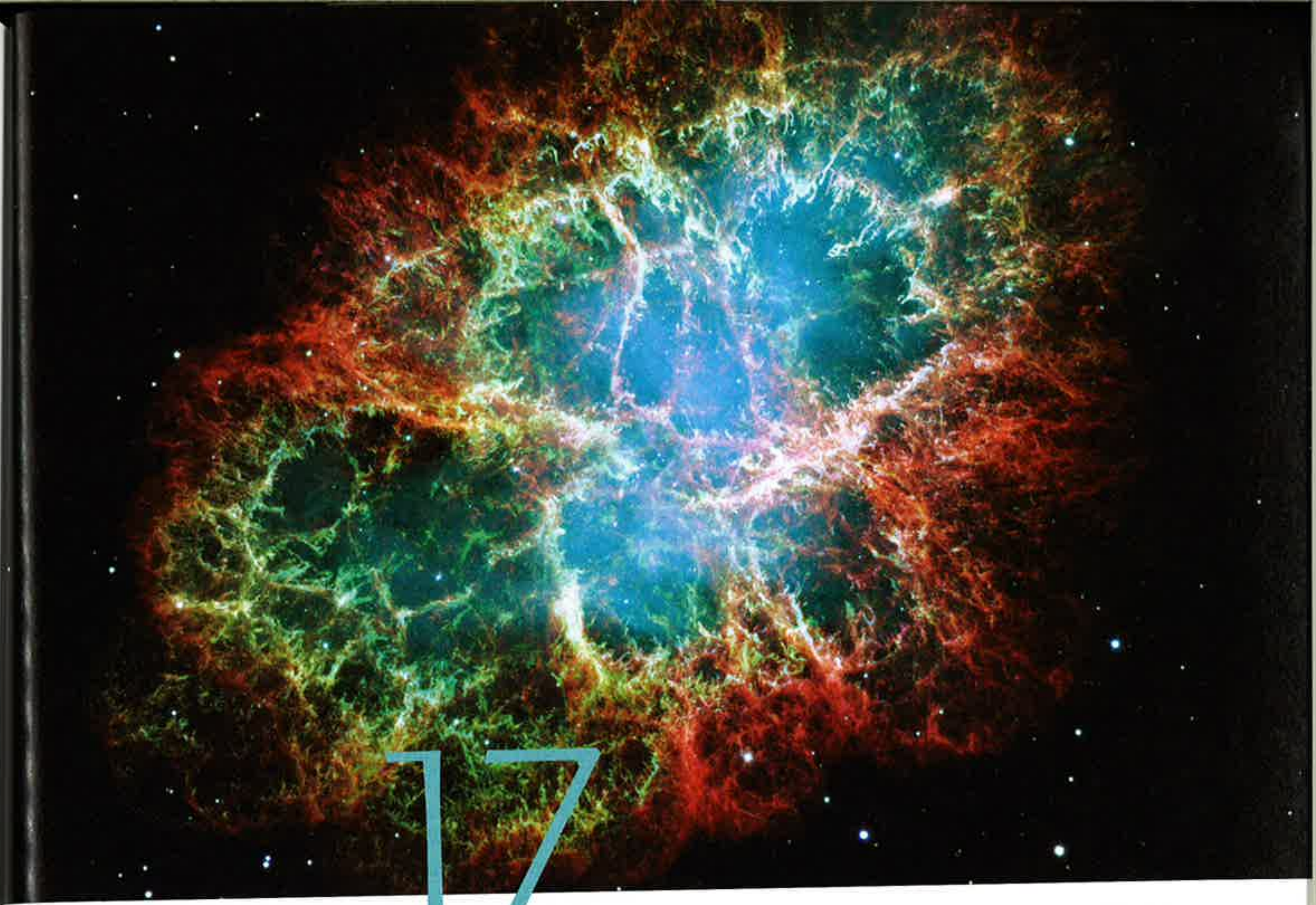


17

STAR STUFF

LEARNING GOALS

17.1 LIVES IN THE BALANCE

- How does a star's mass affect nuclear fusion?

17.2 LIFE AS A LOW-MASS STAR

- What are the life stages of a low-mass star?
- How does a low-mass star die?

17.3 LIFE AS A HIGH-MASS STAR

- What are the life stages of a high-mass star?
- How do high-mass stars make the elements necessary for life?
- How does a high-mass star die?

17.4 THE ROLES OF MASS AND MASS EXCHANGE

- How does a star's mass determine its life story?
- How are the lives of stars with close companions different?

We are, therefore, made out of star stuff ... we feed upon sunbeams, we are kept warm by the radiation of the Sun, and we are made out of the same materials that constitute the stars.

—Harlow Shapley, *The Universe of Stars*, 1929

We inhale oxygen with every breath. Iron-bearing hemoglobin in our blood carries this oxygen through our bodies. Chains of carbon and nitrogen form the backbone of the proteins, fats, and carbohydrates in our cells. Calcium strengthens our bones, while sodium and potassium ions moderate communications of the nervous system. What does all this biology have to do with astronomy? The profound answer, recognized only in the second half of the 20th century, is that life is based on elements created by stars.

We've already discussed in general terms how the elements in our bodies came to exist. Hydrogen and helium were produced in the Big Bang, and stars later created heavier elements that stellar explosions scattered into space. There, in the spaces between the stars, these elements mixed with interstellar gas and became incorporated into subsequent generations of stars.

In this chapter, we will discuss the origins of the elements in greater detail by delving into the lives of stars. As you read, keep in mind that no matter how far removed the stars may seem from our everyday lives, they actually are connected to us in the most intimate way possible: Without the lives and deaths of stars, none of us would be here. We are truly made from "star stuff."

17.1 LIVES IN THE BALANCE

The story of a star's life is in many ways the story of an extended battle between two opposing forces: gravity and pressure. We studied the early stages of this battle in Chapter 16. We examined the conditions under which gravity can overcome pressure in interstellar gas, causing fragments of a molecular cloud to contract into protostars, and we saw that gravity's advantage over pressure continues until fusion begins in a star's core. Once hydrogen fusion begins, the energy it generates balances the energy the star radiates into space. With energy balanced, the star's internal pressure stabilizes and halts the crush of gravity. The star is then in a state of equilibrium much like our Sun, with thermal pressure balancing gravity and fusion energy from the core balancing the flow of radiative energy from the star's surface [Section 14.2].

A star can remain in this state of balance for millions to billions of years, but it will eventually exhaust the hydrogen in its core. When that happens, fusion ceases in the core, and gravity regains the upper hand over pressure. The battle between pressure and gravity then grows increasingly more dramatic, with a final outcome that depends on the star's mass at birth.

How does a star's mass affect nuclear fusion?

We discussed the significance of stellar birth masses in Chapter 15. Main-sequence stars with large masses have much greater luminosities than ones with small masses, which means that their cores must release fusion energy at much greater rates.

Stars with large masses have greater fusion rates because they can attain high core temperatures much more easily than stars of lower mass. All stars approach gravitational equilibrium through gravitational contraction, which converts gravitational potential energy into thermal energy. However, stars of greater mass release larger amounts of gravitational potential energy and therefore heat up more rapidly, achieving the temperatures necessary for hydrogen fusion more quickly. As a result, these stars come into equilibrium with a larger size, a greater luminosity, and a higher core temperature than less massive stars. Because the rate of fusion is very sensitive to temperature [Section 14.2], massive stars achieve equilibrium with fusion rates far higher than those in lower mass stars. High-mass stars therefore burn through their hydrogen so rapidly that they end up with much shorter lifetimes than low-mass stars, even though they have more hydrogen to burn. In other words, the mass of a main-sequence star determines both its luminosity and its lifetime because it determines the core temperature and fusion rate at which the star can remain in gravitational equilibrium.

A star's mass also determines what happens when the star finally exhausts its core supply of hydrogen. Once the hydrogen is gone, fusion shuts down and the central core can no longer support itself against the crush of gravity. The core contracts, and the star's mass determines whether it eventually becomes hot enough to fuse helium or heavier elements. Even at the end of its life, when a star can no longer generate energy through fusion of any kind, its final fate depends on the mass it had at birth. As we will see, relatively low-mass stars like our Sun end up as white dwarfs, while high-mass stars die violently and leave behind either a neutron star or a black hole.

To simplify our discussion of stellar lives, it's useful to divide stars into three basic groups by mass:

- **Low-mass stars** are stars born with less than about 2 solar masses ($2M_{\text{Sun}}$) of material.
- **Intermediate-mass stars** have birth weights between about 2 and 8 solar masses.
- **High-mass stars** are those stars born with masses greater than about 8 solar masses.

We will focus primarily on the dramatic differences between the lives of low- and high-mass stars. The life stages of intermediate-mass stars are quite similar to the corresponding stages of high-mass stars until the very ends of their lives, so we include them in our discussion of high-mass stars.

As we discuss the life stories of stars in detail, you might wonder how we can claim to know what happens inside distant stars over time periods of millions and billions of years. After all, we can't even see what's happening inside any star right now. As always in science, astronomers' confidence in the life stories of stars comes from comparisons of theoretical models with detailed observations. On the theoretical side, we use mathematical models based on the known laws of physics to predict the interior structures and life cycles of stars. On the observational side, we study stars in star clusters (Figure 17.1).

FIGURE 17.1 This star cluster is about 50 million years old. The photo shows both blue main-sequence stars and red supergiants. The supergiants must have had birth masses slightly greater than $7M_{\text{Sun}}$, because the most massive main-sequence stars remaining in the cluster are around $7M_{\text{Sun}}$.

Recall that we can determine the ages of star clusters by finding their main-sequence turnoff points on H-R diagrams [Section 15.3]. By comparing clusters of different ages, we learn what stars of different masses are like at these ages. Occasionally, we even catch a star in its death throes. Our theoretical predictions of the life cycles of stars agree quite well with the observations and confirm the idea that nuclear fusion in stars has produced essentially all the elements heavier than helium. In the remainder of this chapter, we will examine in detail our modern understanding of the life stories of stars and how they manufacture the variety of elements that make our lives possible.

MA™ **Stellar Evolution Tutorial, Lesson 2**

17.2 LIFE AS A LOW-MASS STAR

In the grand hierarchy of stars, our Sun is rather mediocre. But we should be thankful for this mediocrity. If the Sun had been a high-mass star, it would have lasted only a few million years, dying before life could have arisen on Earth. Instead, the Sun has shone steadily for nearly 5 billion years, providing the light and heat that have allowed life to thrive on our planet. Other low-mass stars have similarly long lives. In this section, we investigate the lives and deaths of low-mass stars like our Sun.

