# 5.3: Change Over Time- Evolution of Stars

**What Do You Think: Change**

In this chapter, we have discussed how we measure ages of objects in the night sky. Another thing we want to know about objects like stars and galaxies is whether they evolve or change over time. After all, it would be nice to know if the Sun will change in the near future, and if so, whether it will affect us. Similarly, we would like to know if our Galaxy, the Milky Way, has changed or will be changing. And what about changes in the Universe itself? It turns out that we can learn a lot about how the Sun and the Milky Way have evolved and continue to evolve by comparing them to observations of other stars and galaxies. Similarly, we can learn about the Universe's evolution through our observations of the objects—stars and galaxies—within it.

## 5.3.1: Formation of Stars

Stars form when clouds of gas and dust collapse due to gravity. In our Galaxy, we observe these large clouds as nebulae, and we often observe star-forming regions within them (Figure 5.4). The clouds are supported by the motions of the gas inside them, but if they become too massive or if they get disturbed (say, by colliding with another gas cloud), the resulting compression will allow gravity will take over in the most dense regions. The gas in those regions will begin to collapse and fragment. Eventually, gravitational compression in the densest fragments can cause heating to the point that nuclear fusion begins. A star is born.

Figure 5.4: The Orion Nebula, as seen by Hubble Space Telescope, is a vibrant star-forming region of space. Credit: NASA/STScI/Hubble Space Telescope

As a star-forming cloud becomes more compact, it spins faster, like an ice-skater tucking in her arms (Animated Figure 5.5). It also flattens into a disk. The center of the disk becomes very hot and dense and forms a star, while at the same time, solid particles condense, growing into larger pieces, eventually forming planets and other objects.

An ice skater spins (video link).

Animated Figure 5.5: When the ice-skater pulls her arms in, she increases the rate at which she spins. When she throws her arms out, her spin rate slows down. A similar thing happens in a star-forming nebula. As the cloud contracts in size due to gravity, it spins faster. Credit: Shutterstock.com

The process to form gas giant planets is thought only to occur in the outer part of the pre-stellar disk where temperatures are cold and the amount of gas available is high. Terrestrial planets are thought to form closer to the star.

First, consider the area of a region of a disk at large radius, shown in green in Figure 5.6. Compare it to the area available in the inner parts of the disk, shown in white and blue. The outer part contains much more area, and thus, there is much more material there to form planets. Furthermore, the warmer temperatures in the inner disk (caused by the proximity to the forming star) prevent the lightest elements from condensing into solids in that region.

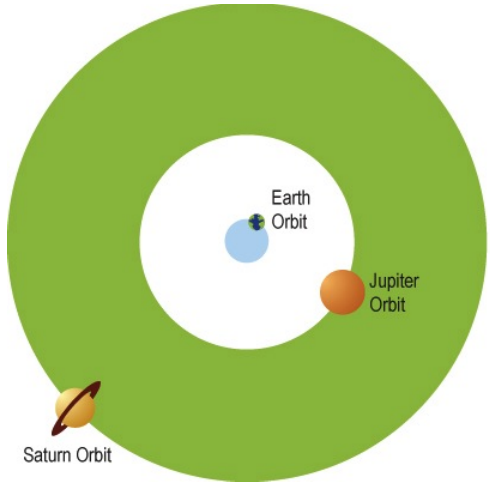


Figure 5.6: More area in the outer Solar System means bigger planets form there. Credit: NASA/SSU/Aurore Simonnet

At higher temperatures, light gases like hydrogen and helium have a lot of energy and are moving too fast to clump together. Only heavier materials, rock-forming silicates and metals, can condense and clump together at the location of the terrestrial planets. The lighter gases only begin to condense in areas with much lower temperatures. This is the outer part of the disk, where temperatures are colder than the freezing point of water. Much colder.

At low temperatures, the gases have less energy and can clump together into solids. As the solids grow, they begin to accumulate the abundantly available hydrogen and helium gas. And as the gases build up, the masses of the forming planets grow. And grow. The resulting stronger gravitational pull from all this mass accumulation allows them to grow ever faster, boosting their gravity further. This positive feedback creates a runaway growth period that only ends when they have gobbled up all the available gas. This is how they become enormous.

Conditions in the inner parts of the star-forming disk do not allow giant planets to form. Conditions are too warm to allow them planets to accumulate large amounts of gas, and there is not very much material available in the inner disk to form planets in the first place. Only, smaller, terrestrial planets can form.

