25.2 Stellar Evolution

Determining how stars are born, age, and then die was difficult because the life of a star can span billions of years. However, by studying stars of different ages, astronomers have been able to piece together the evolution of a star. Imagine that an alien from outer space lands on Earth. This alien wants to study the stages of human life. By examining a large number of humans, the alien observes the birth of babies, the activities of children and adults, and the death of elderly people. From this information, the alien then attempts to put the stages of human development into proper sequence. Based on the number of humans in each stage of development, the alien would conclude that humans spend more of their lives as adults than as children. In a similar way, astronomers have pieced together the story of stars.

Star Birth
The birthplaces of stars are dark, cool interstellar clouds, such as the one in Figure 8. These nebulae are made up of dust and gases. In the Milky Way, nebulae consist of 92 percent hydrogen, 7 percent helium, and less than 1 percent of the remaining heavier elements. For some reason not yet fully understood, some nebulae become dense enough to begin to contract. A shock wave from an explosion of a nearby star may trigger the contraction. Once the process begins, gravity squeezes particles in the nebula, pulling every particle toward the center. As the nebula shrinks, gravitational energy is converted into heat energy.
Protostar Stage  The initial contraction spans a million years or so. As time passes, the temperature of this gaseous body slowly rises until it is hot enough to radiate energy from its surface in the form of long-wavelength red light. This large red object is called a protostar. A protostar is a developing star not yet hot enough to engage in nuclear fusion.

During the protostar stage, gravitational contraction continues—slowly at first, then much more rapidly. This collapse causes the core of the protostar to heat much more intensely than the outer layer. When the core of a protostar has reached about 10 million K, pressure within is so great that nuclear fusion of hydrogen begins, and a star is born.

Heat from hydrogen fusion causes the gases to increase their motion. This in turn causes an increase in the outward gas pressure. At some point, this outward pressure exactly balances the inward force of gravity, as shown in Figure 9. When this balance is reached, the star becomes a stable main-sequence star. Stated another way, a stable main-sequence star is balanced between two forces: gravity, which is trying to squeeze it into a smaller sphere, and gas pressure, which is trying to expand it.

Main-Sequence Stage  From this point in the evolution of a main-sequence star until its death, the internal gas pressure struggles to offset the unyielding force of gravity. Typically, hydrogen fusion continues for a few billion years and provides the outward pressure required to support the star from gravitational collapse.

Different stars age at different rates. Hot, massive blue stars radiate energy at such an enormous rate that they deplete their hydrogen fuel in only a few million years. By contrast, the least massive main-sequence stars may remain stable for hundreds of billions of years. A yellow star, such as the sun, remains a main-sequence star for about 10 billion years.

An average star spends 90 percent of its life as a hydrogen-burning, main-sequence star. Once the hydrogen fuel in the star’s core is depleted, it evolves rapidly and dies. However, with the exception of the least-massive red stars, a star can delay its death by fusing heavier elements and becoming a giant.
Red-Giant Stage The red-giant stage occurs because the zone of hydrogen fusion continually moves outward, leaving behind a helium core. Eventually, all the hydrogen in the star’s core is consumed. While hydrogen fusion is still progressing in the star’s outer shell, no fusion is taking place in the core. Without a source of energy, the core no longer has enough pressure to support itself against the inward force of gravity. As a result, the core begins to contract.

As the core contracts, it grows hotter by converting gravitational energy into heat energy. Some of this energy is radiated outward, increasing hydrogen fusion in the star’s outer shell. This energy in turn heats and expands the star’s outer layer. The result is a giant body hundreds to thousands of times its main-sequence size, as shown in Figure 10.

As the star expands, its surface cools, which explains the star’s reddish appearance. During expansion, the core continues to collapse and heat until it reaches 100 million K. At this temperature, it is hot enough to convert helium to carbon. So, a red giant consumes both hydrogen and helium to produce energy.

Eventually, all the usable nuclear fuel in these giants will be consumed. The sun, for example, will spend less than a billion years as a giant. More massive stars will pass through this stage even more rapidly. The force of gravity will again control the star’s destiny as it squeezes the star into the smallest, most dense piece of matter possible.

Why do red giants have a reddish appearance?
Burnout and Death

Use Visuals

Figure 11 Use this figure to explain how the evolution of stars depends on their mass. Ask: What stages do all stars go through? (nebula, protostar, main-sequence star) Which stars become red giants? (medium-mass and massive stars) Which stars become white dwarfs? (low-mass and medium-mass stars) What are two possible results of the death of a massive star? (It can become a neutron star or a black hole.)

