**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](https://openstax.org/books/astronomy/pages/21-1-star-formation#OSC_Astro_21_01_Orion)). 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.

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](https://openstax.org/books/astronomy/pages/3-thinking-ahead).)

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 (

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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](https://openstax.org/books/astronomy/pages/21-2-the-h-r-diagram-and-the-study-of-stellar-evolution#OSC_Astro_21_02_Track). 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

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](https://openstax.org/books/astronomy/pages/21-3-evidence-that-planets-form-around-other-stars#OSC_Astro_21_03_DRing)). 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.

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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](https://openstax.org/books/astronomy/pages/21-2-the-h-r-diagram-and-the-study-of-stellar-evolution#OSC_Astro_21_02_Track). 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](https://openstax.org/books/astronomy/pages/21-2-the-h-r-diagram-and-the-study-of-stellar-evolution#OSC_Astro_21_02_Track)).

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](https://openstax.org/books/astronomy/pages/18-thinking-ahead)). 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](https://openstax.org/books/astronomy/pages/21-2-the-h-r-diagram-and-the-study-of-stellar-evolution#OSC_Astro_21_02_Track) 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](https://openstax.org/books/astronomy/pages/17-thinking-ahead), 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.