The Life Cycle of Stars

9.4

Every star has a life cycle: a beginning, a middle, and an end. The life of a star may last billions of years. Our Sun, for example, has been around for almost five billion years and is not yet near the end of its life cycle. Using modern instruments, scientists have been able to study stars at different stages of their life cycle. Our knowledge of gravitational forces has also greatly contributed to understanding the life cycle of stars. (Recall from Chapter 8 that a star is a massive collection of gases held together by its own gravity.)

Star Beginnings

A star has its beginning deep inside a massive cloud of interstellar gases and dust called a **nebula** (Figure 1). A nebula consists primarily of hydrogen and helium.

nebula a massive cloud of interstellar gas and dust; the beginning of a star

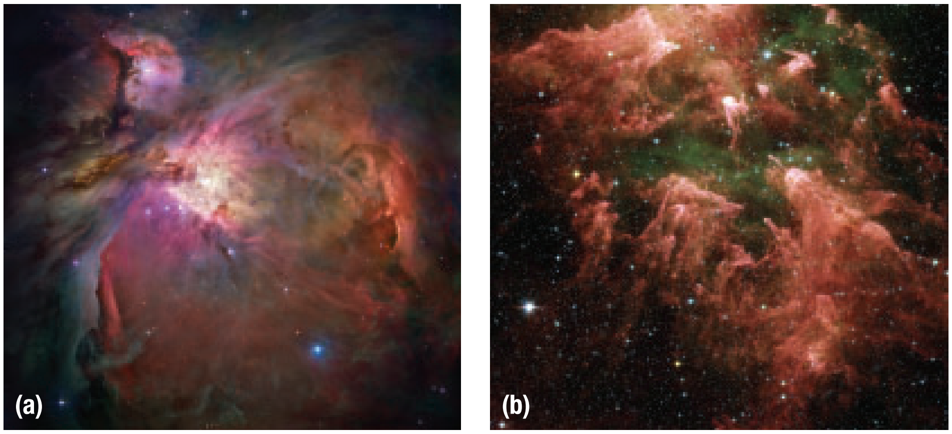

Figure 1 (a) As illustrated by this false-colour Hubble telescope image, the Orion Nebula offers one of the best opportunities to study how stars begin, partly because it is the nearest large star-forming region. (b) The Carina Nebula is another star-forming region. This false-colour telescope image shows young stars (yellow or white) among clouds of thick dust (pink).

LEARNING TIP

Word Meaning
"Proto-" means "first," "original," or "on the way to becoming something."

Stars are formed when parts of nebulas collapse in on themselves. Nebulas extend over vast distances—thousands of light years in space—and the gases within them are unevenly distributed. When a nebula reaches a certain density, gravitational forces begin to pull the gas and dust particles close together, causing clumps to form inside the main cloud of the nebula. As the clumps draw in gas and dust from the cloud, they become more massive and have increasingly stronger gravity. Over time, this gravity causes regions of greater density to form within the nebula. For about a million years, these dense regions continue to pull in gas and dust from the less dense regions of the nebula, forming a **protostar**.

protostar a massive concentration of gas and dust thought to eventually develop into a star after the nebula collapses

As the mass and gravity of a protostar increase, it becomes a tightly packed sphere of matter, drawing more and more matter into its core. The force of gravity eventually causes the atoms in the core of the protostar to become so tightly packed that the pressure in the core rises and nuclear fusion begins (Figure 2).

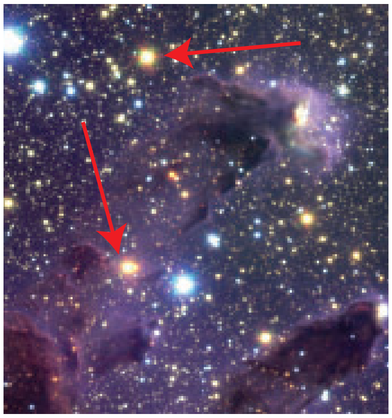

Figure 2 Arrows point to egg-shaped clouds with protostars embedded inside as they bud off from the Eagle Nebula.

