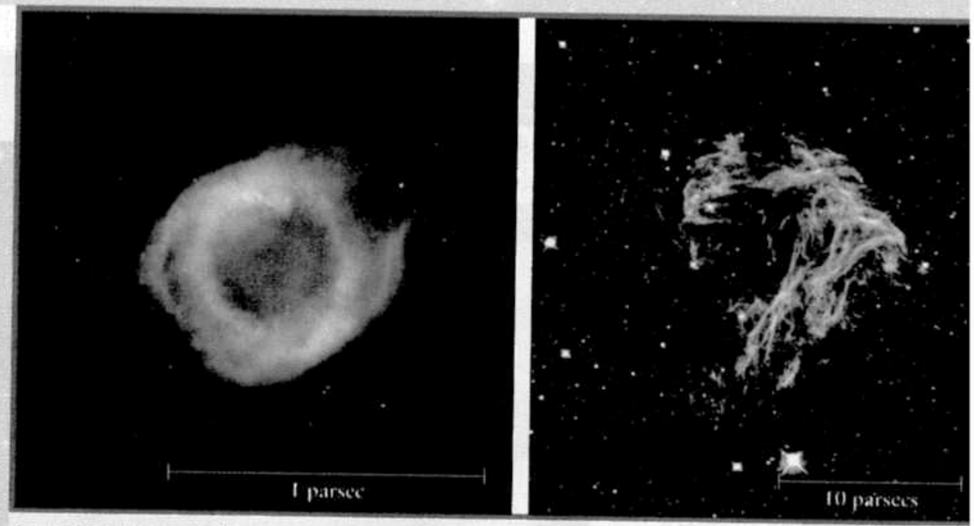
20

Stellar Evolution: The Deaths of Stars



(a) A planetary nebula

(b) A supernova remnant

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Left: The planetary nebula NGC 7293. (the Helix Nebula) Right: The supernova remnant LMC N49. (NASA, NOAO, ESA, the Hubble Helix Nebula Team, M. Meixner/STScI, and T. A. Rector/NRAO; NASA and the Hubble Heritage Team, STScI/AURA)

When a star of 0.4 solar mass or more reaches the end of its main-sequence lifetime and becomes a red giant, it comes to have a compressed core and a bloated atmosphere. Finally, it devours its remaining nuclear fuels and begins to die. The character of its death depends crucially on the value of the star's mass.

A star of relatively low mass—such as our own Sun—ends its evolution by gently expelling its outer layers into space. These ejected gases form a glowing cloud called a *planetary nebula* such as the one shown here in the left-hand image. The burned-out core that remains is called a *white dwarf*.

In contrast, a high-mass star ends its life in almost inconceivable violence. At the end of its short life, the core of such a star collapses suddenly. This triggers a powerful *supernova* explosion that can be as luminous as an entire galaxy of stars. A white dwarf, too, can become a supernova if it accretes gas from a companion star in a close binary system.

Thermonuclear reactions in supernovae produce a wide variety of heavy elements, which are ejected into the interstellar medium. (The supernova remnant shown here in the right-hand image is rich in these elements.) Such heavy elements are essential building blocks for terrestrial worlds like our Earth. Thus, the deaths of massive stars can provide the seeds for planets orbiting succeeding generations of stars.

20-1 Stars of between 0.4 and 4 solar masses go through two distinct red-giant stages

All main-sequence stars convert hydrogen to helium in their cores in a series of energy-releasing thermonuclear reactions. As we saw in Section 19-1, convection within a low-mass main-sequence star—a so-called *red dwarf* with a mass between 0.08 and 0.4 $M_\odot$—will eventually bring all of the star's hydrogen into the core. Over hundreds of billions of years a red dwarf evolves into an inert ball of helium. Convection is less important in main-sequence stars with masses greater than 0.4 $M_\odot$, so these stars are able to consume only the hydrogen that is present within the core. These stars of greater mass then leave the main sequence. Let's examine what happens next to a star of moderately low mass, between 0.4 and 4 $M_\odot$. One example of such a star is our own Sun, with a mass of 1 $M_\odot$. We'll begin by reviewing what we learned

Learning Goals

By reading the sections of this chapter, you will learn

20-1 What kinds of thermonuclear reactions occur inside a star of moderately low mass as it ages

