SECTION 2

Stellar Evolution

Key Ideas

- Describe how a protostar becomes a star.
- Explain how a main-sequence star generates energy.
- Describe the evolution of a star after its main-sequence stage.

Key Terms

main sequence
nebula
giant
white dwarf
nova
neutron star
pulsar
black hole

Why It Matters

Theories of stellar evolution help us to predict the age of our sun, as well as when it will stop shining. In fact, there's nothing to worry about.

Because a typical star exists for billions of years, astronomers will never be able to observe one star throughout its entire lifetime. Instead, they have developed theories about the evolution of stars by studying stars in different stages of development.

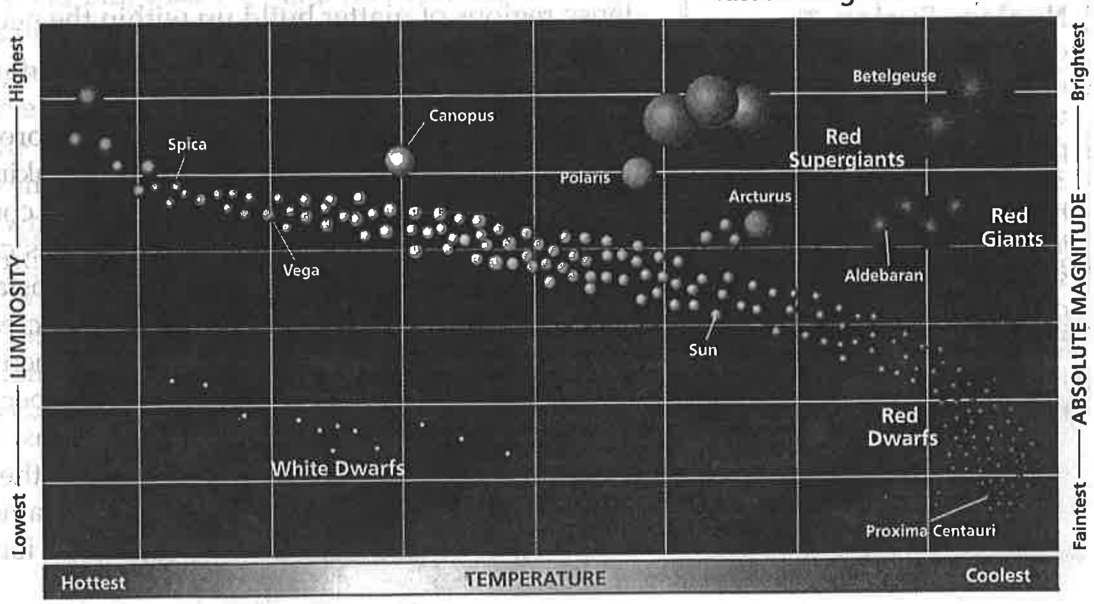
Classifying Stars

Plotting the surface temperatures of stars against their *luminosity*, or the total amount of energy they give off each second, reveals a consistent pattern. The graph that illustrates this pattern is the *Hertzsprung-Russell diagram*, or *H-R diagram*, a simplified version of which is shown in **Figure 1.** The graph is named for Ejnar Hertzsprung and Henry Norris Russell, the astronomers who discovered the pattern nearly 100 years ago.

Astronomers plot the highest temperatures on the left and the highest luminosities at the top. The temperature and luminosity for most stars fall within a band that runs diagonally through the middle of the H-R diagram. This band, which extends from cool, dim, red stars at the lower right to hot, bright, blue stars at the upper left, is known as the **main sequence.** Stars within this band are called *main-sequence stars* or *dwarfs*. The sun is a main-sequence star.

main sequence the location on the H-R diagram where most stars lie; it has a diagonal pattern from the lower right to the upper left