What are the life stages of a low-mass star?

Our Sun is currently in the middle of its roughly 10-billion-year life as a hydrogen-burning, main-sequence star. We therefore expect it to continue to shine steadily for billions of years to come. Eventually, however, the Sun will exhaust its hydrogen and undergo a series of dramatic changes leading up to its death. Let's begin our study of a low-mass star's life stages with a look at what will happen to the Sun.

Main-Sequence Life: Slow and Steady As we discussed in Chapter 14, the Sun slowly and steadily fuses hydrogen into helium in its core via the *proton-proton chain* [Section 14.2]. The Sun shines steadily because of the self-regulating processes that we called the *solar thermostat*, in which gravitational equilibrium and the balance between the core energy production rate and the rate at which energy escapes into space work together to keep the Sun's fusion rate and overall luminosity quite steady.

Other low-mass stars generate energy and shine steadily in much the same way as our Sun throughout their main-sequence lives. Models of those stars indicate that their interior structure is generally like the Sun's, with some minor differences in the way energy moves through them. As in the Sun, the energy released by nuclear fusion in other low-mass stars takes hundreds of thousands of years to travel from the core to the surface, where it finally escapes into space. The energy moves outward from the core through a combination of *radiative diffusion* and *convection* [Section 14.2]. Radiative diffusion transports energy through the random bounces of photons from one electron to another, and convection transports energy through the rising of hot plasma and the sinking of cool plasma.

The depth of a star's convection zone depends on its internal temperature and hence on its mass (Figure 17.2). Deep inside a star like the Sun, the high temperatures allow radiative diffusion to carry energy outward at the same rate as fusion produces it in the core. Convection occurs only in the Sun's outer layers, where the cooler temperatures make it more difficult for photons to transport energy [Section 14.2]. In the Sun, the transition from radiative diffusion to convection occurs about 70% of the way from the center to the surface. Stars less massive than the Sun have cooler interiors and hence deeper convection zones. In very-low-mass stars, the convection zone extends all the way down to the core. Higher-mass stars have hotter interiors and hence shallower convection zones, and the highest-mass stars have no convection zone at all near their surfaces. However, high-mass stars

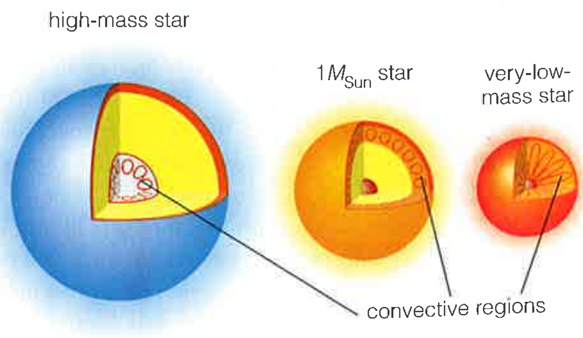


FIGURE 17.2 Among main-sequence stars, convection zones extend deeper in lower-mass stars. High-mass stars have convective cores but no convection zones near their surfaces.

can have convective cores, because they produce energy so furiously that radiative diffusion cannot transport it out of the core quickly enough. Convection therefore transports energy out of the cores of these high-mass stars, but radiative diffusion takes over throughout the rest of their interiors.

Convection plays a major role in determining whether a star has activity similar to that of the sunspot cycle on our Sun [Section 14.3]. Recall that the Sun's activity arises from the twisting and stretching of its magnetic fields by convection and rotation. The most dramatically active stars are very-low-mass stars (spectral type M) that happen to have fast rotation rates in addition to their deep convection zones. The churning interiors of these stars are in a constant state of turmoil, twisting and knotting their magnetic field lines. When these field lines suddenly snap and reconfigure themselves, releasing energy from the magnetic field, spectacular flares can occur. For a few minutes or hours, the flare can produce more radiation in X rays than the total amount of light coming from the star in infrared and visible light. Life on a planet near one of these **flare stars** might be quite difficult.

Aside from flares and other kinds of surface activity, the long lives of low-mass stars remain relatively uneventful as long as hydrogen fusion continues in the core. During that time, the luminosities of low-mass stars gradually rise for reasons we discussed in Chapter 14. Just as in the Sun, fusion in the core of a low-mass star reduces the number of independent particles in the core: Each fusion reaction converts four independent protons into just one independent helium nucleus. As the number of particles drops, the core must shrink and heat up in order to keep pressure in balance with gravity. This slight but continual rise in core temperature slowly raises the fusion rate and therefore the luminosity of the star as it ages. Much more dramatic changes occur only when nuclear fusion finally exhausts the star's central supply of hydrogen.

Red Giant Stage Hydrogen fusion supplies the thermal energy that maintains a star's thermal pressure and holds gravity at bay. But when the star's core hydrogen is finally depleted, nuclear fusion will cease. With no fusion to supply thermal energy and maintain the interior pressure, the star will be out of balance for the first time since it was a protostar. Unable to resist the crush of gravity, the core must begin to shrink. As an example of the dramatic changes that ultimately occur in all low-mass stars, let's consider what will happen to our own Sun as it passes through its final life stages about 5 billion years from now.

Somewhat surprisingly, the Sun's outer layers will expand outward at this time, even though its core will be shrinking under the crush of gravity. At first, the Sun's life track on an H-R diagram (Figure 17.3) will move almost horizontally to the right as it grows in size to become a **subgiant**. Then, as the expansion of the outer layers continues, the Sun's luminosity will begin to increase substantially, and its life track will turn upward on the H-R diagram. Over a period of about a billion years, the Sun will slowly grow in size and luminosity to become a **red giant**. At the end of its red giant stage, the Sun will be more than 100 times larger in radius and more than 1000 times brighter in luminosity than it is today.

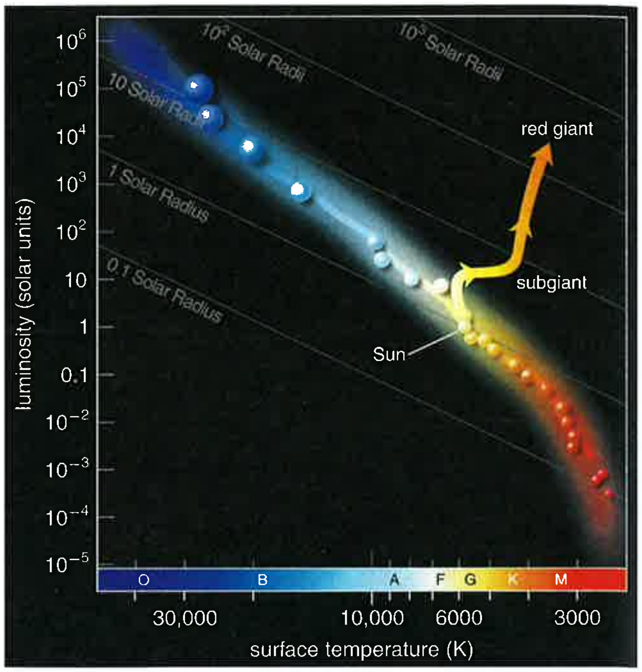


FIGURE 17.3 Interactive Figure The life track of a $1M_{\text{Sun}}$ star on an H-R diagram from the end of its main-sequence life until it becomes a red giant.

To understand why the Sun's outer layers will expand even while its core is shrinking, we need to think about the composition of the core at the end of the Sun's main-sequence life. After the core exhausts its hydrogen, it will be made almost entirely of helium, because helium is the "ash" left behind by hydrogen fusion. However, the gas surrounding the core will still contain plenty of fresh hydrogen that has never previously undergone fusion. Because gravity shrinks both the *inert* (nonburning) helium core and the surrounding *shell* of hydrogen, the hydrogen shell soon becomes hot enough for **hydrogen shell burning**—hydrogen fusion in a shell around the core (Figure 17.4). In fact, the shell will become so hot that hydrogen shell burning will proceed at a much higher rate than core hydrogen fusion does today. This increase in energy output will cause a buildup of thermal pressure inside the Sun, which will push its surface outward until the luminosity rises to match the elevated fusion rate. That is why the Sun will become a huge red giant as seen from the outside, even while most of its mass remains buried deep in its shrinking core.

The situation will grow more extreme as long as the helium core remains inert. Today, the self-correcting feedback process of the solar thermostat regulates the Sun's fusion rate: A rise in the fusion rate causes the core to inflate and cool until the fusion rate drops back down. In contrast, thermal energy generated in the hydrogen-burning shell of a red giant cannot do anything to inflate the inert core that lies underneath. Instead, newly produced helium keeps adding to the mass of the helium core, amplifying its gravitational pull and shrinking it further. The hydrogen-burning shell shrinks along with the core, growing hotter and denser. The fusion rate in the shell consequently rises, feeding even more helium ash to the core. The star is caught in a vicious circle with a broken thermostat.

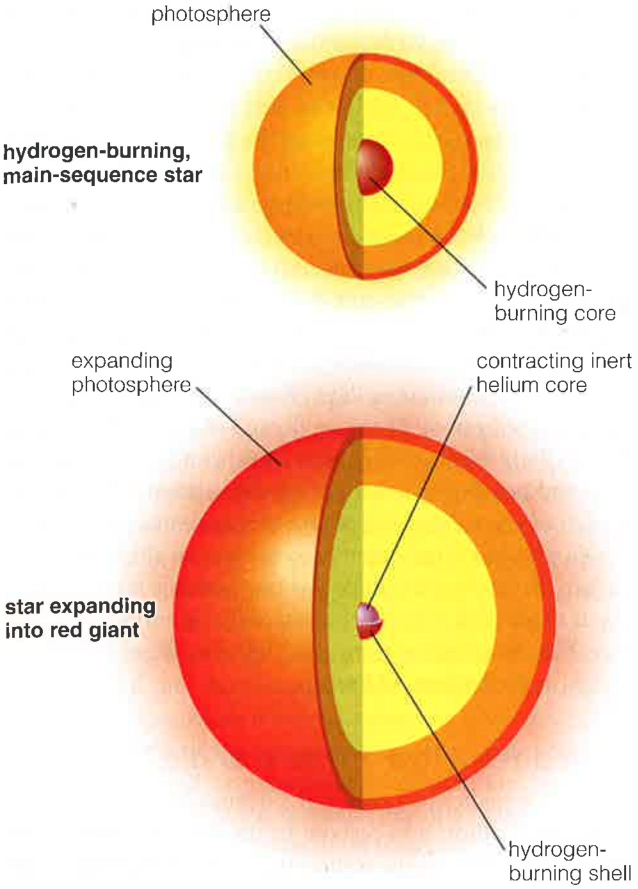


FIGURE 17.4 Interactive Figure After a star ends its main-sequence life, its inert helium core contracts while hydrogen shell burning begins. The high rate of fusion in the hydrogen shell forces the star's upper layers to expand outward.

