998): 62. On protoplanetary disks.

O'Dell, C. R. "Exploring the Orion Nebula." *Sky & Telescope* (December 1994): 20. Good review with Hubble results.

Ray, T. "Fountains of Youth: Early Days in the Life of a Star." *Scientific American* (August 2000): 42. On outflows from young stars.

Young, E. "Cloudy with a Chance of Stars." *Scientific American* (February 2010): 34. On how clouds of interstellar matter turn into star systems.

Young, Monica "Making Massive Stars." *Sky & Telescope* (October 2015): 24. Models and observations on how the most massive stars form.

Exoplanets

Billings, L. "In Search of Alien Jupiters." *Scientific American* (August 2015): 40–47. The race to image jovian planets with current instruments and why a direct image of a terrestrial planet is still in the future.

Heller, R. "Better Than Earth." *Scientific American* (January 2015): 32–39. What kinds of planets may be habitable; super-Earths and jovian planet moons should also be considered.

Laughlin, G. "How Worlds Get Out of Whack." *Sky & Telescope* (May 2013): 26. On how planets can migrate from the places they form in a star system.

Marcy, G. "The New Search for Distant Planets." *Astronomy* (October 2006): 30. Fine brief overview. (The same

issue has a dramatic fold-out visual atlas of extrasolar planets, from that era.)

Redd, N. “Why Haven’t We Found Another Earth?” *Astronomy* (February 2016): 25. Looking for terrestrial planets in the habitable zone with evidence of life.

Seager, S. “Exoplanets Everywhere.” *Sky & Telescope* (August 2013): 18. An excellent discussion of some of the frequently asked questions about the nature and arrangement of planets out there.

Seager, S. “The Hunt for Super-Earths.” *Sky & Telescope* (October 2010): 30. The search for planets that are up to 10 times the mass of Earth and what they can teach us.

Villard, R. “Hunting for Earthlike Planets.” *Astronomy* (April 2011): 28. How we expect to find and characterize super-Earth (planets somewhat bigger than ours) using new instruments and techniques that could show us what their atmospheres are made of.

Websites

Exoplanet Exploration: http://planetquest.jpl.nasa.gov/ (http://planetquest.jpl.nasa.gov/). PlanetQuest (from the Navigator Program at the Jet Propulsion Lab) is probably the best site for students and beginners, with introductory materials and nice illustrations; it focuses mostly on NASA work and missions.

Exoplanets: http://www.planetary.org/exoplanets/ (http://www.planetary.org/exoplanets/). Planetary Society’s exoplanets pages with a dynamic catalog of planets found and good explanations.

Extrasolar Planets Encyclopedia: http://exoplanet.eu/ (http://exoplanet.eu/). Maintained by Jean Schneider of the Paris Observatory, has the largest catalog of planet discoveries and useful background material (some of it more technical).

Formation of Stars: https://www.spacetelescope.org/science/formation_of_stars/ (https://www.spacetelescope.org/science/formation_of_stars/). Star Formation page from the Hubble Space Telescope, with links to images and information.

Kepler Mission: https://www.nasa.gov/mission_pages/kepler/overview/index.html (https://www.nasa.gov/mission_pages/kepler/overview/index.html). The public website for the remarkable telescope in space that is searching planets using the transit technique and is our best hope for finding earthlike planets.

NASA Exoplanet Exploration Dashboard: https://exoplanets.nasa.gov/discovery/discoveries-dashboard/ (https://exoplanets.nasa.gov/discovery/discoveries-dashboard/). A handy place to find up-to-date information of exoplanet discoveries. This page is a summary of all discoveries by method and type. One click takes you to the full exoplanet catalog.

Proxima Centauri Planet Discovery: http://www.eso.org/public/news/eso1629/ (http://www.eso.org/public/news/eso1629/).

Apps

Exoplanet: http://exoplanetapp.com/ (http://exoplanetapp.com/). Allows you to browse through a regularly updated visual catalog of exoplanets that have been found so far.

Videos

A Star Is Born: https://www.youtube.com/watch?v=mkktE_fs4NA (https://www.youtube.com/watch?v=mkktE_fs4NA). Discovery Channel video with astronomer Michelle Thaller (2:25).