Figure 1 The Hertzsprung-Russell Diagram



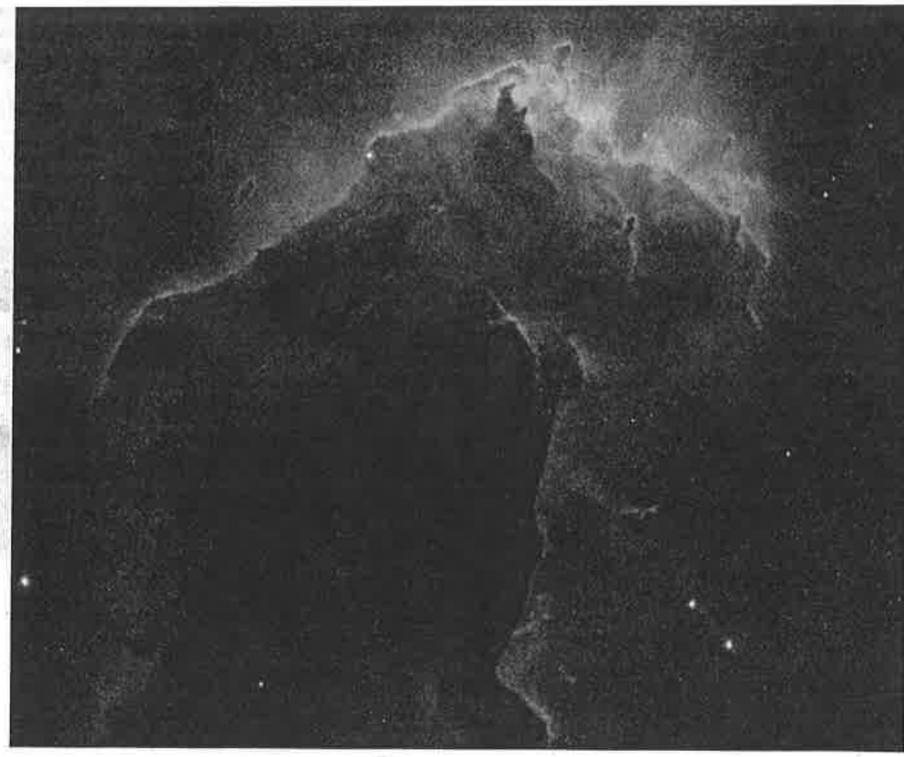


Figure 2 The Eagle Nebula is a region in which star formation is currently taking place. This false-color image of a small part of the Eagle Nebula was captured by the *Hubble Space Telescope.*

READING TOOLBOX

Scientific Theories vs. Scientific Laws
On a sheet of paper, write the name and definition of the law given on this page. Explain why it is a law, not a theory.

nebula a large cloud of gas and dust in interstellar space; a region in space where stars are born

Math Skills

Nuclear Fusion The sun converts nearly 545 million metric tons of hydrogen to helium every second. In the process, approximately 3.6 million metric tons of that hydrogen mass are changed into energy and radiated into space. What percentage of the converted hydrogen is changed into radiated energy? If the sun loses 3.6 million metric tons of mass per second, how many metric tons of mass will it lose in one year?

Star Formation

A star begins in a **nebula** (NEB yu luh), a cloud of gas and dust, such as the one shown in **Figure 2.** A nebula commonly consists of about 70% hydrogen, 28% helium, and 2% heavier elements. When an outside force, such as the explosion of a nearby star, compresses the cloud, some of the particles move close to each other and are pulled together by gravity. Alternatively, the collapse may start randomly, without an identifiable force.

According to Newton's *law of universal gravitation,* all objects in the universe attract each other with a force that increases as the mass of any object increases or as the distance between the objects decreases. Thus, as gravity pulls particles closer together, the attraction on each other increases. This pulls more nearby particles toward an area of increasing mass. As more particles come together, dense regions of matter build up within the nebula.

Protostars

As gravity makes these dense regions more compact, any spin the region has is greatly amplified. The shrinking, spinning region begins to flatten into a disk that has a central concentration of matter called a *protostar.* Gravitational energy is converted into heat energy as more matter is pulled into the protostar. This heat energy causes the temperature of the protostar to increase.

The protostar continues to contract and increase in temperature for several million years. Eventually, the gas becomes so hot that its electrons are stripped from their parent atoms. The nuclei and free electrons move independently, and the gas is then considered a separate state of matter called *plasma.* Plasma is a hot, ionized gas that has an equal number of free-moving positive ions and electrons.

The Birth of a Star

Temperature continues to increase in a protostar to about 10,000,000 °C. At this temperature, nuclear fusion begins. *Nuclear fusion* is a process that occurs when extremely high temperature and pressure cause less-massive atomic nuclei to combine to form more-massive nuclei and, in the process, release enormous amounts of energy. The onset of fusion marks the birth of a star. Once nuclear fusion begins in a star, the process can continue for billions of years.

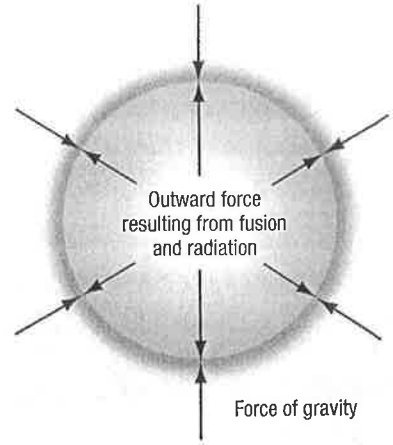


Figure 3 Stellar equilibrium is achieved when the inward force of gravity is balanced by the outward pressure from fusion and radiation inside the star.