The core and shell will therefore continue to shrink in size and heat up—with the Sun as a whole continuing to grow larger and more luminous—until the temperature of the inert helium core reaches about 100 million K. At that point, it will be hot enough for helium nuclei to begin to fuse together, and the Sun will enter the next stage of its life. Meanwhile, the Sun's increasing radius will weaken the pull of gravity at its surface, allowing large amounts of mass to escape via the *solar wind*. Observations of *stellar winds* from red giants show that they carry away much more matter than the solar wind carries away from the Sun today, but at much slower speeds.

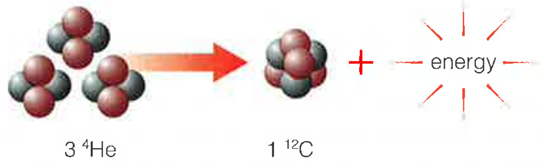
We expect all low-mass stars to expand into red giants in much the same way as the Sun. However, like all phases of stellar lives, the process occurs faster for more massive stars and more slowly for less massive stars. In fact, stars with masses much less than the Sun have such long main-sequence lifetimes that none of them can yet have reached the red giant stage in a 14-billion-year-old universe. Theoretical models tell us that in very-low-mass stars, degeneracy pressure will halt the collapse of their inert helium cores before they become hot enough to fuse helium. As a result, the "dead" cores of these stars will become white dwarfs made mostly of helium, or *helium white dwarfs*.

THINK ABOUT IT

Before you read on, briefly summarize why a star grows larger and brighter after it exhausts its core hydrogen. When does the growth of a red giant finally halt, and why? How would a star's red giant stage be different if the temperature required for helium fusion were around 200 million K, rather than 100 million K? Why?

Helium Burning Recall that fusion occurs only when two nuclei come close enough together for the attractive *strong force* to overcome electromagnetic repulsion [Section 14.2]. Helium nuclei have two protons (and two neutrons) and hence a greater positive charge than the single proton of a hydrogen nucleus. The greater charge means that helium nuclei repel one another more strongly than hydrogen nuclei. **Helium fusion** therefore occurs only when nuclei slam into one another at much higher speeds than those needed for hydrogen fusion, which means that helium fusion requires much higher temperatures than hydrogen fusion.

The helium fusion process (often called the *triple alpha reaction* because helium nuclei are sometimes called *alpha particles*) converts three helium nuclei into one carbon nucleus:



Energy is released because the carbon-12 nucleus has a slightly lower mass than the three helium-4 nuclei, and the lost mass becomes energy in accord with $E = mc^2$.

The ignition of helium burning in a low-mass star like the Sun has one subtlety. Theoretical models show that the thermal pressure in the inert helium core is too low to counteract gravity. Instead, according to the models, the pressure fighting against gravity is *degeneracy pressure*— the same type of pressure that supports brown dwarfs [Section 16.3]. Because degeneracy pressure does *not* increase with temperature, the onset of helium fusion heats the core rapidly without causing it to inflate. The rising temperature causes the helium fusion rate to rocket upward in what is called a **helium flash**.

The helium flash releases an enormous amount of energy into the core. In a matter of seconds, the temperature rises so much that thermal pressure again becomes dominant and degeneracy pressure is no longer important. In fact, the thermal pressure becomes strong enough to push back against gravity, and the core actually begins to expand. This core expansion pushes the hydrogen-burning shell outward, lowering its temperature and its fusion rate. The result is that, even though core helium fusion *and* hydrogen shell burning are taking place simultaneously in the star (Figure 17.5), the total energy production falls from its peak during the red giant stage, reducing the star's luminosity and allowing its outer layers to contract somewhat. As the outer layers contract, the star's surface temperature increases, so its color turns back toward yellow from red. Therefore, after the Sun spends about a billion years expanding into a luminous red giant, its size and luminosity will decline as it becomes a *helium-burning*

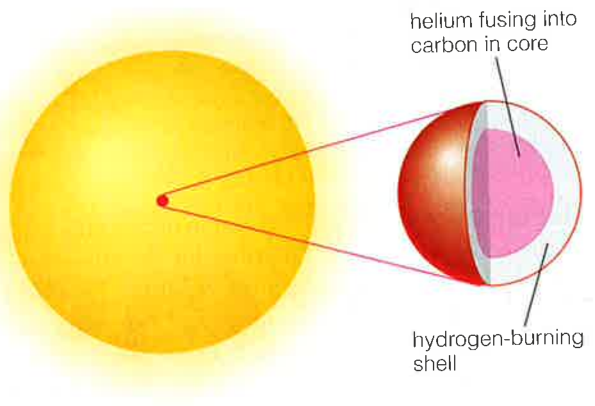


FIGURE 17.5 Interactive Figure Core structure of a helium-burning star. Helium fusion causes the core and hydrogen-burning shell to expand and slightly cool, thereby reducing the overall energy generation rate relative to that occurring during the red giant stage. The outer layers shrink, so a helium-burning star is smaller than a red giant of the same mass.

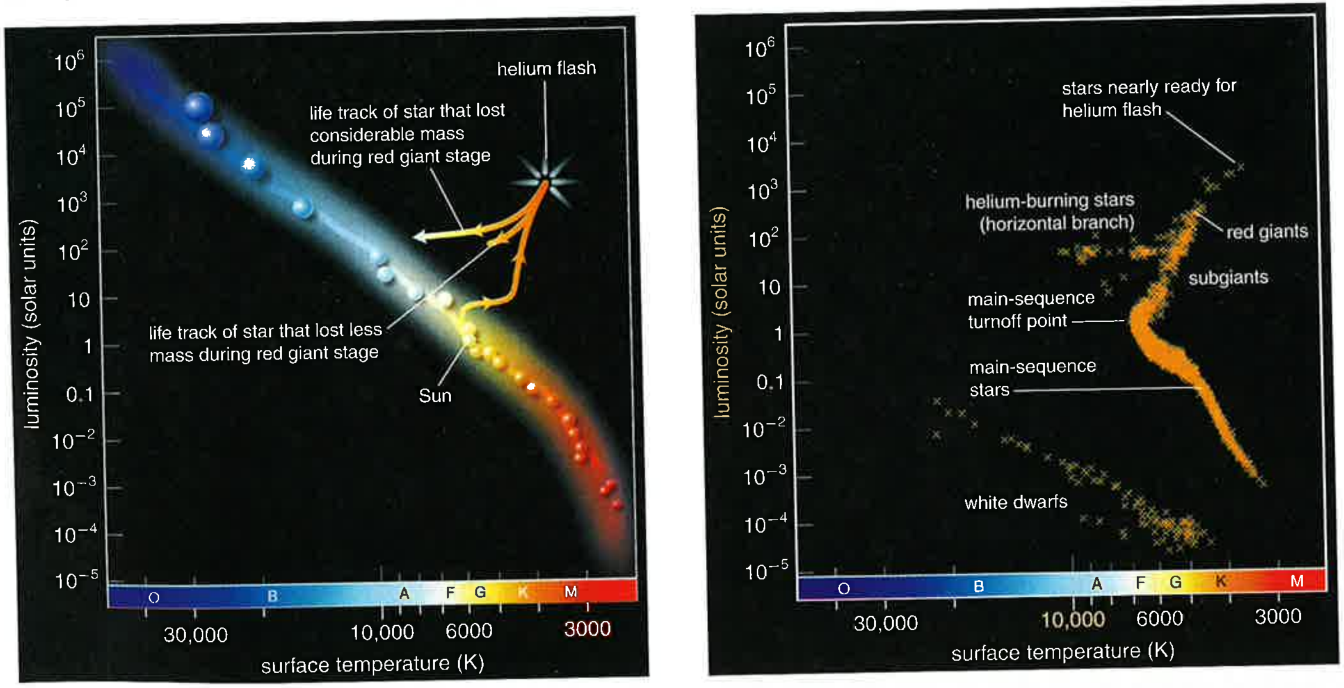
star. With fusion once again operating in the core, the star regains the same sort of balance it had as a main-sequence star, except now it is helium fusion that keeps the central temperature steady.

Because the helium-burning star is now smaller and hotter than it was as a red giant, its life track on the H-R diagram drops downward and to the left (Figure 17.6a). The helium cores of all low-mass stars fuse helium into carbon at about the same rate, so these stars all have about the same luminosity. However, the outer layers of these stars can have different masses depending on how much mass they have expelled through their stellar winds. Stars that expelled more mass end up with smaller radii and higher surface temperatures and hence are farther to the left on the H-R diagram.

We can see examples of low-mass stars in all the life stages we have discussed so far in the H-R diagram of a globular cluster (Figure 17.6b). Stars along the lower right of the H-R diagram, below the main-sequence turnoff point, are still in their hydrogen-burning, main-sequence stage. Just above and to the right of the main-sequence turnoff point we see subgiants—stars that have just begun their expansion into red giants as their cores have shut down and hydrogen shell burning has begun. The longer a star undergoes hydrogen shell burning, the larger and more luminous it becomes, which is why we see a continuous line of stars right up to the most luminous red giants. These are the red giants on the verge of helium flash. The stars that have already undergone a helium flash and become helium-burning stars appear below and to the left of the red giants, because they are somewhat smaller, hotter, and less luminous than they were at the moment of helium flash. Because these helium-burning stars all have about the same luminosity but can differ in surface temperature, they trace out a horizontal line on the H-R diagram known as the **horizontal branch**.

How does a low-mass star die?

It is only a matter of time until a helium-burning star fuses all its core helium into carbon. In the Sun, the core helium will run out after about 100 million years of burning—only about 1% as long as the Sun's 10-billion-year main-sequence lifetime. When the core helium is exhausted, fusion will again cease, and the star will once again go out of balance. The



a Helium fusion begins with the helium flash, after which the star's surface shrinks and heats, making the star's life track move downward and to the left on the H-R diagram.

b An H-R diagram of a globular cluster shows low-mass stars in several different life stages.