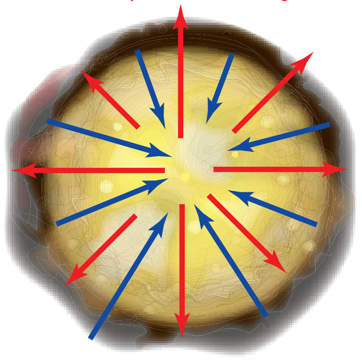

Figure 3 The red arrows represent the outward pressure of hot gas; the blue arrows represent gravity pulling toward the centre of the star.

Nuclear Fusion

For millions of years, the core of a protostar continues to contract due to the pull of gravity. The core temperature rises until it meets a critical temperature of 15 million °C (1.5×10^7 °C). At this temperature, nuclear fusion begins. Hydrogen atoms in the core fuse to form helium atoms, producing an enormous amount of energy. This energy rushes outward from the core of the star, counteracting the gravitational forces that caused the protostar to form (Figure 3).

The new star, buried inside the nebula, emits radiation in the form of heat, light, X-rays, gamma rays, and other energetic particles. Energy generated at the core makes its way to the surface and is radiated away at the photosphere. This radiation causes gases surrounding the star's core to glow, or shine. The star eventually stabilizes at a particular size. Our Sun went through this process, most likely taking up to 30 million years to condense and begin "glowing."

All stars begin in the same way. However, the life of a star is determined by its mass—the more massive the star, the faster its rate of fusion, which results in a shorter life cycle.

The Hertzsprung–Russell Diagram

Uncovering the mystery behind the life cycle of stars became much easier when scientists realized that a star's mass determines its brightness, colour, size, and how long it will "live."

Early in the twentieth century, Danish astronomer Ejnar Hertzsprung and American astronomer Henry Norris Russell organized this information into a diagram called the Hertzpsrung–Russell (H–R) diagram. The H–R diagram plots absolute magnitude against star surface temperature (Figure 4).

DID YOU KNOW?

Star Colour
Although the H–R diagram plots the temperature of stars from blue to red, our eyes perceive the colour of stars slightly differently. Blue stars appear bluish-white to the eye, and red stars appear pale pink or orange.