A Delicate Balancing Act

As gravity increases the pressure on the matter within the star, the rate of fusion increases. In turn, the energy radiated from fusion reactions heats the gas inside the star. The outward pressures of the radiation and the hot gas resist the inward pull of gravity. The stabilizing effect of these forces is shown in **Figure 3.** This equilibrium makes the star stable in size. A main-sequence star maintains a stable size as long as the star has an ample supply of hydrogen to fuse into helium.

Reading Check How does the pressure from fusion and hot gas interact with the force of gravity to maintain a star's stability?

The Main-Sequence Stage

The second and longest stage in the life of a star is the main-sequence stage. During this stage, energy continues to be generated in the core of the star as hydrogen fuses into helium. Fusion releases enormous amounts of energy. For example, when only 1 g of hydrogen is converted into helium, the energy released could keep a 100 W light bulb burning for more than 200 years.

A star that has a mass about the same as the sun's mass stays on the main sequence for about 10 billion years. More-massive stars, on the other hand, fuse hydrogen so rapidly that they may stay on the main sequence for only 10 million years. Because the universe is about 14 billion years old, massive stars that formed long ago have long since left the main sequence. Less massive stars, which are at the bottom right of the main sequence on the H-R diagram, are thought to be able to exist for hundreds of billions of years.

The stages in the life of a star cover an enormous period of time. Scientists estimate that over a period of almost 5 billion years, the sun, shown in **Figure 4,** has converted only 5% of its original hydrogen nuclei into helium nuclei. After another 5 billion years, though, with 10% of the sun's original hydrogen converted, the rate of fusion in the core will decrease significantly, causing the sun's temperature and luminosity to change. Then the sun will move off the main sequence.

READING TOOLBOX

Compare Make a table that compares the life span and energy output of a blue giant star with the life span and energy output of the sun. Then answer the following questions using your data: Which star is more likely to have life on one or more of the planets that orbit it? Why?

Figure 4 Our sun is a yellow dwarf star. It is located in the diagonal band of main-sequence stars on the H-R diagram.

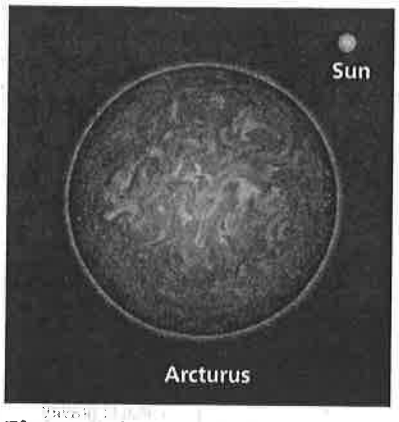


Figure 5 Arcturus is an orange giant that is about 23 times larger than the sun. Despite being about 1,000°C cooler than the sun, Arcturus gives off more than 100 times as much light as the sun does because it has so much surface area.

Leaving the Main Sequence

A star enters its third stage when about 20% of the hydrogen atoms within its core have fused into helium atoms. The core of the star begins to contract under the force of its own gravity. This contraction increases the temperature in the core. As the helium core becomes hotter, it transfers energy into a thin shell of hydrogen surrounding the core. This energy causes hydrogen fusion to continue in the shell of gas. The on-going fusion of hydrogen radiates large amounts of energy outward, which causes the outer shell of the star to expand greatly.

Giant Stars

A star's shell of gases grows cooler as it expands. As the gases in the outer shell become cooler, their glow becomes reddish. These large, red stars are known as **giants** because they are larger than main-sequence stars of the same surface temperature.

giant a very large and bright star whose hot core has used most of its hydrogen

Because of their large surface areas, giant stars are bright. Giants, such as the star Arcturus shown in **Figure 5,** are 10 or more times larger than the sun. Stars that contain about as much mass as the sun will become giants. As they become larger, more luminous, and cooler, they move off the main sequence. Giant stars are above the main sequence on the H-R diagram.