In the inner disk, whatever lighter materials are present, like water, carbon dioxide, methane, ammonia, and others, all remain in the gas phase. Since planets, even gas giants, start forming from the accumulation of solid bodies (rocks), the planets formed in the inner disk tend to be rocky, with only small amounts of light and volatile compounds like water and carbon dioxide. The outer gas giant planets do have rocky cores, but these are buried by the far more abundant lighter gases.

This star/planet formation scenario has a lot of explanatory power. For instance, it easily accounts for the fact that the Sun and planets all rotate in the same direction, because they must all reflect the rotation of the cloud from which they collapsed. In the same way, it naturally describes why all the planets orbit the Sun in the same plane and in the same direction. However, there are some aspects of the Solar System that require other processes to have been at work. For instance, the rotation axis of the planet Uranus is tilted approximately 90 degrees. But we also know that toward the end of the planet-forming process, 4.5 billion years ago, there were many collisions of large bodies. We see evidence of large collisions on the Moon, and these date from that epoch—there is even strong evidence that the Moon itself was formed when a Mars-sized object impacted with the proto-Earth. The large amounts of ejecta blasted into orbit by the collision provided the material that coalesced into the Moon. In addition, the light molecules like water and carbon dioxide that are found in the inner planets could plausibly have been delivered late in their formation, as comets from the outer Solar System impacted with the inner bodies, enriching them with these materials.

The star-formation process is generally understood, though some details must still be worked out. One of the aspects that still puzzles astronomers is how the clouds break up into a number of different stars of different sizes instead of just a single star, or a few very large stars. The reasons probably have to do with turbulent flows within the clouds and angular momentum conservation during the collapse process.

Angular momentum relates to the tendency of spinning objects to continue spinning with a constant spin rate and orientation: It is difficult to either speed up or slow down a spinning object or to change the direction of its axis of rotation. You can test this with a bicycle wheel. Even at low speeds, you will notice the wheel's reluctance to be tipped over, and the faster the wheel spins, the harder it is to tip. This is the same phenomenon that keeps a top from tipping over. You might have also noticed that if you shrink a spinning object, it tends to spin faster, and if you expand it, it will tend to spin more slowly. These are all illustrations of the principle of conservation of angular momentum.

Angular momentum helps support vast clouds of gas against gravitational collapse, and the clouds must overcome this support before they are able to collapse to form stars. However, since total angular momentum must remain constant, a cloud must form stars in a way that allows most of its mass to collapse to relatively tiny objects, while preserving the angular momentum of the whole. Normally, the objects would spin up to very fast rotation rates as they collapsed. These fast rotation rates would halt further collapse at some point. The clouds overcome this through internal collisions in which some of their gas gains energy and angular momentum and moves outward, while the remainder and vast majority of material loses energy and angular momentum and moves inward. As this happens, the clouds tend to flatten into a disk. Most of the material spirals in toward the center of the disk, while all of the angular momentum is contained in a tiny amount of mass that is flung out to large radii through random collisions. Such disks, in which matter is transferred inward as angular momentum is transferred outward, are called accretion disks. They are seen in many different astrophysical settings.

As the disks form, they break up further into smaller rotating vortices. These are really just small disks within the large disks. At the very center of the large disks, stars are formed (Figure 5.7). At the centers of the smaller vortices, gas giant planets like Jupiter and Saturn form. And on still smaller scales, even smaller vortices form the moons around gas giants.