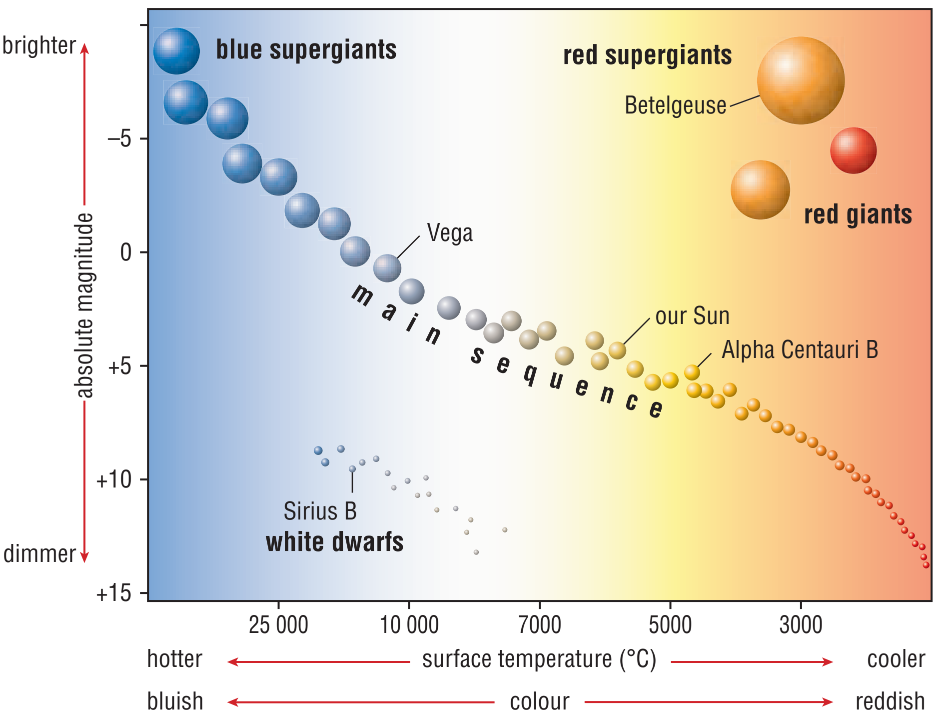

Figure 4 The H–R diagram is a visual representation of stellar evolution.

When astronomers studied the distribution of stars on the H–R diagram, they realized that the diagram offered clues to the evolution of stars. For example, they noticed that as the physical characteristics of a star change over time, the position of the star on the H–R diagram also changes. Hence, the H–R diagram can be used to describe the evolution of stars. In the last hundred years, thousands of stars have been plotted on the H–R diagram.

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Position on the H–R Diagram

Astronomers noticed that 90 percent of stars plotted on the H–R diagram fit into a diagonal band which they called the **main sequence**. In the lower right are the cooler, reddish stars that are dim. Moving along the main sequence to the upper left are the very luminous, hot, bluish stars. They also noticed that while some stars are dim and hot, others are luminous and cool. These stars are located on the H–R diagram off the main sequence, in the upper right corner and lower left corner. How could cooler stars, which likely produce less energy per unit area, be more luminous than hotter stars? It was reasoned that these cooler stars have a greater surface area than the hotter, dim stars, resulting in more light being produced. The large, bright, cool stars are called red giants. The small, dim, hot stars are called white dwarfs. The hottest, most luminous stars are very large stars called blue supergiants. You will learn more about these types of stars later in the section. As you can see from the H–R diagram, our Sun is an average star.

main sequence the stars (including the Sun) that form a narrow band across the H–R diagram from the upper left to the lower right

MAIN SEQUENCE STARS

Most stars, including our Sun, can be found along the main sequence band. These main sequence stars vary in surface temperature, as you can see from the shape of the band in the H–R diagram in Figure 4. The hotter these stars are, the more luminous they are. Astronomers have determined that hotter, more luminous main sequence stars are more massive, while cooler, less luminous stars are less massive.

Main sequence stars fuse hydrogen to produce helium in their cores. Stars do not move through the main sequence as they age. Once a star is formed with a particular mass, it stays in one position on the main sequence until all its hydrogen is used up. Most stars spend the bulk of their existence as main sequence stars.

DID YOU KNOW?

Red Supergiant
The largest known star is VY Canis Majoris, a red supergiant. Recent calculations suggest that it is more than two thousand times bigger than the Sun, which makes it about one quarter the size of the Solar System.

The Death of a Star

Billions of years after forming, a star begins to burn out as it nears the end of its life cycle. Depending on what type of star it is, this can happen in two different ways.

Stars Like the Sun: Red Giant to White Dwarf

After spending approximately 10 billion years as a main sequence star, a star's available hydrogen will have been converted to helium by nuclear fusion. This results in the formation of a helium-rich core, surrounded by an outer layer of hydrogen. With less hydrogen to burn, the outward flow of energy slows and the core begins to contract. This contraction heats the core, which heats up the remaining hydrogen enough for fusion to restart in the outer layer. While the core contracts and gets hotter, the outer layers of the star expand and then cool, becoming a **red giant** (Figure 5).