Visual, Logical

Students may be confused by the term planetary nebula and think that planets form from planetary nebulae. Explain that a planetary nebula is a stage in the evolution of a star and has nothing to do with planets. The name is a result of historical accident. When planetary nebulae were discovered 200 years ago, they looked like small greenish disks similar to the planet Uranus. Even though they are not related to planets, the name stuck.

Verbal

Burnout and Death

Most of the events of stellar evolution discussed so far are well documented. What happens next is based more on theory. We do know that all stars, regardless of their size, eventually run out of fuel and collapse due to gravity. With this in mind, let’s consider the final stages of stars of different masses.

Death of Low-Mass Stars As shown in Figure 11A, stars less than one half the mass of the sun consume their fuel at a fairly slow rate. Consequently, these small, cool red stars may remain on the main sequence for up to 100 billion years. Because the interior of a low-mass star never reaches high enough temperatures and pressures to fuse helium, its only energy source is hydrogen. So, low-mass stars never evolve into red giants. Instead, they remain as stable main-sequence stars until they consume their hydrogen fuel and collapse into a white dwarf, which you will learn more about later.

Death of Medium-Mass Stars As shown in Figure 11B, stars with masses similar to the sun evolve in essentially the same way. During their giant phase, sunlike stars fuse hydrogen and helium fuel at a fast rate. Once this fuel is exhausted, these stars also collapse into white dwarfs.

During their collapse from red giants to white dwarfs, medium-mass stars are thought to cast off their bloated outer layer, creating an expanding round cloud of gas. The remaining hot, central white dwarf heats the gas cloud, causing it to glow. These often beautiful, gleaming spherical clouds are called planetary nebulae. An example of a planetary nebula is shown in Figure 12.

Facts and Figures

In a few billion years, the sun’s core will run out of hydrogen fuel, triggering hydrogen fusion in the surrounding shell. As a result, the sun’s outer envelope will expand, producing a red giant hundreds of times larger and brighter. Intense solar radiation will boil Earth’s oceans, and solar winds will drive away Earth’s atmosphere. Another billion years later, the sun will expel its outermost layer, producing a planetary nebula. The interior will collapse to produce a small, dense white dwarf. Gradually the sun will emit its remaining energy and become a cold black dwarf.
Death of Massive Stars
In contrast to sunlike stars, which die gracefully, stars with masses three times that of the sun have relatively short life spans, as shown in Figure 11C. These stars end their lives in a brilliant explosion called a supernova. During a supernova, a star becomes millions of times brighter than its prenova stage. If one of the nearest stars to Earth produced such an outburst, it would be brighter than the sun. Supernovae are rare. None have been observed in our galaxy since the invention of the telescope, although Tycho Brahe and Galileo each recorded one about 30 years apart. An even larger supernova was recorded in 1054 by the Chinese. Today, the remnant of this great outburst is the Crab Nebula, shown in Figure 13.

A supernova event is thought to be triggered when a massive star consumes most of its nuclear fuel. Without a heat engine to generate the gas pressure required to balance its immense gravitational field, the star collapses. This implosion, or bursting inward, is huge, resulting in a shock wave that moves out from the star’s interior. This energetic shock wave destroys the star and blasts the outer shell into space, generating the supernova event.

H-R Diagrams and Stellar Evolution Hertzsprung-Russell diagrams have been helpful in formulating and testing models of stellar evolution. They are also useful for illustrating the changes that take place in an individual star during its life span. Refer back to Figure 10, which shows the evolution of a star about the size of the sun. Keep in mind that the star does not physically move along this path. Its position on the H-R diagram represents the color and absolute magnitude of the star at various stages in its evolution.

What is a supernova?

Integrate Chemistry
Formation of Heavy Elements Tell students that all of the heavy (high atomic mass) atoms on Earth were formed inside stars. Initially the universe contained almost entirely hydrogen and helium. Biologically important elements such as carbon, nitrogen, and oxygen form inside many stars. However, very heavy elements such as lead and gold form only in the incredible explosions of supernovas. When the supernova fades, the elements are scattered throughout the area and may become part of a new solar system such as our own. Have students research the chain reactions inside stars and supernovas that produce heavy elements.