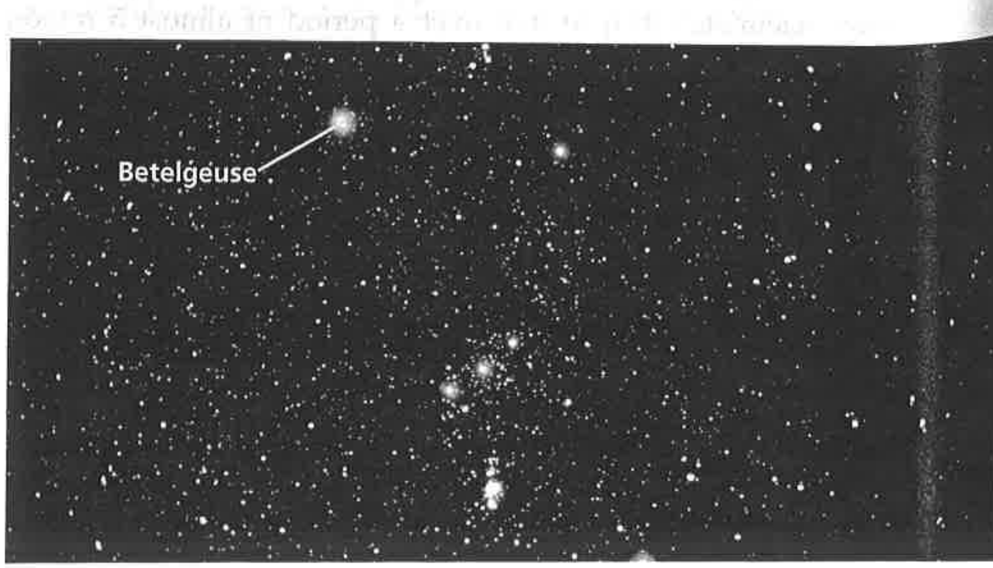
Supergiants

Main-sequence stars that are more massive than the sun will become larger than giants in their third stage. These highly luminous stars are called *supergiants*. These stars appear along the top of the H-R diagram. Supergiants are often at least 100 times larger than the sun. Betelgeuse, the large, orange-red star shown in **Figure 6,** is one example of a supergiant. Located in the constellation Orion, Betelgeuse is 1,000 times larger than the sun.

Though such supergiant stars make up only a small fraction of all the stars in the sky, their high luminosity makes the stars easy to find in a visual scan of the night sky. However, despite the high luminosity of supergiants, their surfaces are relatively cool.

Reading Check Where are giants and supergiants found on the H-R diagram?

Figure 6 If the sun were replaced by the red supergiant Betelgeuse, the surface of this star would be farther out than Jupiter's orbit. ***How does the temperature of Betelgeuse compare with that of the sun?***



The Final Stages of a Sunlike Star

In the evolution of a medium-sized star, fusion in the core will stop after the helium atoms have fused into carbon and oxygen. With energy no longer available from fusion, the star enters its final stages.

Planetary Nebulas

As the star's outer gases drift away, the remaining core heats these expanding gases. The gases appear as a *planetary nebula*, a cloud of gas that forms around a sunlike star that is dying. Some of these clouds may form a simple sphere or ring around the star. However, many planetary nebulas form more-complex shapes. For example, the Ant nebula has a double-lobed shape, as shown in **Figure 7.**

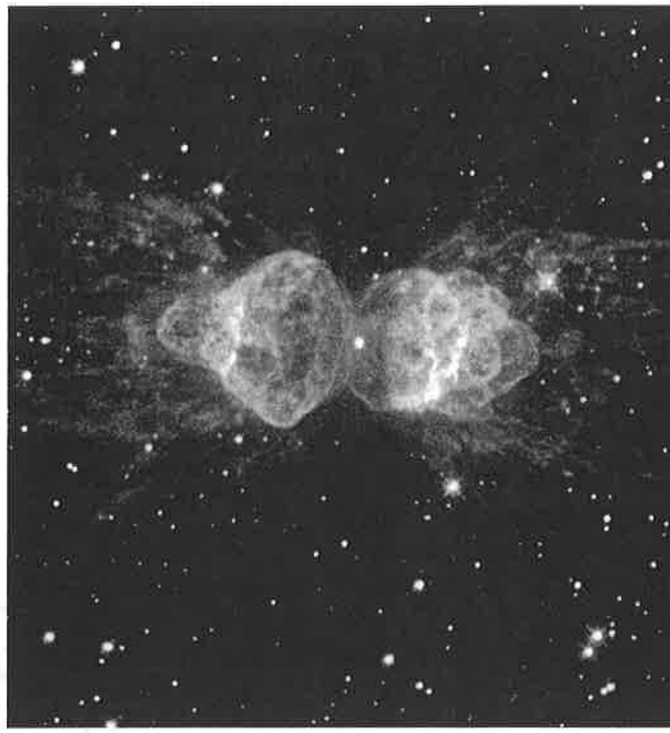


Figure 7 The Ant nebula is a planetary nebula that is located more than 3,000 light-years from Earth in the southern constellation Norma.