20-2 How evolving stars disperse carbon into the interstellar medium

20-3 How stars of moderately low mass eventually die

20-4 The nature of white dwarfs and how they are formed

20-5 What kinds of reactions occur inside a high-mass star as it ages

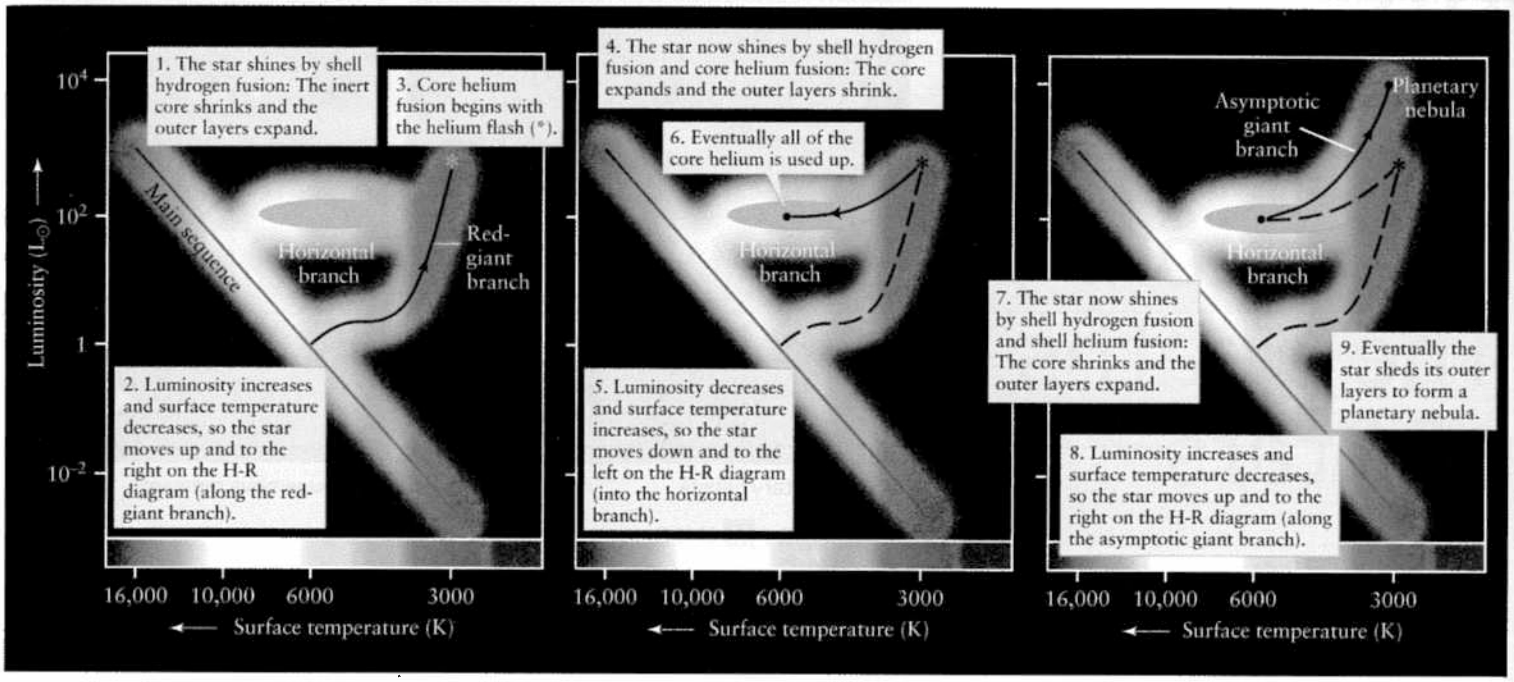
20-6 How high-mass stars explode and die

20-7 Why supernova SN 1987A was both important and unusual

20-8 What role neutrinos play in the death of a massive star

20-9 How white dwarfs in close binary systems can explode

20-10 What remains after a supernova explosion



(a) Before the helium flash: A red-giant star **(b)** After the helium flash: A horizontal-branch star **(c)** After core helium fusion ends: An AGB star

Figure 20-1

The Post-Main-Sequence Evolution of a 1-$M_\odot$ Star These H-R diagrams show the evolutionary track of a star like the Sun as it goes through the stages of being **(a)** a red-giant star, **(b)** a horizontal-branch star, and **(c)** an asymptotic giant branch (AGB) star. The star eventually evolves into a planetary nebula (described in Section 20-3).

in Chapter 19 about the first stages of post–main-sequence evolution for such a star. (Later in this chapter we'll study the evolution of more massive stars.)