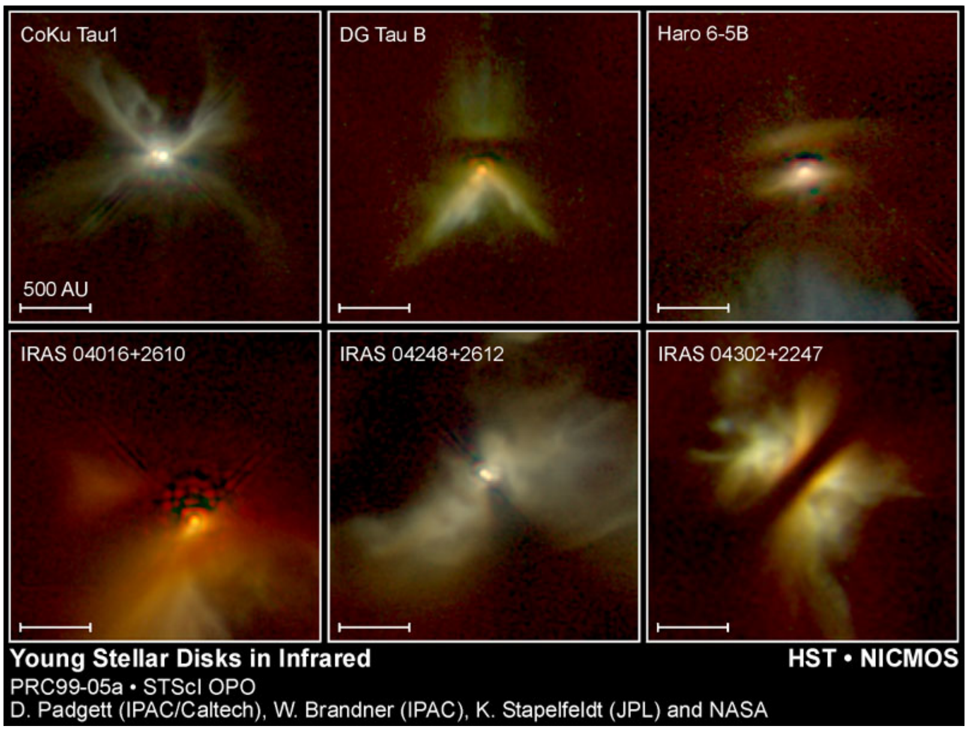


Figure 5.7: Viewed in infrared, six star-forming disks of young stars, some of which may also lead to the creation of companion planets. Credit: NASA/STScI/Hubble Space Telescope

Another result of star formation seems to be the production of high-speed outflows, and even narrow jets of material. These are seen in the later stages of star formation. Molecular CO is seen to be rushing outward from young stellar systems. The outflowing gas has a conical shape and is centered on the rotational axis of the protoplanetary disk. It flows out in both directions perpendicular to the disk. In so-called T-Tauri stars, the outflows are in the form of narrow jets that move at several hundred kilometers per second (Figure 5.8). These jets extend hundreds of light-years from the star, and their termination shocks form nebulosities called Herbig-Haro objects, named after the two astronomers who first studied them.

The causes for outflows from newly formed or forming stars is still not understood. Nor are all the details of the planet-formation process. But, in the past decade, astronomers have begun to catalog hundreds of stars besides the Sun that have planetary companions. We expect our studies of these systems to give us a better picture of how stars and planets form.

We will see the themes of accretion disks and outflowing jets (Figure 5.9) repeated several times in several different contexts throughout the modules.

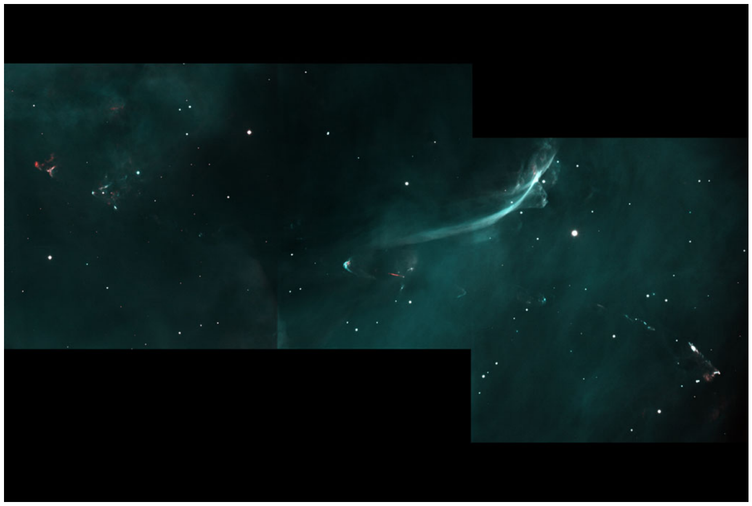

Figure 5.8: Image of outflows from a T-Tauri stars, HH34. Credit: John Bally (CASA, U Colorado, Boulder), Bo Reipurth (IfA, U Hawaii, Hilo), and ESO/NTT