FIGURE 17.6 Interactive Figure After a low-mass star exhausts its core hydrogen, hydrogen shell burning causes it to grow into a red giant. Once its helium core becomes hot enough for fusion, it temporarily settles down as a helium-burning star.

core, now made of the carbon "ash" from helium fusion, will begin to shrink once again under the crush of gravity.

Last Gasps The exhaustion of core helium will cause the Sun to expand once again, just as it did when it became a red giant. This time, the trigger for the expansion will be helium fusion in a shell around the inert carbon core. Meanwhile, the hydrogen shell will still burn atop the helium layer. The Sun will have become a *double shell–burning giant.* Both shells will contract along with the inert core, driving their temperatures and fusion rates so high that the Sun will expand to an even greater size and luminosity than it had in its first red giant stage. Theoretical models show that helium burning inside such a star never reaches equilibrium but instead proceeds in a series of **thermal pulses** during which the fusion rate spikes upward every few thousand years.

The furious burning in the helium and hydrogen shells cannot last long—maybe a few million years or less. The Sun's only hope of extending its life will then lie with its carbon core, but this is a false hope for a low-mass star like the Sun. Carbon fusion is possible only at temperatures above about 600 million K, but degeneracy pressure will halt the collapse of the Sun's core before it ever gets that hot. With the carbon core unable to undergo fusion and provide a new source of energy, the Sun will have reached the end of its life.

During this final stage, the huge size of a dying star gives it only a very weak grip on its outer layers. As the star's luminosity and radius rise, increasing amounts of matter flow outward with the star's stellar wind. Meanwhile, during each thermal pulse, strong convection dredges up carbon from the core, enriching the surface of the star with carbon. Red giants whose photospheres become especially carbon-rich in this way are called **carbon stars.**

Carbon stars have cool, low-speed stellar winds, and the temperature of the gas in these winds drops with distance from the stellar surface. At the point at which the temperature has dropped to 1000–2000 K, some of the gas atoms in these slow-moving winds begin to stick together in microscopic clusters, forming small, solid particles of dust. These dust particles continue their slow drift with the stellar wind into interstellar space, where they become the interstellar dust grains that we discussed in Chapter 16. The process of particulate formation is similar to the formation of smoke particles in a fire. Thus, in a sense, carbon stars are the most voluminous polluters in the universe. However, this "carbon smog" is essential to life: Most of the carbon in your body (and in all life on Earth) was manufactured in carbon stars and blown into space by their stellar winds.

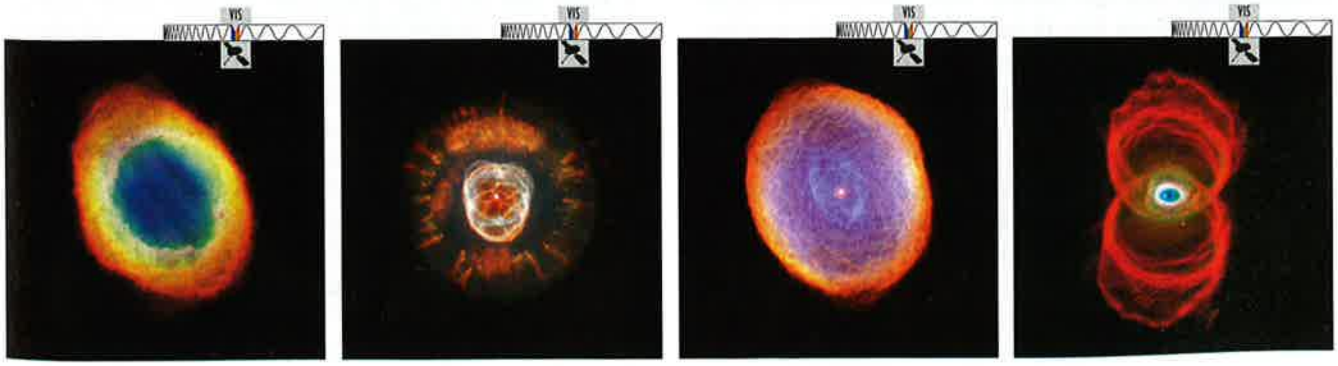
THINK ABOUT IT

Suppose the universe contained only low-mass stars. Would elements heavier than carbon exist? Why or why not?

Planetary Nebula The Sun's end will be beautiful to those who witness it, as long as they stay far away. Through winds and other processes, the Sun will eject its outer layers into space, creating a huge shell of gas expanding away from the inert carbon core. The exposed core will still be very hot and will therefore emit intense ultraviolet radiation. This radiation will ionize the gas in the expanding shell, making it glow brightly as a **planetary nebula.** We have photographed many examples of planetary nebulae around other low-mass stars that have recently died in this way (Figure 17.7). Note that, despite their name, planetary nebulae have nothing to do with planets. The name comes from the fact that nearby planetary nebulae look much like planets through small telescopes, appearing as simple disks.

The glow of the planetary nebula will fade as the exposed core cools and the ejected gas disperses into space. The nebula will disappear within a million years, leaving the Sun's cooling carbon core behind as a *white dwarf.* Recall from Chapter 15 that white dwarfs are small in radius and often quite hot. We can now understand why: They are small in radius because they are the exposed cores of dead stars, supported against the crush of gravity by degeneracy pressure. They are often hot because some of them were only recently in the center of a star and have not yet had time to cool much.

In the ongoing battle between gravity and a star's internal pressure, white dwarfs are in a sort of stalemate. As long as no mass is added to the white dwarf from some other source (such as a companion star in a binary system), neither the strength of gravity nor the strength of the degeneracy pressure



a Ring Nebula **b** Eskimo Nebula **c** Spirograph Nebula **d** Hourglass Nebula

FIGURE 17.7 Hubble Space Telescope photos of planetary nebulae, which form when low-mass stars in their final death throes cast off their outer layers of gas. The central white dots are the remaining hot cores of the stars that ejected the gas. These hot cores ionize and energize the shells of gas that surround them. As the gas of the nebula disperses into space, the hot core remains as a white dwarf.

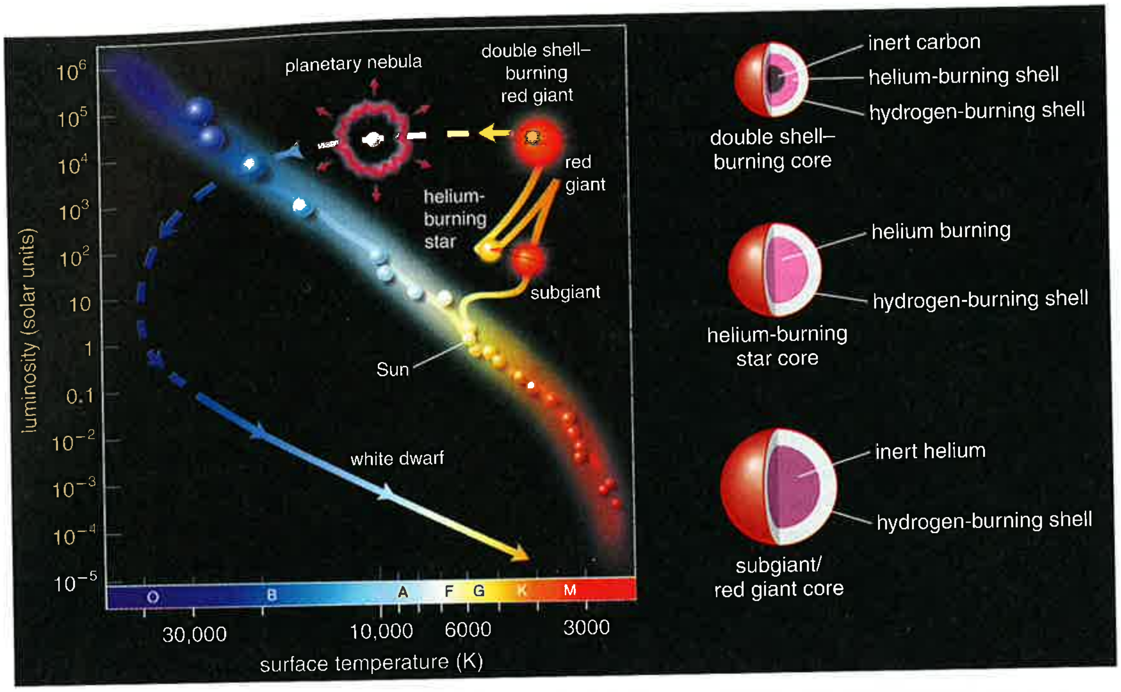


FIGURE 17.8 Interactive Figure The life track of a $1M_{\text{Sun}}$ star from the time it first becomes a hydrogen-burning, main-sequence star to the time it dies as a white dwarf. Core structure is shown at key stages.

that holds gravity at bay will ever change. A white dwarf is therefore little more than a decaying corpse that will cool for the indefinite future, eventually disappearing from view as it becomes too cold to emit any more visible light.

Figure 17.8 summarizes the life stages of a $1M_{\text{Sun}}$ star on an H-R diagram, starting from the time it reaches the main sequence and continuing until it produces a planetary nebula and leaves a white dwarf behind. We have already examined the life track to the point at which the star becomes a helium-burning star (see Figures 17.3 and 17.6). On this new diagram, we can see what happens after core helium burning ends. The life track again turns upward as the star enters its second red giant phase, this time with energy generated by fusion in shells of both helium and hydrogen. As the star ejects the gases of the planetary nebula, the dashed curve indicates that we are shifting from plotting the surface temperature of a red giant to plotting the surface temperature of the exposed stellar core left behind. The curve becomes solid again near the lower left, indicating that this core is a hot white dwarf. From that point, the curve continues downward and to the right as the remaining ember cools and fades.