Logical
Use Community Resources Invite an astronomer or astrophysicist from a local college or university to the classroom to discuss astronomy and research. Ask students to prepare questions in advance to ask the visitor.

Interpersonal

Figure 13 Crab Nebula
This nebula, found in the constellation Taurus, is the remains of a supernova that took place in 1054.

Answer to . . .

A supernova is the brilliant explosion that marks the end of a massive star.
Eventually, all stars consume their nuclear fuel and collapse into one of three documented states—white dwarf, neutron star, or black hole. Although different in some ways, these small, compact objects are all composed of incomprehensibly dense material and all have extreme surface gravity.

**White Dwarfs** White dwarfs are the remains of low-mass and medium-mass stars. They are extremely small stars with densities greater than any known material on Earth. Although some white dwarfs are no larger than Earth, the mass of such a dwarf can equal 1.4 times that of the sun. So, their densities may be a million times greater than water. A spoonful of such matter would weigh several tons. Densities this great are possible only when electrons are displaced inward from their regular orbits, around an atom’s nucleus, allowing the atoms to take up less than the “normal” amount of space. Material in this state is called degenerate matter.

In degenerate matter, the atoms have been squeezed together so tightly that the electrons are displaced much nearer to the nucleus. Degenerate matter uses electrical repulsion instead of molecular motion to support itself from total collapse. Although atomic particles in degenerate matter are much closer together than in normal Earth matter, they still are not packed as tightly as possible. Stars made of matter that has an even greater density are thought to exist.

As a star contracts into a white dwarf, its surface becomes very hot, sometimes exceeding 25,000 K. Even so, without a source of energy, it can only become cooler and dimmer. Although none have been observed, the last stage of a white dwarf must be a small, cold cinder called a black dwarf. Table 2 summarizes the evolution of stars of various masses.

As you can see, the sun begins as a nebula, spends much of its life as a main-sequence star, becomes a red giant, planetary nebula, white dwarf, and finally, black dwarf.

<table>
<thead>
<tr>
<th>Initial Mass of Interstellar Cloud (Sun = 1)</th>
<th>Main-Sequence Stage</th>
<th>Giant Phase</th>
<th>Evolution After Giant Phase</th>
<th>Final Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–3</td>
<td>Yellow</td>
<td>Yes</td>
<td>Planetary nebula</td>
<td>White dwarf</td>
</tr>
<tr>
<td>6</td>
<td>White</td>
<td>Yes</td>
<td>Supernova</td>
<td>Neutron star</td>
</tr>
<tr>
<td>20</td>
<td>Blue</td>
<td>Yes (Supergiant)</td>
<td>Supernova</td>
<td>Black hole</td>
</tr>
</tbody>
</table>
**Neutron Stars** After studying white dwarfs, scientists made what might at first appear to be a surprising conclusion. The smallest white dwarfs are the most massive, and the largest are the least massive. The explanation for this is that a more massive star, because of its greater gravitational force, is able to squeeze itself into a smaller, more densely packed object than can a less massive star. So, the smaller white dwarfs were produced from the collapse of larger, more massive stars than were the larger white dwarfs.

This conclusion led to the prediction that stars smaller and more massive than white dwarfs must exist. These objects, called **neutron stars**, are thought to be the remnants of supernova events. In a white dwarf, the electrons are pushed close to the nucleus, while in a neutron star, the electrons are forced to combine with protons to produce neutrons. If Earth were to collapse to the density of a neutron star, it would have a diameter equal to the length of a football field. A pea-size sample of this matter would weigh 100 million tons. This is approximately the density of an atomic nucleus. Neutron stars can be thought of as large atomic nuclei.

**Supernovae** During a supernova, the outer layer of the star is ejected, while the core collapses into a very hot neutron star about 20 kilometers in diameter. Although neutron stars have high surface temperatures, their small size would greatly limit their brightness. Finding one with a telescope would be extremely difficult.

However, astronomers think that a neutron star would have a very strong magnetic field. Further, as a star collapses, it will rotate faster, for the same reason ice skaters rotate faster as they pull in their arms. Radio waves generated by these rotating stars would be concentrated into two narrow zones that would align with the star’s magnetic poles. Consequently, these stars would resemble a rapidly rotating beacon emitting strong radio waves. If Earth happened to be in the path of these beacons, the star would appear to blink on and off, or pulsate, as the waves swept past.