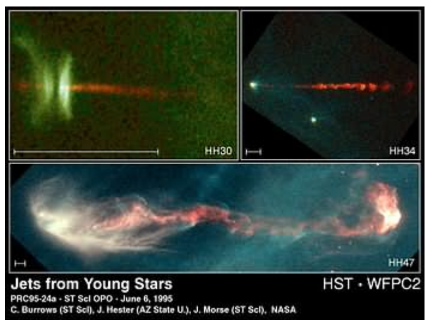


Figure 5.9: As stars form, they can produce jets, expulsions of accreted materials along their magnetic poles, which are perpendicular to their disks. Credit: NASA/STScI/Hubble Space Telescope

### Orion Nebula Fly-through

Play this video to take a voyage through the Orion Nebula, a nearby star-forming region. It uses volume visualization to combine images and measured distances to create a three-dimensional fly-through experience.

- As the fly-through approaches the nebula, you will see the hot, bright stars that light up the gases in the nebula. Their radiation hollows out the space in the center.
- Next, the fly-through will pass by some tear-drop-shaped objects; these are young solar systems in the process of being formed.
- Then, we zoom in on one of these objects; you can see the accretion disk and jets.

This video contains no audio. Credit: Greg Bacon (STScI), model based on data by C.R. O'Dell (Vanderbilt University), and The American Museum of Natural History/Rose Center for Earth and Space. Video link.

Now answer the following questions:

1.

2.

## 5.3.2: Death of Stars Like the Sun

Stars create energy and light through nuclear fusion. At the centers of stars like the Sun, there is so much heat and pressure due to gravity that the nuclei of hydrogen atoms fuse together and create helium nuclei (plus a lot of energy). What happens when the Sun runs out of hydrogen? And what happens in other stars?

In all stars, two major forces are at play: (1) pressure due to gravity, which pushes in toward the center of the star, and (2) pressure due to heat, which pushes outward. As we discussed previously, in main sequence stars, these two forces are in balance, so that the star does not collapse due to too much gravitational pull or fly apart due to too much thermal pressure outward. This “balanced” phase in a star’s lifetime can last for billions of years. But, when the star eventually runs out of hydrogen at its center, there is nothing more to fuse together. Without the energy from nuclear fusion, the temperature drops and there is less outward pressure as a result. The center of the star collapses inward due to gravity, causing this inner region to heat up once again. A thin shell of hydrogen gas outside the star’s core begins fusion into helium. Pressure related to these fusion reactions pushes the outer layers of the star’s gas even further outward, so that the star expands and its outer layers cool down. The star appears red (cool outer layers) and large, and very bright due to the fusion in the hydrogen shell. At this point in its lifetime, the star is called a red giant. Red giant stars are bright and cool, so they can be found in the upper-right portion of the H-R diagram.

During the red giant phase, the very center of the star continues to collapse and heat up so that helium nuclei begin to fuse into carbon. When the helium in the star’s core is used up, the core again collapses, causing it to heat up. A thin shell of helium around the core begins fusion, with a shell of fusing hydrogen lying just outside that. Again the star expands, its surface cools, and the star brightens.

However, for a star with a mass like that of the Sun, the core does not continue to contract. The carbon core of the star is already so compressed that the star’s gravity cannot push it significantly further inward (it only compresses a little bit and then stops). Instead, the electrons become so compressed that they hold up the carbon core against further gravitational contraction. The hydrogen and helium shells around the carbon core continue fusion but become unstable, and the outer layers of gas around the star are eventually pushed away forming a planetary nebula (Figure 5.10). The small, hot carbon core of the star is called a white dwarf. Over time, white dwarfs cool and fade until we can no longer observe them. White dwarfs are dim, lying below the main sequence, but they are quite hot, so they are found below and to the left of the main sequence (Figure 5.10).

Figure 5.10: At only 2,000 light-years away, the Spirograph Nebula is a planetary nebula spanning less than half a light-year in diameter. At its core is a white dwarf. Credit: NASA/STScI

How do we know the Sun's fate is to turn into a red giant and then a white dwarf, and when will this happen? Astronomers investigate how the Sun will change over time by observing the basic properties of other stars, including their color, brightness, size, and mass. They also determine the stars' ages. They can look at stars that have similar mass to the Sun and see how their properties are similar to or different from the Sun's, and how these things depend on their age. From these observations, astronomers gain clues about what the Sun looked like in the past and what it might look like in the future. Astronomers also compare their observations to our understanding of processes like nuclear fusion that occur at the centers of stars.