White Dwarfs

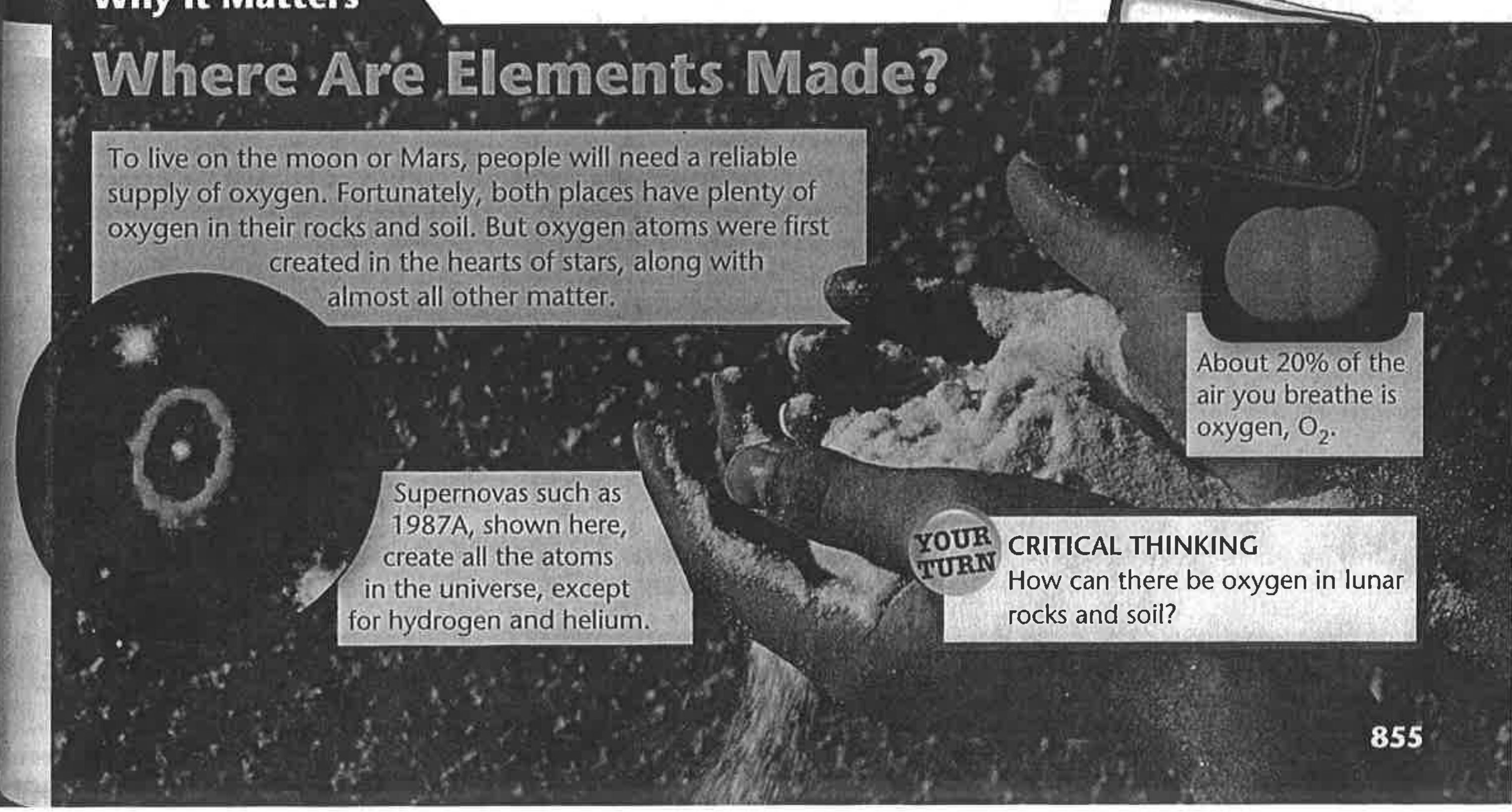
As a planetary nebula disperses, gravity causes the remaining matter in the star to collapse inward. The matter collapses until it cannot be pressed further together. A hot, extremely dense core of matter—a **white dwarf**—is left. White dwarfs shine for billions of years before they cool completely.

White dwarfs are in the lower left of the H-R diagram. They are hot but dim. These stars are very small, about the size of Earth. As white dwarfs cool, they become fainter. This is the final stage in the life cycle of many stars.

white dwarf a small, hot, dim star that is the leftover center of an old sunlike star

Why It Matters

Where Are Elements Made?



To live on the moon or Mars, people will need a reliable supply of oxygen. Fortunately, both places have plenty of oxygen in their rocks and soil. But oxygen atoms were first created in the hearts of stars, along with almost all other matter.

About 20% of the air you breathe is oxygen, O_2.

Supernovas such as 1987A, shown here, create all the atoms in the universe, except for hydrogen and helium.

YOUR TURN

CRITICAL THINKING
How can there be oxygen in lunar rocks and soil?