In the early 1970s, a source that radiates short bursts or pulses of radio energy, called a **pulsar**, was discovered in the Crab Nebula. Studies of this radio source revealed it to be a small spinning star centered in the nebula. The pulsar found in the Crab Nebula is undoubtedly the remains of the supernova of 1054.

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**Facts and Figures**

Pulsars were discovered by Jocelyn Bell Burnell in 1967. Burnell was a graduate student working on her advisor Anthony Hewish’s project to study rapid fluctuations in radio waves received from stars. One day she noticed some strong, rapid, and regular pulses coming from fixed points on the sky. Some people thought the pulses might be signals sent by an alien civilization, or “little green men,” so the sources were at first called LGM 1, LGM 2, LGM 3, and LGM 4. However, astronomers soon concluded that the signals had natural sources, which were named pulsars.
Section 25.2 (continued)

Use Visuals

Figure 15 Use this figure to explain how black holes can be detected. Ask: Can a black hole be detected directly? Why or why not? (no, because its gravity is so strong that not even light can escape)

What may happen if a black hole has a companion star? (The black hole may pull material out of the star and into itself.)

What happens to material as it falls into a black hole? (It becomes very hot and emits X-rays.) What would be good evidence for a black hole? (stellar material being heated and then apparently disappearing into nothingness)

Visual, Logical

3 ASSESS

Evaluate Understanding

Call on students to describe the stages that stars of different masses go through during their life cycles.

Reteach

Use Figure 10 to review the life cycle of a sunlike star and to emphasize that the H-R diagram is a graph, not a star chart.

Connecting Concepts

Sample answer: The effect on Earth would likely be devastating. Depending on the intensity of the radiation, living organisms would either be destroyed or genetically and physically damaged. Because the biosphere interacts with the remaining Earth systems, the entire Earth would be altered eventually.

Black Holes Are neutron stars made of the most dense materials possible? No. During a supernova event, remnants of stars three times more massive than the sun apparently collapse into objects even smaller and denser than neutron stars. Even though these objects, called black holes, are very hot, their gravity is so strong that not even light can escape their surface. So they disappear from sight. Anything that moves too near a black hole would be swept in by its gravity and lost forever.

How can astronomers find an object whose gravitational field prevents the escape of all matter and energy? One strategy is to find evidence of matter being rapidly swept into a region of apparent nothingness. Scientists think that as matter is pulled into a black hole, it should become very hot and emit a flood of X-rays before being pulled in. Because isolated black holes would not have a source of matter to swallow up, astronomers first looked at binary-star systems.

A likely candidate for a black hole is Cygnus X-1, a strong X-ray source in the constellation Cygnus. In this case, the X-ray source can be observed orbiting a supergiant companion with a period of 5.6 days. It appears that gases are pulled from this companion and spiral into the disk-shaped structure around the black hole, as shown in Figure 15.

Visual, Logical

ASSESS

Evaluate Understanding

Call on students to describe the stages that stars of different masses go through during their life cycles.

Reteach

Use Figure 10 to review the life cycle of a sunlike star and to emphasize that the H-R diagram is a graph, not a star chart.

Sample answer: The effect on Earth would likely be devastating. Depending on the intensity of the radiation, living organisms would either be destroyed or genetically and physically damaged. Because the biosphere interacts with the remaining Earth systems, the entire Earth would be altered eventually.

Section 25.2 Assessment

Reviewing Concepts

1. What is a protostar?
2. At what point is a star born?
3. What causes a star to die?
4. Describe the life cycle of the sun.

Critical Thinking

5. Inferring Why are less massive stars thought to age more slowly than more massive stars, even though less massive stars have much less “fuel”?

6. Relating Cause and Effect Why is interstellar matter important to stellar evolution?

Supernova If a supernova explosion were to occur near our solar system, what might be some possible consequences of the intense X-ray radiation that would reach Earth?

Section 25.2 Assessment

1. A protostar is a developing star not yet hot enough to engage in nuclear fusion.
2. When the core of a protostar has reached about 10 million K, pressure within it is so great that nuclear fusion of hydrogen begins, and a star is born.
3. A star runs out of fuel and collapses due to gravity.
4. The sun began as a nebula, became a protostar and then a main-sequence star. It will become a red giant, planetary nebula, white dwarf, and finally a black dwarf.
5. A less massive star will live longer because it consumes fuel at a slower rate than do more massive stars.
6. Stars are born out of clouds of interstellar matter.