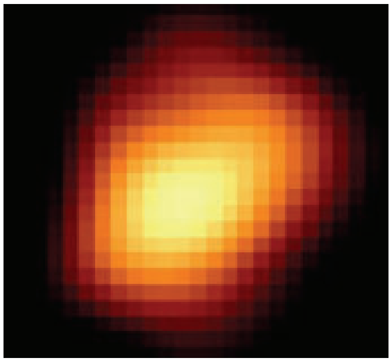


Figure 5 This Hubble Space Telescope image shows a red giant star, Mira (Omicron Ceti). It is approximately 700 times the size of the Sun!

red giant a star near the end of its life cycle with a mass that is equal to or smaller than that of the Sun; becomes larger and redder as it runs out of hydrogen fuel red supergiant a star near the end of its life cycle with a mass that is 10 times (or more) larger than that of the Sun; becomes larger and redder as it runs out of hydrogen fuel

In about 5 billion years, our Sun will become a red giant. A star with a mass that is equal to or smaller than that of the Sun becomes a red giant, whereas a star with a mass that is 10 times (or more) larger than that of the Sun becomes a **red supergiant**.

As a red giant ages it consumes the remaining supply of hydrogen and the core contracts further. This causes the temperature and pressure in the core to once again rise, and the helium-rich core begins to undergo fusion. The fusion of helium continues the expansion of the red giant and produces heavier elements, such as carbon (Figure 6). The red giant is now fully formed, and its luminosity has increased by several thousand times. Examples of red giants we can see in our night sky include Aldebaran and Betelgeuse.

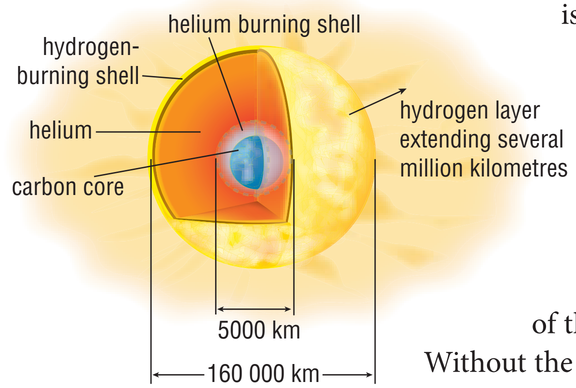


Figure 6 In main sequence stars, the helium burns in a shell around a carbon core, expanding and cooling the star even more as it ages.

As a red giant expands, it sends gas and dust into space and begins to lose mass. The increased surface area of the star has caused it to move off the main sequence band in the H–R diagram.

A star with a mass that is equal to or smaller than that of the Sun is said to "die" when nuclear fusion stops occurring. Without the outward pressure generated by nuclear fusion, the star's core begins to collapse due to its own gravity. The outer layers of the star drift away and, eventually, the hot core is all that remains of the star. The matter that remains is known as a **white dwarf**—a small, dim, hot star. After developing into a red giant, our Sun will eventually become a white dwarf. Astronomers believe that once a white dwarf cools down, all that remains is dark, cold matter, which they refer to as a black dwarf.

white dwarf a small, hot, dim star created by the remaining material that is left when a red giant dies

The hot white dwarf emits ultraviolet light that collides with the gas and dust shed in the last stages of its life as a red giant. The energy illuminates the clouds of dust and gas and creates a beautiful planetary nebula, which is a nebula that results from the death of certain stars (Figure 7). A white dwarf will continue to radiate its energy into space, becoming cooler and dimmer, until its light goes out.

Figure 7 This Hubble Space Telescope image shows the Cat's Eye nebula, 3000 ly from Earth. The planetary nebula is illuminated by the white dwarf at its centre.

Stars More Massive than the Sun

Not all stars end up as white dwarfs. Some stars can be tens of times more massive than the Sun (but these high-mass stars are rare). Recall that the mass of a star determines how long a star will "live." A star with a high mass consumes hydrogen much faster than a star with low mass, resulting in a shorter life cycle.

When a massive star runs out of hydrogen for fusion, it begins to fuse helium into carbon (like our Sun). The core of a massive star becomes so hot that when helium is no longer available for fusion, carbon undergoes fusion. This produces heavier elements, beginning with oxygen and up to iron. Once iron is produced in the core, fusion can no longer occur. (This is because fusing iron requires more energy than it releases.)