Are We Alone: An Evening Dialogue with the Kepler Mission Leaders: http://www.youtube.com/watch?v=O7ItAXfl0Lw (http://www.youtube.com/watch?v=O7ItAXfl0Lw). A non-technical panel discussion on Kepler results and ideas about planet formation with Bill Borucki, Natalie Batalha, and Gibor Basri (moderated by Andrew Fraknoi) at the University of California, Berkeley (2:07:01).

Finding the Next Earth: The Latest Results from Kepler: https://www.youtube.com/watch?v=ZbijeR_AALo (https://www.youtube.com/watch?v=ZbijeR_AALo). Natalie Batalha (San Jose State University & NASA Ames) public talk in the Silicon Valley Astronomy Lecture Series (1:28:38).

From Hot Jupiters to Habitable Worlds: https://vimeo.com/37696087 (https://vimeo.com/37696087) (Part 1) and https://vimeo.com/37700700 (https://vimeo.com/37700700) (Part 2). Debra Fischer (Yale University) public talk in Hawaii sponsored by the Keck Observatory (15:20 Part 1, 21:32 Part 2).

Search for Habitable Exoplanets: http://www.youtube.com/watch?v=RLWb_T9yaDU (http://www.youtube.com/watch?v=RLWb_T9yaDU). Sara Seeger (MIT) public talk at the SETI Institute, with Kepler results (1:10:35).

Collaborative Group Activities

A. Your group is a subcommittee of scientists examining whether any of the “hot Jupiters” (giant planets closer to their stars than Mercury is to the Sun) could have life on or near them. Can you come up with places on, in, or near such planets where life could develop or where some forms of life might survive?

B. A wealthy couple (who are alumni of your college or university and love babies) leaves the astronomy program several million dollars in their will, to spend in the best way possible to search for “infant stars in our section of the Galaxy.” Your group has been assigned the task of advising the dean on how best to spend the money. What kind of instruments and search programs would you recommend, and why?

C. Some people consider the discovery of any planets (even hot Jupiters) around other stars one of the most important events in the history of astronomical research. Some astronomers have been surprised that the public is not more excited about the planet discoveries. One reason that has been suggested for this lack of public surprise and excitement is that science fiction stories have long prepared us for there being planets around other stars. (The Starship Enterprise on the 1960s *Star Trek* TV series found some in just about every weekly episode.) What does your group think? Did you know about the discovery of planets around other stars before taking this course? Do you consider it exciting? Were you surprised to hear about it? Are science fiction movies and books good or bad tools for astronomy education in general, do you think?

D. What if future space instruments reveal an earthlike exoplanet with significant amounts of oxygen and methane in its atmosphere? Suppose the planet and its star are 50 light-years away. What does your group suggest astronomers do next? How much effort and money would you recommend be put into finding out more about this planet and why?

E. Discuss with your group the following question: which is easier to find orbiting a star with instruments we have today: a jovian planet or a proto-planetary disk? Make a list of arguments for each side of this question.

F. (This activity should be done when your group has access to the internet.) Go to the page which indexes all the publicly released Hubble Space Telescope images by subject: http://hubblesite.org/newscenter/archive/browse/image/. Under “Star,” go to “Protoplanetary Disk” and find a system—not mentioned in this chapter—that your group likes, and prepare a short report to the class about why you find it interesting. Then, under “Nebula,” go to “Emission” and find a region of star formation not mentioned in this chapter, and prepare a short report to the class about what you find interesting about it.

G. There is a “citizen science” website called Planet Hunters (http://www.planethunters.org/) where you can participate in identifying exoplanets from the data that Kepler provided. Your group should access the site, work together to use it, and classify two light curves. Report back to the class on what you have done.

H. Yuri Milner, a Russian-American billionaire, recently pledged $100 million to develop the technology to send many miniaturized probes to a star in the Alpha Centauri triple star system (which includes Proxima Centauri, the nearest star to us, now known to have at least one planet.) Each tiny probe will be propelled by powerful lasers at 20% the speed of light, in the hope that one or more might arrive safely and be able to send back information about what it’s like there. Your group should search online for more information about this project (called “Breakthrough: Starshot”) and discuss your reactions to this project. Give specific reasons for your arguments.