Novas and Supernovas

Some white dwarf stars are part of binary star systems. If a white dwarf revolves around a red giant, the gravity of the very dense white dwarf may capture loosely held gases from the red giant. As these gases accumulate on the surface of the white dwarf, pressure begins to build up. This pressure may cause large explosions, which release energy and stellar material into space. Such an explosion is called a **nova.**

nova a star that suddenly becomes brighter

A nova may cause a star to become many thousands of times brighter than it normally is. However, within days, the nova begins to fade to its normal brightness. Because these explosions rarely disrupt the stability of the binary system, the process may start again and a white dwarf may become a nova several times.

A white dwarf star in a binary system may also become a *supernova*, a star that has such a tremendous explosion that it blows itself apart. Unlike an ordinary nova, a white dwarf can sometimes accumulate so much mass on its surface that gravity overwhelms the outward pressure. The star collapses and becomes so dense that the outer layers rebound and explode outward. Supernovas are thousands of times more violent than novas. The explosions of supernovas completely destroy the white dwarf star and may destroy much of the red giant.

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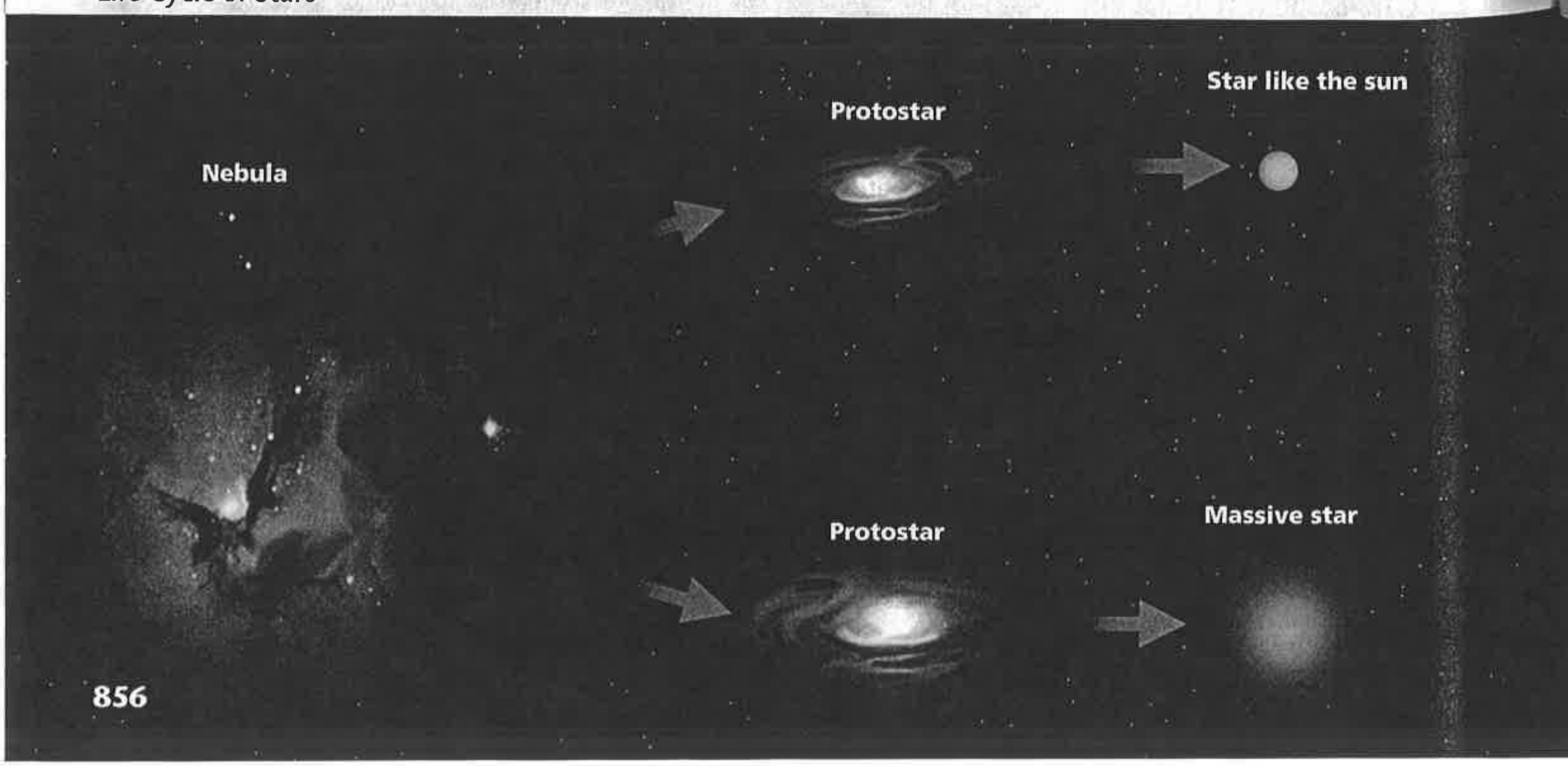
The Final Stages of Massive Stars

Stars that have masses of more than 8 times the mass of the sun may produce supernovas without needing a secondary star to fuel them. In 1054, Chinese astronomers saw a supernova so bright that it was seen during the day for more than three weeks. At its peak, the supernova radiated an amount of energy that was equal to the output of about 400 million suns.