Once fusion stops, the star collapses under its own gravity and the iron core increases in temperature. The inward rush of gas is suddenly halted by the core, and, like a rubber ball bouncing off a brick wall, the gases bounce back outward with great force. The outer layers of the star explode outwards in what is called a **supernova**, sending out a series of shock waves. This creates a rapidly expanding nebula of gas and dust.

The energy released by such massive supernova explosions is capable of causing many fusion reactions. These fusion reactions are responsible for the formation of all the additional elements in the periodic table.

Supernovas are rare astronomical events. One of the few supernovas that have been observed is the supernova that created the Crab Nebula in the year 1054 (Figure 8). Since the invention of the telescope 400 years ago, only one supernova has ever been seen with the unaided eye. This was in 1987, when Canadian astronomer Ian Shelton discovered a supernova now known as Supernova 1987A.

DID YOU KNOW?

We Are Made of Star Dust

The nickel we use for making coins and the silver and gold we wear as jewellery were all created by fusion reactions inside a supernova explosion long before the formation of our solar system. In fact, with the exception of hydrogen, every atom in your body was originally formed inside a star or an exploding star!

supernova a stellar explosion that occurs at the end of a massive star's life

Figure 8 The supernova that formed the famous Crab Nebula was so bright that it was visible even during daylight hours.

TRY THIS MODELLING A SUPERNOVA EXPLOSION

SKILLS: Predicting, Observing, Analyzing

When the core of a star collapses, it does so with such enormous force that it rebounds. As the core collapses, all the outer atmospheric layers are also collapsing. The less dense outer layers are still falling in toward the core when the core rebounds. The rebounding core collides with the outer layers with enough energy to blow the atmospheric layers away from the star. This is the supernova explosion. In this activity, the basketball models the core, and the tennis ball models the star's outer atmospheric layers.

Equipment and Materials: basketball; tennis ball

1. Drop the basketball and then the tennis ball. Record your observations.
2. Place the tennis ball on top of the basketball, and hold them out in front of you. Predict how each ball will bounce.
3. Let go of both balls at the same time. Record your observations.

A. How far above the floor did each ball rebound in step 1? K/U

B. What did you observe when both balls hit the floor? K/U

C. What is the source of the extra energy that caused the result you observed? T/I

D. How is this model like a supernova explosion? K/U T/I

E. What parts of this model are not like a supernova explosion? T/I

NEUTRON STARS

neutron star an extremely dense star made up of tightly packed neutrons; results when a star over 10 solar masses collapses

When a star with an initial mass between 10 and 30 solar masses explodes into a supernova, the core left behind becomes a **neutron star**—an extremely dense star composed of tightly packed neutrons. Although these stars are tiny (only about 10 km across—the size of a large city on Earth), the neutrons within them are so tightly packed that the mass of a neutron star can be more than 10^{30} kg. A spoonful of a neutron star would weigh as much as Mount Everest! The gravity of a neutron star is 300 000 times that of Earth.

Some neutron stars spin very quickly—hundreds of times per second at first. As they spin, they emit high-frequency radio waves, which we detect intermittently as pulses—like the beam from the rotating light of a lighthouse. For this reason, these neutron stars are also called pulsars, and they can be seen from thousands of light years away in spite of their small size (Figure 9).

Figure 9 NASA's Chandra X-ray Observatory and the Hubble Space Telescope captured this image of a pulsar at the centre of the Crab nebula. The bright rings are made up of high-energy particles that are propelled outward by the Crab pulsar.