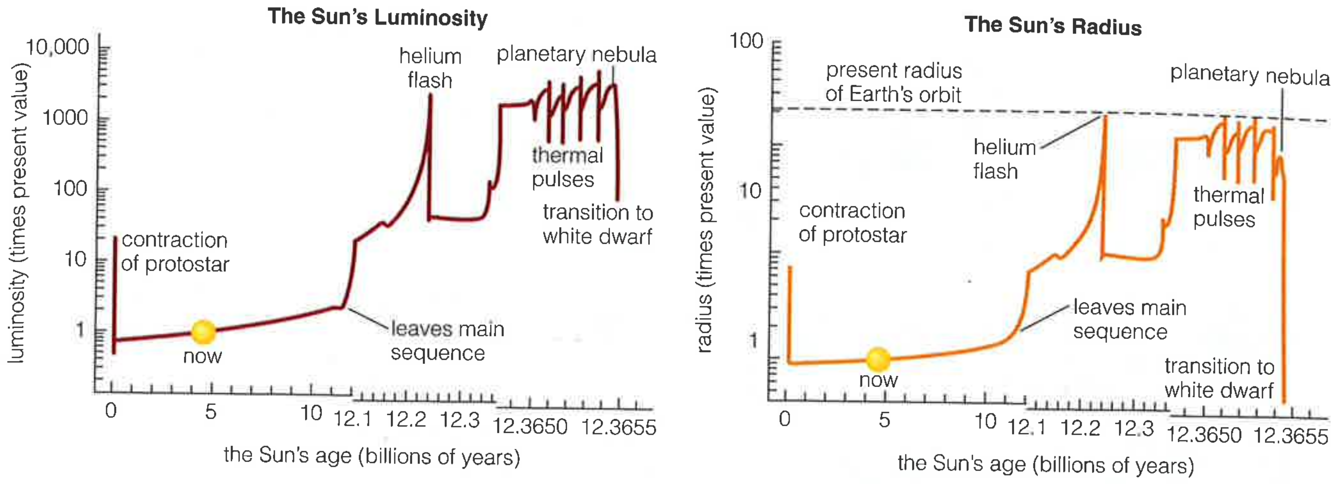
The Fate of the Earth The death of the Sun will obviously have consequences for Earth, and some of these consequences will begin even before the Sun enters the final stages of its life. The Sun will gradually brighten during its remaining time as a main-sequence star, just as it has been brightening since its birth more than 4 billion years ago [Section 14.2]. The Sun's past brightening has not threatened the long-term survival of life on Earth, because Earth's climate self-regulates by adjusting the strength of the greenhouse effect (through the carbon dioxide cycle [Section 10.6]). However, this climate regulation will eventually break down as the Sun warms.

We still do not understand climate regulation well enough to be certain when the warming Sun will begin to overheat Earth. Some climate models predict that the oceans will begin to evaporate about a billion years from now, while other models suggest that our planet's climate may remain stable much longer. All models agree that, by about 3–4 billion years from now, the Sun will have brightened enough to doom Earth to a runaway greenhouse effect like that on Venus [Section 10.5]. The oceans will boil away, presumably spelling the end for any living organisms that have not stored water in well-protected enclosures.

Temperatures on Earth will rise even more dramatically when the Sun finally exhausts its core supply of hydrogen, somewhere around the year A.D. 5,000,000,000, and conditions will become even worse as the Sun grows into a red giant over the next several hundred million years. Just before the helium flash, the Sun will be more than 1000 times as luminous as it is today, and this huge luminosity will heat Earth's surface to more than 1000 K (Figure 17.9a). Clearly, any surviving humans will need to have found a new home. Saturn's moon Titan [Section 11.2] might not be a bad choice. Its surface temperature will have risen from well below freezing to about the present temperature of Earth.

The Sun will shrink and cool somewhat after its helium flash turns it into a helium-burning star, providing a temporary lull in the incineration of Earth. However, this respite will last only 100 million years or so, and then Earth will suffer one final disaster.

After exhausting its core helium, the Sun will expand again during its last million years. Its luminosity will soar to thousands of times what it is today, and its radius will grow to nearly the present radius of Earth's orbit—so large that solar prominences might lap at Earth's surface (Figure 17.9b). Finally, the Sun will eject its outer layers, creating a planetary nebula



a Changes in the Sun's luminosity over time.

b Changes in the Sun's radius over time.

FIGURE 17.9 Evolution of the Sun. These graphs show results from a theoretical model of how the Sun's luminosity (left) and radius (right) should change throughout its life. (This model gives a main-sequence lifetime of about 11 billion years, slightly greater than the more commonly quoted 10-billion-year lifetime.)

that will engulf Jupiter and Saturn and eventually extend into interstellar space. If Earth is not destroyed, its charred surface will be cold and dark in the faint, fading light of the white dwarf that the Sun will become.

MA™ **Stellar Evolution Tutorial, Lesson 3**

17.3 LIFE AS A HIGH-MASS STAR

Human life would be impossible without both low- and high-mass stars. The long lives of low-mass stars allow evolution to proceed for billions of years, but only high-mass stars produce the full array of elements on which life depends.

The early stages of a high-mass star's life are similar to the early stages of the Sun's life, except they proceed much more rapidly. But the late stages of life are quite different for high-mass stars. The cores of low-mass stars never become hot enough to fuse elements heavier than helium. Heavier nuclei contain more positively charged protons and therefore repel each other more strongly than lighter nuclei. As a result, these nuclei can fuse only at extremely high temperatures—temperatures that occur only in the core of a high-mass star nearing the end of its life, when the immense weight of its overlying layers bears down on a core that has already exhausted its hydrogen fuel.

The highest-mass stars proceed to fuse increasingly heavy elements until they have exhausted all possible fusion sources. When fusion finally stops for good, gravity causes the core to implode suddenly. As we will soon see, the implosion of the core causes the star to self-destruct in the titanic explosion we call a *supernova*. The fast-paced life and cataclysmic death of a high-mass star are surely among the great dramas of the universe.

What are the life stages of a high-mass star?

Like all other stars, a high-mass star forms out of a cloud fragment that gravity forces to contract into a protostar. Hydrogen burning begins when the gravitational potential energy released by the contracting protostar makes the core hot enough for fusion. However, hydrogen fusion inside a high-mass star proceeds through a different set of steps than those for hydrogen fusion in a low-mass star, which is part of the reason why high-mass stars live such brief but brilliant lives.

Hydrogen Fusion in a High-Mass Star Recall that a low-mass star like our Sun fuses hydrogen into helium through the *proton-proton chain* (see Figure 14.7). In a high-mass star, the strong gravity compresses the hydrogen core to a higher temperature than we find in lower-mass stars. The hotter core temperature makes it possible for protons to slam into carbon, oxygen, or nitrogen nuclei as well as into other protons. Although carbon, nitrogen, and oxygen make up less than 2% of the material from which stars form in interstellar space, this 2% is more than enough to be useful in a stellar core. The carbon, nitrogen, and oxygen act as catalysts for hydrogen fusion, making it proceed at a far higher rate than would be possible by the proton-proton chain alone. (A *catalyst* is something that aids the progress of a reaction without being consumed in the reaction.) This faster chain of hydrogen fusion reactions is called the **CNO cycle**, with the letters C, N, and O standing for carbon, nitrogen, and oxygen, respectively. Figure 17.10 shows the six steps of the CNO cycle.

Notice that the overall reaction of the CNO cycle is the same as that of the proton-proton chain: Four hydrogen nuclei fuse into one helium-4 nucleus. The amount of energy generated in each reaction cycle therefore is also the same—it is equal to the difference in mass between the four hydrogen nuclei and the one helium nucleus multiplied by c^2. However, the CNO cycle allows hydrogen fusion to proceed at a rate far higher than would be possible by the proton-proton chain alone. That is why the luminosities of high-mass stars are so much higher than those of low-mass stars and why their lives are so much shorter.

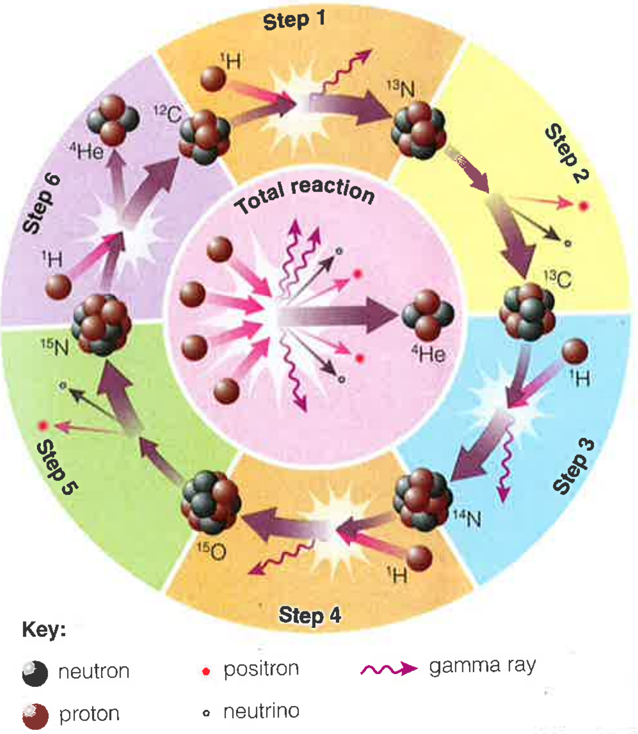


FIGURE 17.10 This diagram illustrates the six steps of the CNO cycle by which massive stars fuse hydrogen into helium. The overall result is the same as that of the proton-proton chain: Four hydrogen nuclei fuse to make one helium nucleus. The carbon, nitrogen, and oxygen nuclei are catalysts that help the cycle proceed but are neither consumed nor created in the overall cycle.

The enormous fusion rates in high-mass stars generate remarkable amounts of power. Many more photons stream from the photospheres of high-mass stars than from the Sun, and many more photons are bouncing around inside. These photons exert a significant amount of *radiation pressure* in high-mass stars. Recall that radiation pressure ultimately blows apart the highest-mass stars, which is why there is an upper limit to stellar masses [Section 16.3]. Near the photosphere of a very-high-mass star, the radiation pressure can drive strong, fast-moving winds. The wind from such a star can expel as much as 10^{-5} solar mass of gas per year at speeds greater than 1000 kilometers per second. This wind would cross the United States in about 5 seconds and would send a mass equivalent to that of our Sun hurtling into space in only 100,000 years. Such a wind cannot last long because it would blow away all the mass of even a very massive star in just a few million years.

THINK ABOUT IT

Did the very first high-mass stars in the history of the universe produce energy through the CNO cycle? Explain.