Life Cycle of Stars



Supernovas in Massive Stars

While only a small percentage of white dwarfs become supernovas, massive stars become supernovas as part of their life cycle, which is shown in **Figure 8.** After the supergiant stage, these stars contract with a gravitational force that is much greater than that of small-mass stars. The collapse produces such high pressures and temperatures that nuclear fusion begins again. This time, carbon atoms in the core of the star fuse into heavier elements such as oxygen, magnesium, or silicon.

Fusion continues until the core is almost entirely made of iron. Because iron has a very stable nuclear structure, fusion of iron into heavier elements takes energy from the star rather than giving off energy. Having used up its supply of fuel, the core begins to collapse under its own gravity. Energy released as the core collapses is transferred to the outer layers of the star, which explode outward with tremendous force. Within a few minutes, the energy released by the supernova may surpass the amount of energy radiated by a sunlike star over its entire lifetime.

Academic Vocabulary

structure (STRUHK chuhr) the arrangement of the parts of a whole; a whole that is built or put together from parts

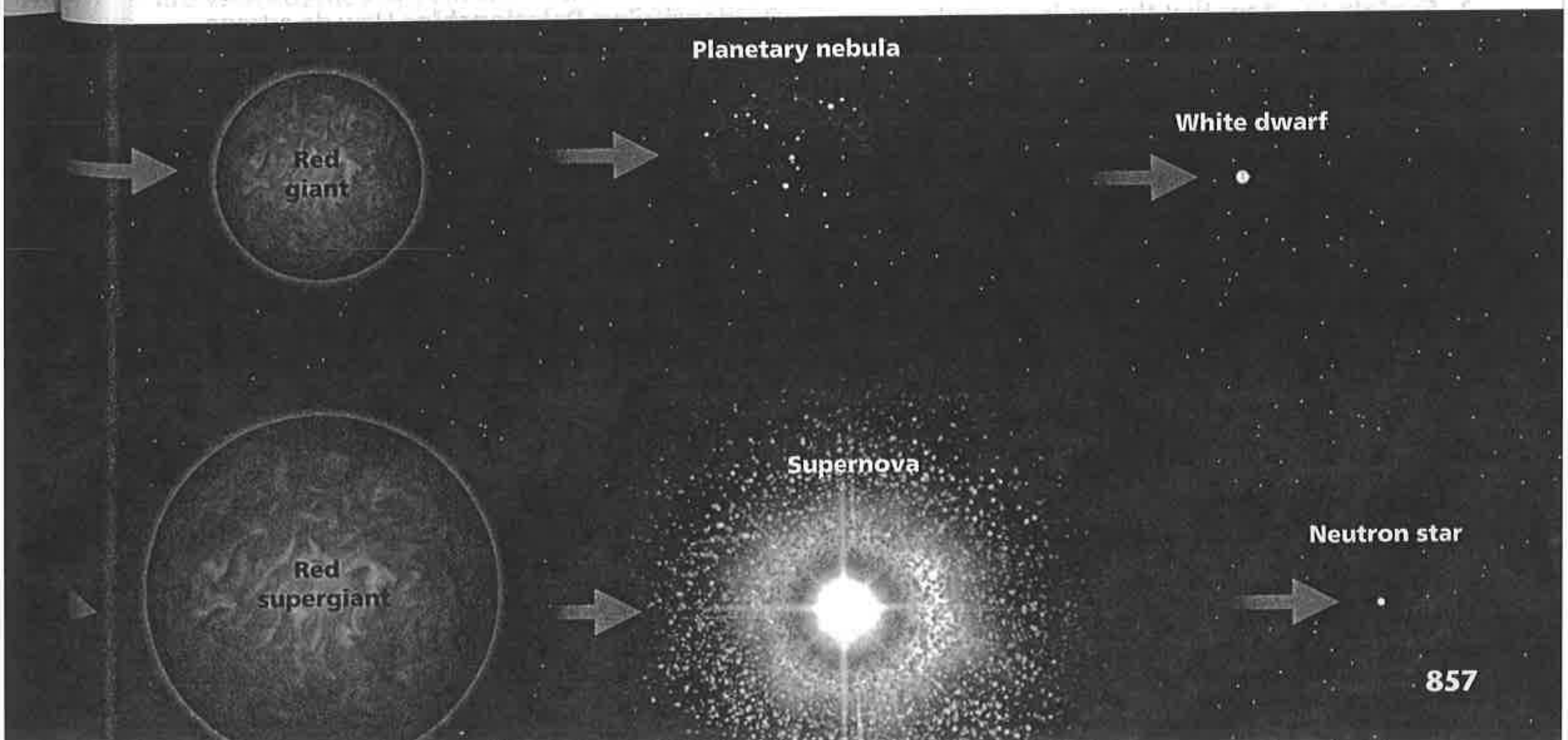
Reading Check **What causes a supergiant star to explode as a supernova?**