BLACK HOLES

When a star with an initial mass larger than 30 solar masses dies, it leaves behind a core so massive that it collapses under its own gravity into a **black hole**—a quantity of matter so dense and with gravity so strong that not even light can escape. The word "hole" is misleading because it sounds like there is nothing there. In reality, there is a huge amount of matter packed into a dense core.

black hole an extremely dense quantity of matter in space from which no light or matter can escape

Astronomers cannot see black holes because they do not allow any light to escape. How do they know that black holes exist? They see the gravitational effect that a quantity of matter believed to be a black hole has on the surrounding area. The gravity of a black hole is so strong that it pulls in any nearby matter. The matter forms a disc of gas and dust around the black hole, much like water swirling down a drain (Figure 10). Just before the matter spirals into the black hole and disappears, it heats up and emits powerful X-ray radiation. This radiation can be detected by instruments on a satellite.

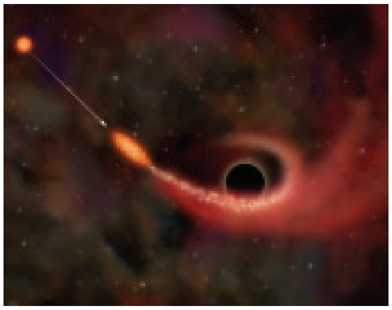


Figure 10 This illustration depicts a star (orange circle) close to a massive black hole. The enormous gravity of the black hole stretched the star until it was torn apart, pulling in some of the star's mass while the rest is flung out into space.

Figure 11 shows the different paths that a star's life can take, depending on its mass.

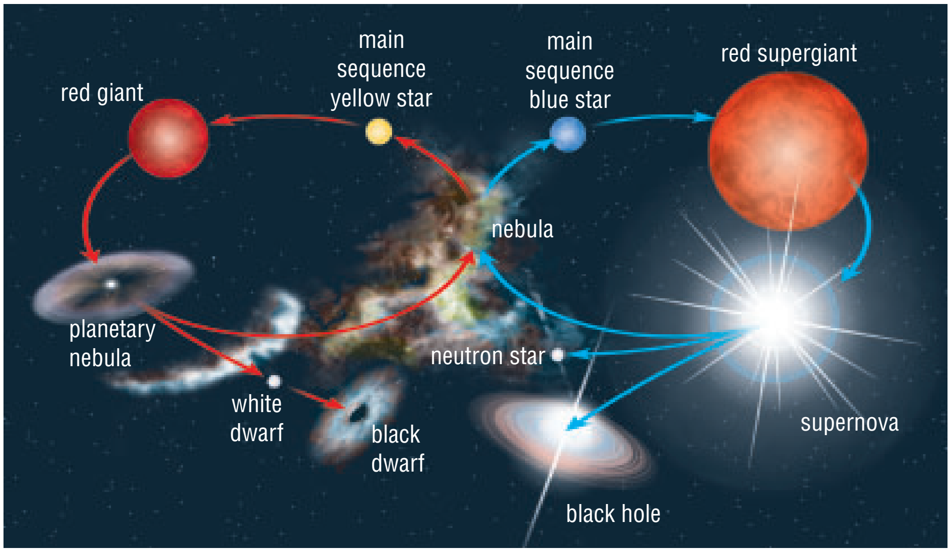
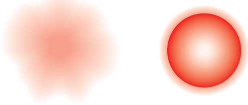
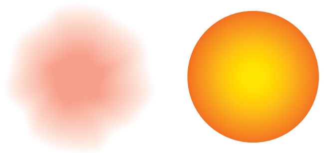
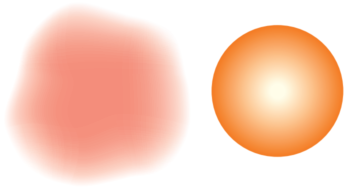
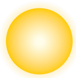
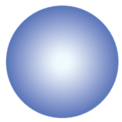
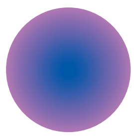
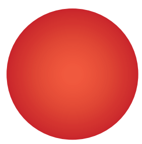
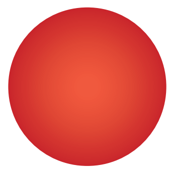
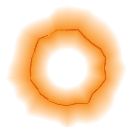
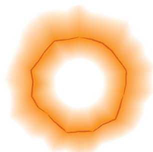


Figure 11 The red arrows show the life cycle of low-mass stars like the Sun. The blue arrows show the life cycle of large-mass stars that are more massive than the Sun.