Becoming a Supergiant With hydrogen fusion proceeding at a fast rate via the CNO cycle, high-mass stars soon begin to run low on core hydrogen fuel. For example, a $25M_{\text{Sun}}$ star can last only a few million years as a hydrogen-burning, main-sequence star. As its core hydrogen runs out, a high-mass star responds much like a low-mass star, but much faster. It develops a hydrogen-burning shell, and its outer layers begin to expand outward, ultimately turning it into a *supergiant*. At the same time, the core contracts, and this gravitational contraction releases energy that raises the core temperature until it becomes hot enough to fuse helium into carbon. However, there is no helium flash in stars of more than 2 solar masses. Their core temperatures are so high that thermal pressure remains strong, preventing degeneracy pressure from being a factor. Helium burning therefore ignites gradually, just as hydrogen burning did at the beginning of the star's life.

A high-mass star fuses helium into carbon so rapidly that it is left with an inert carbon core after no more than a few hundred thousand years. Once again, the absence of fusion leaves the core without an energy source to fight off the crush of gravity. The inert carbon core shrinks, the crush of gravity intensifies, and the core pressure, temperature, and density all rise. Meanwhile, a helium-burning shell forms between the

SPECIAL TOPIC

How Long Is 5 Billion Years?

The Sun's demise in about 5 billion years might at first seem worrisome, but 5 billion years is a very long time. It is longer than Earth has yet existed, and human time scales pale by comparison. A single human lifetime, if we take it to be about 100 years, is only 2×10^{-8}, or two-hundred-millionths, of 5 billion years. Because 2×10^{-8} of a human lifetime is about 1 minute, we can say that a human lifetime compared to the life expectancy of the Sun is roughly the same as 60 heartbeats compared to a human lifetime.

What about human creations? The Egyptian pyramids have often been described as "eternal," but they are slowly eroding due to wind, rain, air pollution, and the impact of tourists. All traces of them will have vanished within a few hundred thousand years. While a few hundred thousand years may seem like a long time, the Sun's remaining lifetime is more than 1000 times longer.

On a more somber note, we can gain perspective on 5 billion years by considering evolutionary time scales. During the past century, our species has acquired sufficient technology and power to destroy human life totally, if we so choose. However, even if we make that unfortunate choice, some species (including many insects) are likely to survive.

Would another intelligent species ever emerge on Earth? We have no way to know [Section 24.4], but we can look to the past for guidance. Many species of dinosaurs were biologically quite advanced, if not truly intelligent, when they were suddenly wiped out about 65 million years ago. Some small rodent-like mammals survived, and here we are 65 million years later. We therefore might guess that another intelligent species could evolve some 65 million years after a human extinction. If these beings also destroyed themselves, another species could evolve 65 million years after that, and so on.

Even at 65 million years per shot, Earth would have *nearly 80* more chances for an intelligent species to evolve in 5 billion years (5 billion/65 million = 77). Perhaps one of those species will not destroy itself, and future generations might move on to other star systems by the time the Sun finally dies. Perhaps this species will be our own.

inert core and the hydrogen-burning shell. The star's outer layers swell further.

Up to this point, the life stories of intermediate-mass stars (2–8M_{Sun}) and high-mass stars (>8M_{Sun}) are very similar, except that all stages proceed more rapidly in high-mass stars. However, degeneracy pressure prevents the cores of intermediate-mass stars from reaching the temperatures required to burn carbon or oxygen and produce anything heavier. These stars eventually blow away their upper layers and finish their lives as white dwarfs. The rest of a high-mass star's life, on the other hand, is unlike anything that a low- or intermediate-mass star ever experiences.

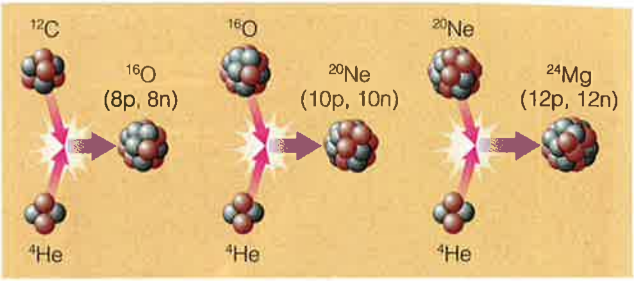
How do high-mass stars make the elements necessary for life?

A low-mass star can't make elements heavier than carbon because degeneracy pressure halts the contraction of its inert carbon core before it can get hot enough for fusion. A high-mass star has no such problem. The crush of gravity in a high-mass star keeps its carbon core so hot that degeneracy pressure never comes into play. After helium fusion stops, the gravitational contraction of the carbon core continues until it reaches the 600 million K required to fuse carbon into heavier elements.

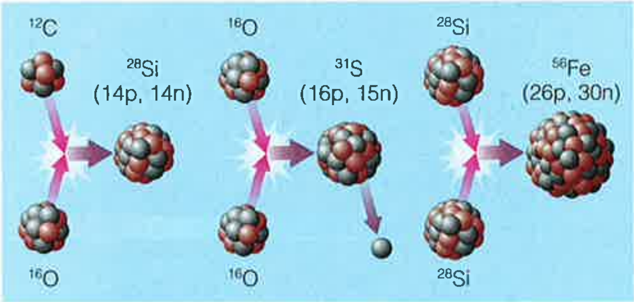
Carbon fusion provides the core with a new source of energy that restores gravitational equilibrium, but only temporarily. In the highest-mass stars, carbon burning may last only a few hundred years. When the core carbon has been depleted, the core again begins to collapse, shrinking and heating once more until it can fuse a still heavier element. The star is engaged in the final phases of a desperate battle against the ever-strengthening crush of gravity. The star will ultimately lose the battle, but it will be a victory for life in the universe: In the process of its struggle against gravity, the star will produce the heavy elements of which Earth-like planets and living things are made.

Advanced Nuclear Burning The nuclear reactions in a high-mass star's final stages of life become quite complex, and many different reactions may take place simultaneously. The simplest sequence of fusion stages occurs through successive **helium-capture reactions**—reactions in which a helium nucleus fuses with some other nucleus (Figure 17.11a). Helium capture reactions can change carbon into oxygen, oxygen into neon, neon into magnesium, and so on.*

At high enough temperatures, a star's core plasma can fuse heavy nuclei to one another. For example, fusing carbon to oxygen creates silicon, fusing two oxygen nuclei creates sulfur, and fusing two silicon nuclei generates iron (Figure 17.11b). Some of these heavy-element reactions release free neutrons, which may fuse with heavy nuclei to make still rarer elements. The star is forging the variety of elements that, in our solar system at least, became the stuff of life.



a Helium-capture reactions.



b Other reactions. (Note: Fusion of two silicon nuclei first produces nickel-56, which decays rapidly to cobalt-56 and then to iron-56.)

FIGURE 17.11 A few of the many nuclear reactions that occur in the final stages of a high-mass star's life.

Each time the core depletes the elements it is fusing, it shrinks and heats until it becomes hot enough for other fusion reactions. Meanwhile, a new type of shell burning ignites between the core and the overlying shells of fusion. Near the end, the star's central region resembles the inside of an onion, with layer upon layer of shells burning different elements (Figure 17.12). During the star's final few days, iron begins to pile up in the silicon-burning core.

Despite the dramatic events taking place in its interior, the high-mass star's outer appearance changes slowly. As each stage of core fusion ceases, the surrounding shell burning intensifies and further inflates the star's outer layers. Each time the core flares up, the outer layers contract somewhat but the star's overall luminosity remains about the same. The

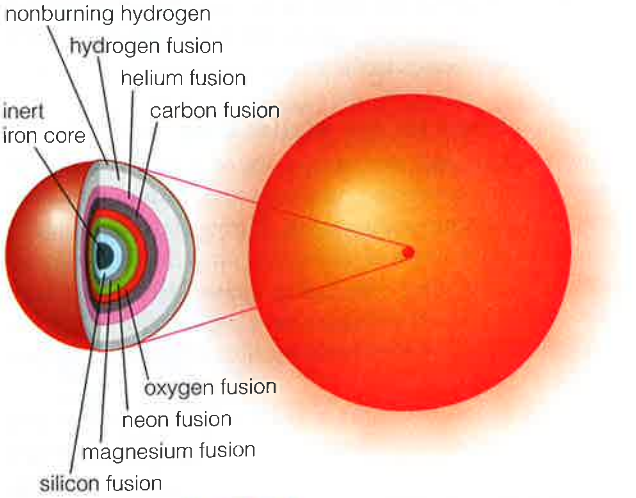


FIGURE 17.12 Interactive Figure The multiple layers of nuclear burning in the core of a high-mass star during the final days of its life.

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*These reactions can still proceed even after the star has used up its initial supply of core helium because there are other reactions that release helium nuclei. For example, when two carbon nuclei fuse together, the reaction can produce a neon nucleus and a helium nucleus.

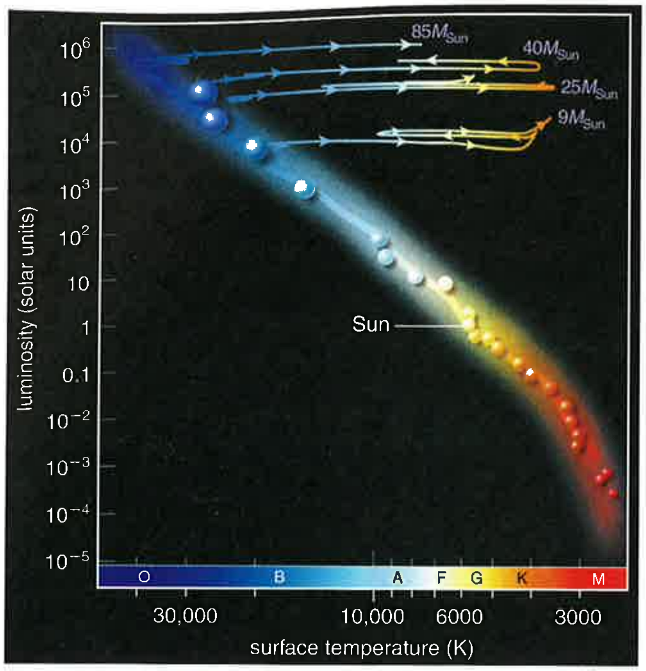


FIGURE 17.13 Interactive Figure Life tracks on the H-R diagram from main-sequence star to red supergiant for a few high-mass stars. Labels on the tracks give the star's mass at the beginning of its main-sequence life. Because of the strong wind from such a star, its mass can be considerably smaller when it leaves the main sequence. (Based on models from A. Maeder and G. Meynet.)

result is that the star's life track zigzags across the top of the H-R diagram (Figure 17.13). In the most massive stars of all, the core changes happen so quickly that the outer layers don't have time to respond, and the star progresses steadily toward becoming a red supergiant.