On the basis of our current observations and calculations, we know that the Sun began nuclear fusion about 5 billion years ago. We also know that the Sun will continue to fuse hydrogen into helium for another 4 to 5 billion years before it runs out of hydrogen in its core and begins the red giant phase.

## 5.3.3: Death of More Massive Stars

We have learned that more massive stars run through their fuel more quickly than the Sun. This causes the most massive stars to have much shorter lifetimes than the Sun. How do we know this? As with the Sun, we can learn about how massive stars evolve by observing the color, brightness, size, and mass of many other stars, and by measuring their ages. Graphing the properties of stars on the H-R diagram is a great way to do this. If we compare a group of stars that have the same age (for example, we may look at a cluster of stars that we know all formed at the same time), we find that the most massive stars in the group are no longer present on the Main Sequence, and that many star are found in the upper right corner of the plot. In other words, the massive stars have already begun their red giant phase, whereas the lower-mass stars are still fusing hydrogen, much like the Sun is doing now.

In some cases, when we look at a cluster of stars, we see that the stars that have masses like the Sun's have already reached the red giant phase (bright, red, large), and other stars are already white dwarfs (faint, blue, small). We do not see any high-mass stars in these cases. Where have they gone? The key to understanding this lies in understanding how high-mass stars evolve.

Massive stars generate light and heat through nuclear fusion, just like the Sun. Just like lower-mass stars, when massive stars run out of hydrogen at their cores, they begin a "shell burning" phase, where the gas in a shell around the star's core begins fusion. In this case, as with lower-mass stars, the outer layers of the star are pushed outward, and the star enters the red giant phase. The core of the star collapses due to gravity and begins fusing helium into carbon.

Unlike lower-mass stars, however, very massive stars (about 10 times more massive than the Sun) do not enter a white dwarf phase when they run out of helium for fusion into carbon. Because of their high masses, these stars have enough gravity that the inward pressure and temperature at their cores become large enough to begin carbon fusion into nitrogen. The process of nuclear fusion in the core of the star and in shells around the core continues, and heavier and heavier elements (nitrogen, oxygen, and silicon) are made, assuming the star is massive enough to generate the temperatures needed to fuse these elements. For the most massive stars, the process continues until the silicon in the star's core fuses to form iron.

Fusion does not continue in the iron core. It turns out that the fusion of iron requires energy, it does not release energy (Figure 5.11). This is a catastrophe for any star that reaches this stage.

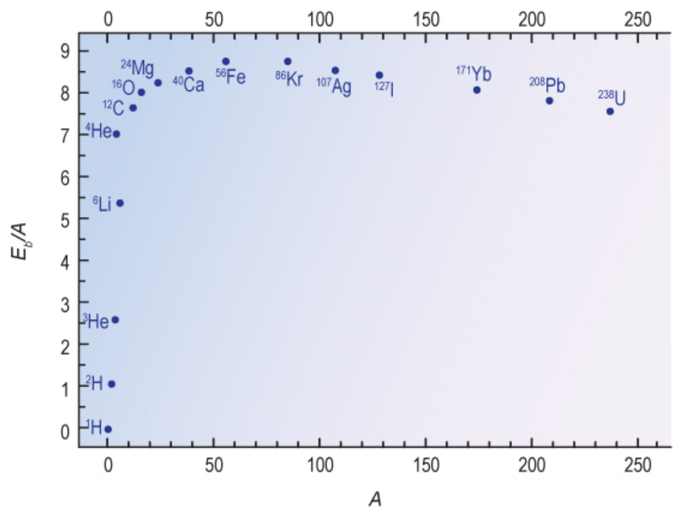


Figure 5.11: Binding energy is plotted vs. atomic number. The binding energy is a measure of how much energy is released when elements undergo fusion (elements lighter than iron) or fission (elements heavier than iron). Stars stop fusing at iron because it is no longer energetically favorable. Credit: NASA/SSU/Aurore Simmonet

What happens at this point? The high pressures and temperatures force the iron to fuse, but this cools the star: remember, iron fusion requires energy, it does not release energy. As the fusion continues, the temperature *drops*. This causes the outward thermal pressure to go away. As a result, there is nothing supporting the stellar layers above the core, or even the core itself. It all comes crashing down.