Every star has its own unique life cycle. Although scientists have learned much about the characteristics of stars, they have only recently uncovered the mystery of star evolution. Scientific theories are always changing based on new observations. Table 1 summarizes what scientists have learned about the life cycle of stars, based on mass.

Table 1 The Evolution of Different Types of Stars Based on Mass

	Small to medium star (<5 solar masses)	**Large star (10–30 solar masses)**	**Extremely large star (>30 solar masses)**
Birth and early life	 Forms from a small- or medium-sized portion of a nebula; gradually turns into a hot, dense clump that begins producing energy.	 Forms from a large portion of a nebula, and in a fairly short time turns into a hot, dense clump that produces large amounts of energy.	 Forms from an extremely large portion of a nebula, very quickly turning into a hot, dense clump that produces very large amounts of energy.
Main sequence phase	 Uses nuclear fusion to produce energy for about 10 billion years if the mass is the same as the Sun's, or 100 billion years or more if the mass is less than the Sun's.	 Uses nuclear fusion to produce energy for only a few million years. It is thousands of times brighter than the Sun.	 Uses nuclear fusion to produce energy for only a few million years. It is extremely bright.
Old age	 Uses up hydrogen and other fuels and swells to become a large, cool red giant.	 Uses up hydrogen and other fuels and swells to become a red supergiant.	 Uses up hydrogen and other fuels and swells to become a red supergiant.
Death	 Outer layers of gas drift away, and the core shrinks to become a small, hot, dense white dwarf star.	 Core collapses inward, sending the outer layers exploding as a supernova.	 Core collapses, sending the outer layers exploding as a very large supernova.
Remains	 White dwarf star eventually cools and fades.	 Core material packs together as a neutron star. Gases drift off as a nebula to be recycled.	 Core material packs together as a black hole. Gases drift off as a nebula to be recycled.

Note: these drawings are not to scale.

UNIT TASK Bookmark

How could you apply the information you learned about the life cycle of stars as you work on the Unit Task described on page 446?

IN SUMMARY

- Stars are formed inside giant clouds of gas and dust called nebulas.
- Stars shine through a process known as nuclear fusion.
- When stars run out of fuel, they turn into white dwarfs, black holes, or neutron stars.
- Astronomers use the Hertzsprung–Russell diagram to identify where stars are in their life cycle based on their luminosity and temperature.
- The mass of a star determines its life cycle or evolution.

CHECK YOUR LEARNING

1. At what temperature do stars begin the process of nuclear fusion? K/U
2. In what ways do stars change their physical properties over time? K/U
3. Using the H–R diagram as a guide, list three physical properties of the Sun. K/U
4. (a) What is the factor that determines whether a black hole will form at the end of a star's life?
   (b) Will the Sun form a black hole at the end of its life? Explain your reasoning. K/U T/I
5. In a paragraph, describe the importance of nuclear fusion. Use the title "Why Do Stars Shine?" K/U C
6. Compare a red giant with a white dwarf by referring to some of the physical properties of the stars covered in this section. K/U
7. (a) What unit do astronomers use to measure the masses of stars and star-like objects in the Universe?
   (b) Why do they use this unit instead of something more traditional, such as kilograms? K/U
8. How can the evolution of a star over its lifetime be tracked using the H–R diagram? Give a specific example of a category of star on the H–R diagram. K/U
9. How can astronomers detect black holes if they do not give off visible light? K/U
10. Re-examine Table 1 and identify three ways in which a high mass star evolves differently than a low mass star. K/U