One of these massive, red supergiant stars happens to be relatively nearby: Betelgeuse, the upper left shoulder of Orion. Its radius is greater than 500 solar radii, or more than twice the distance from the Sun to Earth. We have no way of knowing what stage of nuclear burning is now taking place in Betelgeuse's core. Betelgeuse may have a few thousand years of nuclear burning still ahead, or we may be seeing it as iron piles up in its core. If the latter is the case, then sometime in the next few days we will witness one of the most dramatic events that ever occurs in the universe.

Iron: Bad News for the Stellar Core As a high-mass star develops an inert core of iron, the core continues shrinking and heating while iron continues to pile up from nuclear burning in the surrounding shells. If iron were like the other elements in prior stages of nuclear burning, this core contraction would stop when iron fusion ignited. However, iron is unique among the elements in a very important way: It is the one element from which it is *not* possible to generate any kind of nuclear energy.

To understand why iron is unique, remember that only two basic processes can release nuclear energy: *fusion* of light elements into heavier ones and *fission* of very heavy elements into not-so-heavy ones (see Figure 14.5). Recall that hydrogen fusion converts four protons (hydrogen nuclei) into a helium nucleus that consists of two protons and two neutrons. The total number of *nuclear particles* (protons and neutrons combined) does not change. However, this fusion reaction generates energy (in accord with $E = mc^2$) because the *mass* of the helium nucleus is less than the combined mass of the four hydrogen nuclei that fused to create it—despite the fact that the *number* of nuclear particles is unchanged.

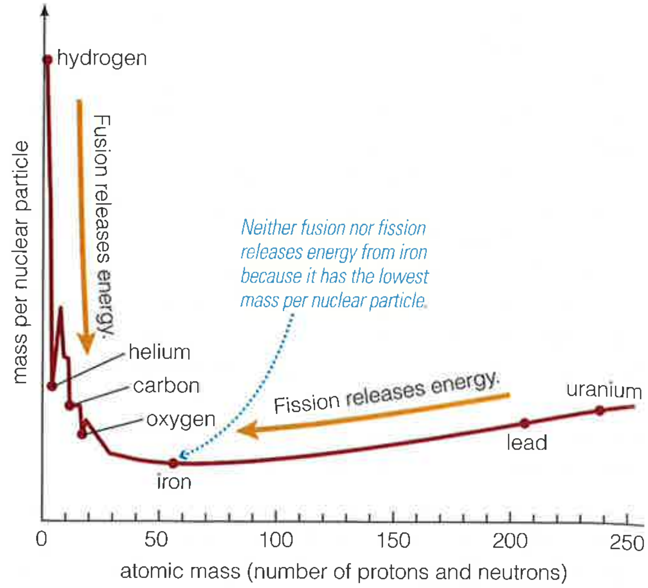


FIGURE 17.14 Overall, the average mass per nuclear particle declines from hydrogen to iron and then increases. Selected nuclei are labeled to provide reference points. (This graph shows the most general trends only. A more detailed graph would show numerous up-and-down bumps superimposed on the general trends. The vertical scale is arbitrary, but shows the general idea.)

In other words, fusing hydrogen into helium generates energy because helium has a lower *mass per nuclear particle* than hydrogen. Similarly, fusing three helium-4 nuclei into one carbon-12 nucleus generates energy because carbon has a lower mass per nuclear particle than helium, which means that some mass disappears and becomes energy in this fusion reaction. This decrease in mass per nuclear particle from hydrogen to helium to carbon is part of a general trend shown in Figure 17.14.

The mass per nuclear particle tends to decrease as we go from light elements to iron, which means that fusion of light nuclei into heavier nuclei generates energy. This trend reverses beyond iron: The mass per nuclear particle tends to *increase* as we look to still heavier elements. As a result, elements heavier than iron can generate nuclear energy only through fission into lighter elements. For example, uranium has a greater mass per nuclear particle than lead, so uranium fission (which ultimately leaves lead as a by-product) must convert some mass into energy.

Iron has the lowest mass per nuclear particle of all nuclei and therefore cannot release energy by either fusion or fission. Once the matter in a stellar core turns to iron, it can generate no further energy. The core's only hope of resisting the crush of gravity lies with degeneracy pressure, but iron keeps piling up until even degeneracy pressure cannot support it. What ensues is the ultimate nuclear waste catastrophe: The star explodes as a supernova, scattering all the newly made elements into interstellar space.

THINK ABOUT IT

How would the universe be different if hydrogen, rather than iron, had the lowest mass per nuclear particle? Why?

Evidence for the Origin of Elements Before we look at how a supernova happens, let's consider the evidence that indicates we actually understand the origin of the elements. We cannot see inside stars, so we cannot directly observe elements being created in the ways we've discussed. However, the signature of nuclear reactions in massive stars is written in the patterns of elemental abundances across the universe.

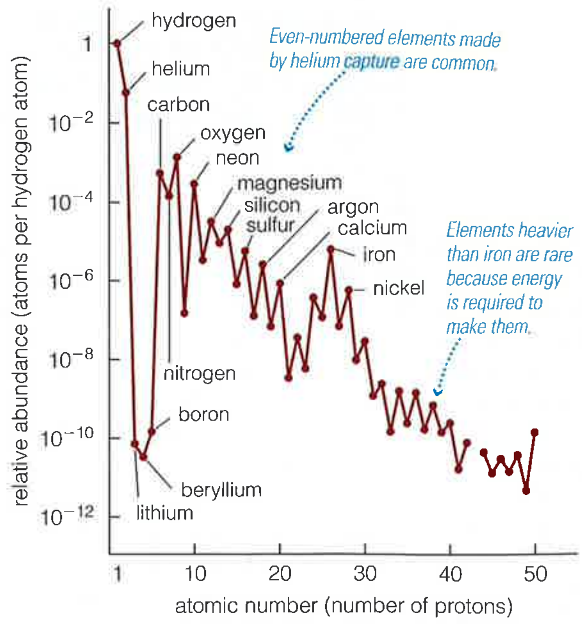
For example, if massive stars really produce heavy elements (that is, elements heavier than hydrogen and helium) and scatter these elements into space when they die, the total amount of these heavy elements in interstellar gas should gradually increase with time (because additional massive stars have died). We should expect stars born recently to contain a greater proportion of heavy elements than stars born in the distant past, because these stars formed from interstellar gas that contained more heavy elements.

Stellar spectra confirm this prediction: Older stars do indeed contain smaller amounts of heavy elements than younger stars. For very old stars in globular clusters, elements besides hydrogen and helium typically make up as little as 0.1% of the total mass. In contrast, young stars that formed in the recent past contain about 2–3% of their mass in the form of heavy elements.

We gain even more confidence in our model of element creation when we compare the abundances of various elements in the cosmos. For example, because helium-capture reactions add two protons (and two neutrons) at a time, we expect nuclei with even numbers of protons to outnumber those with odd numbers of protons that fall between them. Indeed, even-numbered nuclei such as carbon, oxygen, and neon are relatively abundant (Figure 17.15). Similarly, because elements heavier than iron are made primarily by rare fusion reactions shortly before and during a supernova, we expect these elements to be extremely rare.* Again, observations verify this prediction made by our model of nuclear creation.

How does a high-mass star die?

Let's return now to our high-mass star, with iron piling up in its core. As we've discussed, it has no hope of generating any energy by fusion of this iron. After shining brilliantly for a few million years, the star will not live to see another day.



Even-numbered elements made by helium capture are common.

Elements heavier than iron are rare because energy is required to make them.

FIGURE 17.15 The observed abundances of elements in the Milky Way, relative to the abundance of hydrogen (set to 1 in this comparison). For example, the graph shows a nitrogen abundance of about 10^{-4}, which means there are about $10^{-4} = 0.0001$ times as many nitrogen atoms as hydrogen atoms.

The Supernova Explosion The degeneracy pressure that briefly supports the inert iron core arises because the laws of quantum mechanics prohibit electrons from getting too close together [Section S4.4]. Once gravity pushes the electrons past the quantum mechanical limit, however, they can no longer exist freely. In an instant, the electrons disappear by combining with protons to form neutrons, releasing neutrinos in the process (Figure 17.16). The degeneracy pressure provided by the electrons instantly vanishes, and gravity has free rein.

In a fraction of a second, an iron core with a mass comparable to that of our Sun and a size larger than that of Earth collapses into a ball of neutrons just a few kilometers across. The collapse halts only because the neutrons have a degeneracy pressure of their own. The entire core then resembles a giant atomic nucleus. If you recall that ordinary atoms are made almost entirely of empty space [Section 5.3] and that almost all their mass is in their nuclei, you'll realize that a giant atomic nucleus must have an astoundingly high density.

The gravitational collapse of the core releases an enormous amount of energy—more than a hundred times what the Sun will radiate over its entire 10-billion-year lifetime. Where does this energy go? It drives the outer layers of the star off into space in a titanic explosion called a **supernova**.

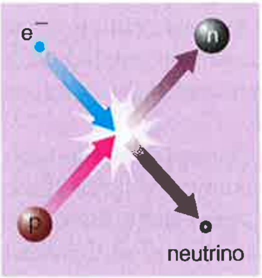


FIGURE 17.16 During the final, catastrophic collapse of a high-mass stellar core, electrons and protons combine to form neutrons, accompanied by the release of neutrinos.

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*Nuclei heavier than iron grow by capturing neutrons, which then decay into protons, releasing an electron and an antineutrino with each decay. Because this process requires energy, it happens most rapidly in supernova explosions, but it can also happen slowly to heavy nuclei in the helium-burning zones of giant and supergiant stars.

The ball of neutrons left behind is called a **neutron star**. In some cases, the remaining mass may be so large that gravity also overcomes neutron degeneracy pressure, and the core continues to collapse until it becomes a *black hole* [Sections S3.3 and 18.3].

Theoretical models of supernovae successfully reproduce the observed energy outputs of real supernovae, but the precise mechanism of the explosion is not yet clear. Two general processes could contribute to the explosion. In the first process, neutron degeneracy pressure halts the gravitational collapse, causing the core to rebound slightly and ram into overlying material that is still falling inward. Until recently, most astronomers thought that this *core-bounce process* ejected the star's outer layers. Current models of supernovae, however, suggest that the more important process involves the neutrinos formed when electrons and protons combine to make neutrons. Although neutrinos rarely interact with anything [Section 14.2], so many are produced when the core implodes that they drive a shock wave that propels the star's upper layers outward at a speed of 10,000 kilometers per second—fast enough to travel the distance from the Sun to Earth in only about 4 hours.