Exercises

Review Questions

1. Give several reasons the Orion molecular cloud is such a useful “laboratory” for studying the stages of star formation.
2. Why is star formation more likely to occur in cold molecular clouds than in regions where the temperature of the interstellar medium is several hundred thousand degrees?
3. Why have we learned a lot about star formation since the invention of detectors sensitive to infrared radiation?
4. Describe what happens when a star forms. Begin with a dense core of material in a molecular cloud and trace the evolution up to the time the newly formed star reaches the main sequence.
5. Describe how the T Tauri star stage in the life of a low-mass star can lead to the formation of a Herbig-Haro (H-H) object.
6. Look at the four stages shown in Figure 21.8. In which stage(s) can we see the star in visible light? In infrared radiation?
7. The evolutionary track for a star of 1 solar mass remains nearly vertical in the H–R diagram for a while (see Figure 21.12). How is its luminosity changing during this time? Its temperature? Its radius?
8. Two protostars, one 10 times the mass of the Sun and one half the mass of the Sun are born at the same time in a molecular cloud. Which one will be first to reach the main sequence stage, where it is stable and getting energy from fusion?
9. Compare the scale (size) of a typical dusty disk around a forming star with the scale of our solar system.
10. Why is it so hard to see planets around other stars and so easy to see them around our own?
11. Why did it take astronomers until 1995 to discover the first exoplanet orbiting another star like the Sun?
12. Which types of planets are most easily detected by Doppler measurements? By transits?
13. List three ways in which the exoplanets we have detected have been found to be different from planets in our solar system.
14. List any similarities between discovered exoplanets and planets in our solar system.
15. What revisions to the theory of planet formation have astronomers had to make as a result of the discovery of exoplanets?
16. Why are young Jupiters easier to see with direct imaging than old Jupiters?

Thought Questions

17. A friend of yours who did not do well in her astronomy class tells you that she believes all stars are old and none could possibly be born today. What arguments would you use to persuade her that stars are being born somewhere in the Galaxy during your lifetime?

18. Observations suggest that it takes more than 3 million years for the dust to begin clearing out of the inner regions of the disks surrounding protostars. Suppose this is the minimum time required to form a planet. Would you expect to find a planet around a 10-M_{Sun} star? (Refer to Figure 21.12.)

19. Suppose you wanted to observe a planet around another star with direct imaging. Would you try to observe in visible light or in the infrared? Why? Would the planet be easier to see if it were at 1 AU or 5 AU from its star?

20. Why were giant planets close to their stars the first ones to be discovered? Why has the same technique not been used yet to discover giant planets at the distance of Saturn?

21. Exoplanets in eccentric orbits experience large temperature swings during their orbits. Suppose you had to plan for a mission to such a planet. Based on Kepler's second law, does the planet spend more time closer or farther from the star? Explain.

Figuring for Yourself

22. When astronomers found the first giant planets with orbits of only a few days, they did not know whether those planets were gaseous and liquid like Jupiter or rocky like Mercury. The observations of HD 209458 settled this question because observations of the transit of the star by this planet made it possible to determine the radius of the planet. Use the data given in the text to estimate the density of this planet, and then use that information to explain why it must be a gas giant.

23. An exoplanetary system has two known planets. Planet X orbits in 290 days and Planet Y orbits in 145 days. Which planet is closest to its host star? If the star has the same mass as the Sun, what is the semi-major axis of the orbits for Planets X and Y?

24. Kepler's third law says that the orbital period (in years) is proportional to the square root of the cube of the mean distance (in AU) from the Sun ($P \propto a^{1.5}$). For mean distances from 0.1 to 32 AU, calculate and plot a curve showing the expected Keplerian period. For each planet in our solar system, look up the mean distance from the Sun in AU and the orbital period in years and overplot these data on the theoretical Keplerian curve.

25. Calculate the transit depth for an M dwarf star that is 0.3 times the radius of the Sun with a gas giant planet the size of Jupiter.

26. If a transit depth of 0.00001 can be detected with the Kepler spacecraft, what is the smallest planet that could be detected around a 0.3 R_{sun} M dwarf star?

27. What fraction of gas giant planets seems to have inflated radii?