The Red-Giant and Horizontal-Branch Stages: A Review

We can describe a star's post–main-sequence evolution using an evolutionary track on a H-R diagram. Figure 20-1 shows the track for a 1-$M_\odot$ star like the Sun. Once core hydrogen fusion ceases, the core shrinks, heating the surrounding hydrogen and triggering shell hydrogen fusion. The new outpouring of energy causes the star's outer layers to expand and cool, and the star becomes a red giant. As the luminosity increases and the surface temperature drops, the post–main-sequence star moves up and to the right along the **red-giant branch** on an H-R diagram (Figure 20-1*a*).

Next, the helium-rich core of the star shrinks and heats until eventually **core helium fusion** begins. This second post–main-sequence stage begins gradually in stars more massive than about 2–3 $M_\odot$, but for less massive stars it comes suddenly—in a *helium flash*. During core helium fusion, the surrounding hydrogen-fusing shell still provides most of the red giant's luminosity.

As we learned in Section 19-3, the core expands when core helium fusion begins, which makes the core cool down a bit. (We saw in Box 19-1 that letting a gas expand tends to lower its temperature, while compressing a gas tends to increase its temperature.) The cooling of the core also cools the surrounding hydrogen-fusing shell, so that the shell releases energy more slowly. Hence, the luminosity goes down a bit after core helium fusion begins.

The slower rate of energy release also lets the star's outer layers contract. As they contract, they heat up, so the star's surface temperature increases and its evolutionary track moves to the left on the H-R diagram in Figure 20-1*b*. The luminosity changes relatively little during this stage, so the evolutionary track moves almost horizontally, along a path called the **horizontal branch.** Horizontal-branch stars have helium-fusing cores surrounded by hydrogen-fusing shells. Figure 19-12 shows horizontal-branch stars in a globular cluster, and Figure 19-8 shows the evolution of the luminosity of a 1-$M_\odot$ star up to this point in its history.

AGB Stars: The Second Red-Giant Stage

Helium fusion produces nuclei of carbon and oxygen. After about a hundred million (10^8) years of core helium fusion, essentially all the helium in the core of a 1-$M_\odot$ star has been converted into carbon and oxygen, the fusion of helium in the core ceases. (This corresponds to the right-hand end of the graph in Figure 19-8.) Without thermonuclear reactions to maintain the core's internal pressure, the core again contracts, until it is stopped by degenerate-electron pressure (described in Section 19-3). This contraction releases heat into the surrounding helium-rich gases, and

Stars like the Sun go through a second red-giant phase, during which helium fusion takes place in a shell around an inert core

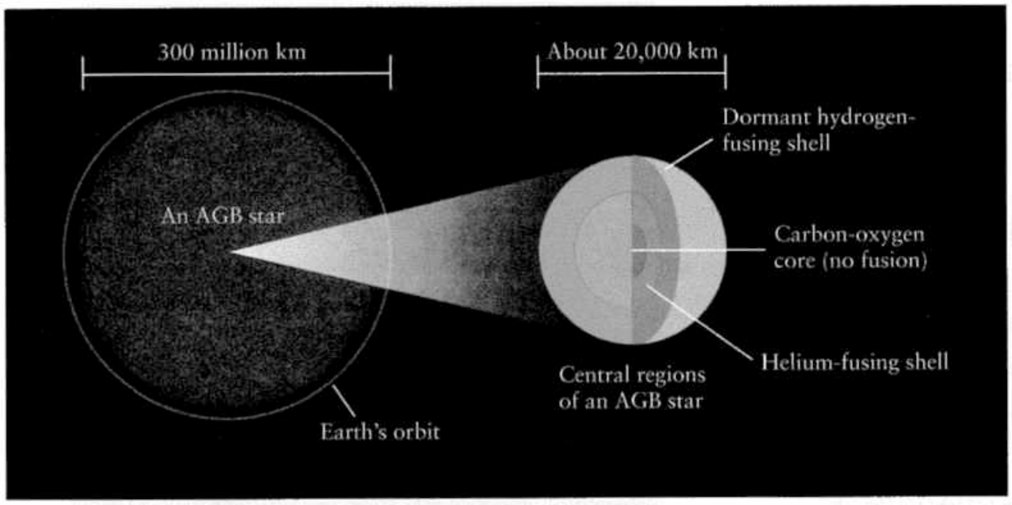


Figure 20-2

The Structure of an Old, Moderately Low-Mass AGB Star Near the end of its life, a star like the Sun becomes an immense, red, asymptotic giant branch (AGB) star. The star's inert core, active helium-fusing shell, and dormant hydrogen-fusing shell are all contained within a volume roughly the size of the Earth. Thermonuclear reactions in the helium-fusing shell are so rapid that the star's luminosity is thousands of times that of the present-day Sun. (The relative sizes of the shells in the star's interior are not shown to scale.)