The heat of the explosion makes the gas shine with dazzling brilliance. For about a week, a supernova blazes as powerfully as 10 billion Suns, rivaling the luminosity of a moderate-size galaxy. The ejected gases slowly cool and fade in brightness over the next several months, continuing to expand outward until they eventually mix with other gases in interstellar space. The scattered debris from the supernova carries with it the variety of elements produced in the star's nuclear furnace, as well as additional elements created when some of the neutrons produced during the core collapse slam into other nuclei. Millions or billions of years later, this debris may be incorporated into a new generation of stars. We are truly "star stuff," because we and our planet were built from the debris of stars that exploded long ago.

SEE IT FOR YOURSELF

To see an effect similar to the core-bounce process in a supernova, find a tennis ball and a basketball. Then place the tennis ball directly on top of the basketball and drop them together on a hard floor. How does the speed at which the tennis ball bounces back up compare to the speed at which it fell? How is the response of the tennis ball like the response of the supernova's outer layers to the rebound of the core?

Historical Supernovae Observations The study of supernovae owes a great debt to astronomers of many different epochs and cultures. Careful scrutiny of the night skies allowed ancient people to identify several supernovae whose remains can still be seen. The most famous example is the Crab Nebula in the constellation Taurus. The Crab Nebula is a **supernova remnant**—an expanding cloud of debris from a supernova explosion (Figure 17.17).

A spinning neutron star lies at the center of the Crab Nebula, providing evidence that supernovae really do create neutron stars. Photographs taken years apart show that the nebula is growing larger at a rate of several thousand kilometers per second. Calculating backward from its present size, we can trace the supernova explosion that created it to somewhere near A.D. 1100. Thanks to observations made by ancient astronomers, we can be even more precise.

FIGURE 17.17 Interactive Photo This Hubble Space Telescope photograph shows the Crab Nebula, the remnant of the supernova observed in A.D. 1054.

The official history of the Song Dynasty in China contains a record of a remarkable celestial event:

> *In the first year of the period Chih-ho, the fifth moon, the day chi-ch'ou, a guest star appeared approximately several [degrees] southeast of Thien-kuan. After more than a year it gradually became invisible.*

This description of the sudden appearance and gradual dimming of a "guest star" matches what we expect for a supernova, and the location "southeast of Thien-kuan" corresponds to the Crab Nebula's location in Taurus. Moreover, the Chinese date described in the excerpt corresponds to July 4, 1054, telling us precisely when the Crab supernova became visible from Earth. Descriptions of this particular supernova also appear in Japanese astronomical writings and in an Arabic medical textbook. Some people have claimed that it is even recorded in Native American paintings in the southwestern United States, but these claims now seem doubtful. Curiously, European records do not mention this supernova even though it would have been clearly visible.

Other historical records of supernovae have allowed us to age-date additional supernova remnants, which in turn allows us to determine the kinds of supernovae that produced the remnants and to assess how frequently stars explode in our region of the Milky Way Galaxy. At least four supernovae have been observed during the past thousand years, appearing as brilliant new stars for a few months in the years 1006, 1054, 1572, and 1604. The supernova of 1006, the brightest of these four, could be seen during the daytime and cast shadows at night.

Supernovae may even have influenced human history. The Chinese were meticulous in recording their observations because they believed that celestial events foretold the future, and they may have acted in accord with such fortune-telling. The 1572 supernova was witnessed by Tycho Brahe and helped convince him and others that the heavens were not as perfect and unchanging as Aristotle had imagined [Section 3.3]. Kepler saw the 1604 supernova at a time when he was struggling to make planetary orbits fit perfect circles. Perhaps this "imperfection" of the heavens helped push him to consider elliptical orbits instead.

THINK ABOUT IT

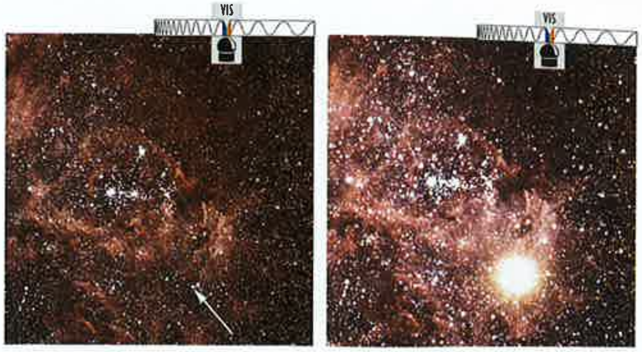
When Betelgeuse explodes as a supernova, it will be more than 10 times as bright as the full moon in our sky. If our ancestors had seen Betelgeuse explode a few hundred or a few thousand years ago, do you think it could have had any effect on human history? How do you think our modern society would react if we saw Betelgeuse explode tomorrow?

Modern Supernova Observations No supernova has been seen in our own galaxy since 1604, but today astronomers routinely discover supernovae in other galaxies. The nearest of these extragalactic supernovae, and the only one near enough to be visible to the naked eye, burst into view in 1987. Because it was the first supernova detected that year, it was given the name **Supernova 1987A.** Supernova 1987A was the explosion of a star in the *Large Magellanic Cloud,* a small galaxy that orbits the Milky Way and is visible only from Earth's southern latitudes. The Large Magellanic Cloud is about 150,000 light-years away, so the star really exploded some 150,000 years ago.

As the nearest supernova witnessed in four centuries, Supernova 1987A provided a unique opportunity to study a supernova and its debris in detail. Astronomers from all over the world traveled to the Southern Hemisphere to observe it, and several orbiting spacecraft added observations in many different wavelengths of light.

Older photographs of the Large Magellanic Cloud allowed astronomers to determine which star had exploded (Figure 17.18). It turned out to be a blue star, not the red supergiant expected when core fusion has ceased. The likely explanation is that the star's outer layers were unusually thin and warm near the end of its life, changing its appearance from that of a red supergiant to a blue one. The surprising color of the pre-explosion star demonstrates that we still have much to learn about supernovae. Reassuringly, most other theoretical predictions of stellar life cycles were well matched by observations of Supernova 1987A.

One of the most remarkable findings from Supernova 1987A was a burst of neutrinos, recorded by neutrino detectors in Japan and Ohio. The neutrino data confirmed that the explosion released most of its energy in the form of neutrinos, suggesting that we are correct in believing that the stellar core undergoes sudden collapse to a ball of neutrons. The capture of neutrinos from Supernova 1987A also spurred scientific interest in building more purposeful "neutrino telescopes." Many are now operating or are in development and will soon provide us with a new way of studying events in the distant universe.



Before. The arrow points to the star observed to explode in 1987.

After. The supernova actually appeared as a bright point of light. It appears larger than a point in this photograph only because of overexposure.

FIGURE 17.18 Before and after photos of the location of Supernova 1987A.

17.4 THE ROLES OF MASS AND MASS EXCHANGE

Throughout this chapter, we have focused on the key role of birth mass in determining a star's destiny. However, we have so far treated stars as if they live in isolation, even though nearly half the stars we see in the sky are actually binary star systems. In this final section, we will first summarize what we have learned about the lives of stars when they are not part of close binary star systems. We will then examine how a star's life story can change if it happens to orbit another star closely enough that mass can sometimes flow from one star to the other.

How does a star's mass determine its life story?

A star's birth mass determines its life cycle because that mass governs how nuclear fusion progresses in the core. Fusion proceeds relatively slowly in low-mass stars and does not make elements much heavier than carbon. These stars therefore live long lives and die in planetary nebulae, leaving behind white dwarfs composed mostly of carbon. Fusion reactions proceed somewhat faster in the hotter cores of intermediate-mass stars. However, these stars never manage to make iron and also die in planetary nebulae, leaving white dwarfs that can contain elements heavier than carbon. Fusion proceeds most quickly in the very hot cores of high-mass stars, eventually leading to iron production. When too much iron accumulates, the high-mass star explodes as a supernova, leaving behind a neutron star or a black hole.

Figure 17.19 summarizes the stages in the life cycles of stars by focusing on two illustrative cases: a high-mass star

COSMIC CONTEXT FIGURE 17.19 *Summary of Stellar Lives*

All stars spend most of their time as main-sequence stars and then change dramatically near the ends of their lives. This figure shows the life stages of a high-mass star and a low-mass star, using the cosmic calendar from Chapter 1 to illustrate the relative lengths of these life stages. On this calendar, the 14-billion-year lifetime of the universe corresponds to a single year.

LIFE OF A HIGH-MASS STAR ($25M_{\text{Sun}}$)

This high-mass star goes from protostar to supernova in about 6 million years, corresponding to less than 4 hours on the cosmic calendar.

① **Protostar:** A star system forms when a cloud of interstellar gas collapses under gravity.

② **Blue main-sequence star:** In the core of a high-mass star, four hydrogen nuclei fuse into a single helium nucleus by the series of reactions known as the CNO cycle.

③ **Red supergiant:** After core hydrogen is exhausted, the core shrinks and heats. Hydrogen shell burning begins around the inert helium core, causing the star to expand into a red supergiant.

	①	②	③
Actual Length of Stage	40,000 years	5 million years	100,000 years
Time on Cosmic Calendar	12:00:00 AM → 12:01:30 AM	12:01:30 AM → 3:10:00 AM	3:10:00 AM → 3:14:00 AM

These times correspond to the life stages of a $25M_{\text{Sun}}$ star born around midnight on a typical day of the cosmic calendar.

LIFE OF A LOW-MASS STAR ($1M_{\text{Sun}}$)

This low-mass star goes from protostar to planetary nebula in about 11.5 million years, corresponding to 10 months on the cosmic calendar.

① **Protostar:** A star system forms when a cloud of interstellar gas collapses under gravity.

② **Yellow main-sequence star:** In the core of a low-mass star, four hydrogen nuclei fuse into a single helium nucleus by the series of reactions known as the proton-proton chain.

③ **Red giant star:** After core hydrogen is exhausted, the core shrinks and heats. Hydrogen shell burning begins around the inert helium core, causing the star to expand into a red giant.

	①	②	③
Actual Length of Stage	30 million years	10 billion years	1 billion years
Time on Cosmic Calendar	March 1 → March 2	March 2 → November 30	November 30 → December 27

These dates correspond to the life stages of a $1M_{\text{Sun}}$ star born in early March on the cosmic calendar.