Neutron Stars

Stars that contain about 8 or more times the mass of the sun do not become white dwarfs. After a star explodes as a supernova, the core may contract into a very small but incredibly dense ball of neutrons, called a **neutron star.** A single teaspoon of matter from a neutron star would have a mass of 2×10^{30} kilograms (a 2 followed by 30 zeroes). A neutron star that has more mass than the sun may have a diameter of only about 20 km but may emit the same amount of energy as 100,000 suns. Neutron stars rotate very rapidly.

neutron star a star that has collapsed under gravity to the point that the electrons and protons have smashed together to form neutrons

Figure 8 A star the mass of the sun becomes a white dwarf near the end of its life cycle. A more massive star may become a neutron star.



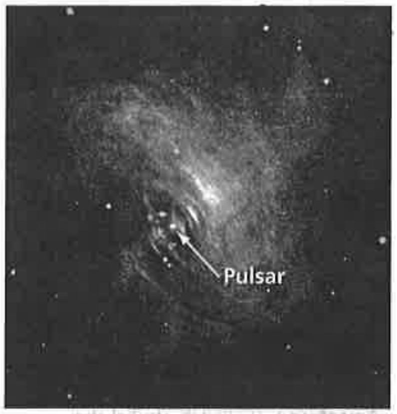


Figure 9 This pulsar, located in the heart of the Crab nebula, is still surrounded by the remains of a supernova explosion that took place less than 1,000 years ago.

pulsar a rapidly spinning neutron star that emits pulses of radio and optical energy

black hole an object so massive and dense that even light cannot escape its gravity

Pulsars

Some neutron stars emit a beam of radio waves that sweeps across space like a lighthouse light beam sweeps across water. Because we detect pulses of radio waves every time the beam sweeps by Earth, these stars are called **pulsars.** For each pulse we detect, we know that the star has rotated within that period. Newly formed pulsars, such as the one shown in **Figure 9,** are commonly surrounded by the remnants of a supernova. But most known pulsars are so old that these remnants have long since dispersed and have left behind only the spinning star.

Black Holes

Some massive stars produce leftovers too massive to become stable neutron stars. If the remaining core of a star contains more than 3 times the mass of the sun, the star may contract further under its greater gravity. The force of the contraction crushes the dense core of the star and leaves a **black hole.** The gravity of a black hole is so great that nothing, not even light, can escape it.

Because black holes do not give off light, locating them is difficult. But a black hole can be observed by its effect on a companion star. Matter from the companion star is pulled into the black hole. Just before the matter is absorbed, it swirls around the black hole. The gas becomes so hot that X rays are released. Astronomers locate black holes by detecting these X rays. Scientists then try to find the mass of the object that is affecting the companion star. Astronomers conclude that a black hole exists only if the companion star's motion shows that a massive, invisible object is present nearby.

Section 2 Review

Key Ideas

1. **Explain** the steps that the gas in a nebula goes through as it becomes a star.
2. **Describe** the process that generates energy in the core of a main-sequence star.
3. **Explain** how a main-sequence star like the sun is able to maintain a stable size.
4. **Describe** how nuclear fusion in a main-sequence star is different from nuclear fusion in a giant star.
5. **Describe** how a star similar to the sun changes after it leaves the main-sequence stage of its life cycle.
6. **Describe** what causes a nova explosion.
7. **Explain** why only very massive stars can form black holes.
8. **Describe** two types of supernovas.

Critical Thinking

9. **Identifying Relationships** How do astronomers conclude that a supergiant star is larger than a main-sequence star of the same temperature?
10. **Analyzing Ideas** Why would an older main-sequence star be composed of a higher percentage of helium than a young main-sequence star?
11. **Compare and Contrast** Why does temperature increase more rapidly in a more massive protostar than in a less massive protostar?
12. **Analyzing Ideas** How can astronomers detect a black hole if it is invisible to an optical telescope?

Concept Mapping

13. Use the following terms to create a concept map: *main-sequence star, nebula, supergiant, white dwarf, planetary nebula, black hole, supernova, protostar, giant, pulsar,* and *neutron star.*