The force of gravity pushing inward on the star is so great that even the outward push of the electrons in the iron atoms cannot withstand it. Some of the electrons are pushed into the nuclei of the iron atoms, where they combine with protons to form neutrons. This process further lowers the pressure in the core. The stellar core collapses so rapidly that in less than a second, the outer layers of gas fall inward at nearly a tenth of the speed of light. The combination of the electrons with protons (this is inverse beta decay) releases a tremendous number of neutrinos, and these carry away the accumulated binding energy gained by the star over its lifetime. A small fraction, about one percent, of the neutrinos interact with and heat the stellar layers just outside the core. As a result of this near instantaneous heating, the outer layers of the star are rapidly ejected outward in a tremendous explosion called a supernova.

The time required for this entire process to trigger, from the initial onset of iron fusion to the catastrophic heating and expulsion of the layers just above the core, is on the order of a tenth of a second. For these layers to push upward through the overlaying star and eject the remaining layers into space takes several hours; these are typically very big, expanded stars, and they would fill much of the inner part of our solar system. Some of them would fill all of it. In the weeks following the explosion, a supernova is so bright that it can outshine an entire galaxy. It then gradually fades away over many months.

After a supernova occurs, a small remnant of the star’s core, made only of neutrons, is left over. This is called a neutron star. A neutron star has a mass of about 1.4 times the mass of the Sun, but is only about 20 km (12.4 miles) in diameter. The neutrons in a neutron star are packed so tightly together that the entire object resembles a huge atomic nucleus. This is incredibly dense—a teaspoonful of neutron star material would weigh over a billion tons!

Surrounding the neutron star is the expanding cloud of gas ejected during the explosion, or in other words, the rest of the star. The expanding cloud is called a supernova remnant (Figure 5.12), and in addition to the outer layers of the star that exploded, it contains any surrounding gas that gets swept up. Thus the remnant includes the elements created in the star during its lifetime and during the supernova explosion as well as the gas in the stars immediate environment.

As the remnant expands, it can collide with adjacent clouds, causing them to collapse and trigger a new generation of stars to be formed. These new stars will incorporate some of the elements that were thrown out into space during the supernova explosion. The elements that are most common in our bodies and in the air we breathe, including carbon, oxygen, nitrogen, and iron, were formed this way, in stars. The iron in your blood was forged in the cores of massive stars billions of years ago and the gold in your jewelry in supernova explosions. This is what the famous astronomer Carl Sagan meant when he said we are all made of “star stuff.”

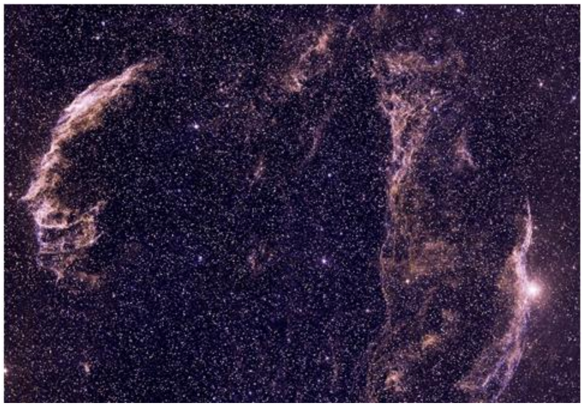

Figure 5.12: The explosive power and legacy of a massive star's death seen here in the Cygnus loop. Credit: ESA and Digitized Sky Survey (Caltech).

If a star is exceptionally massive, more than 20 times the mass of the Sun, then it will have such a strong inward gravitational push, such that even the tightly packed neutrons in a neutron star will not be able to hold themselves up. In that case the star collapses to the theoretical limit. At the center of the budding supernova explosion, a black hole forms. It swallows the stellar core entirely, along with all the neutrinos that are needed to heat the stellar layers above and blast them into space. So in this kind of event, the entire star collapses into its core, a black hole, making a brief gasp of gamma rays before it disappears completely.

A black hole can be described by the point at its very center, called the singularity, which seems to contain the entire mass of the collapsed core, plus whatever additional material from the stellar envelope might have fallen in. Around this is a sphere defined by the event horizon, the radius within which nothing, not even light, can escape the gravitational pull of the black hole. Black holes are incredibly interesting objects, and we will discuss them in much greater detail (including how we can try to observe them) in Chapter 11.

**Stellar Evolution**

The life cycles for high- and low-mass stars are depicted graphically. Place the tiles for the different stages of stellar evolution in the correct places for each cycle. When you are finished, check your work using the "check" button.

**Play Activity**

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