a new stage of helium fusion begins in a thin shell around the core. This process is called **shell helium fusion.**

History now repeats itself—the star enters a *second* red-giant phase. A star first becomes a red giant at the end of its main-sequence lifetime, when the outpouring of energy from shell hydrogen fusion makes the star's outer layers expand and cool. In the same way, the outpouring of energy from shell *helium* fusion causes the outer layers to expand again. The low-mass star ascends into the red-giant region of the H-R diagram for a second time (Figure 20-1*c*), but now with even greater luminosity than during its first red-giant phase.

Stars in this second red-giant phase are commonly called **asymptotic giant branch stars,** or **AGB stars,** and their evolutionary tracks follow what is called the **asymptotic giant branch.** (*Asymptotic* means "approaching"; the name means that a star on the asymptotic giant branch approaches the red-giant branch from the left on an H-R diagram.)

When a low-mass star first becomes an AGB star, it consists of an inert, degenerate carbon-oxygen core and a helium-fusing shell, both inside a hydrogen-fusing shell, all within a volume not much larger than the Earth. This small, dense central region is surrounded by an enormous hydrogen-rich envelope about as big as Earth's orbit around the Sun. After a while, the expansion of the star's outer layers causes the hydrogen-fusing shell to also expand and cool, and thermonuclear reactions in this shell temporarily cease. This leaves the aging star's structure as shown in Figure 20-2.

We saw in Section 19-1 that the more massive a star, the shorter the amount of time it remains on the main sequence. Similarly, the greater the star's mass, the more rapidly it goes through the stages of post–main-sequence evolution. Hence, we can see all of these stages by studying star clusters, which contain stars that are all the same age but that have a range of masses (see Section 19-4). Figure 20-3 shows a color-magnitude diagram for the globular cluster M55, which is at least 13 billion years old. The least massive stars in this cluster are still on the main sequence. Progressively more massive stars have evolved to the red giant branch, the horizontal branch, and the asymptotic giant branch.

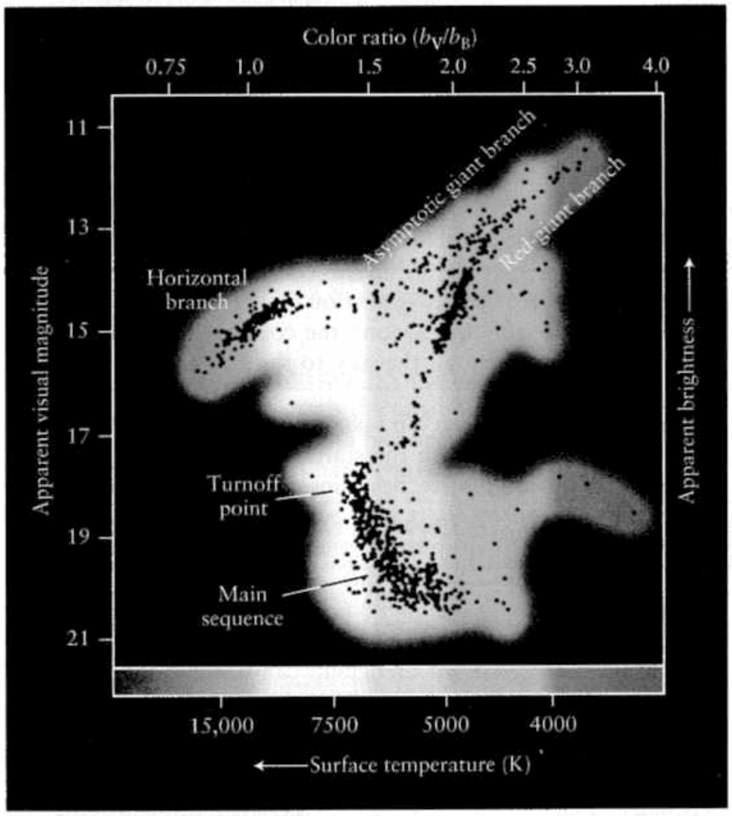


Figure 20-3

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Stellar Evolution in a Globular Cluster In the old globular cluster M55, stars with masses less than about 0.8 $M_\odot$ are still on the main sequence, converting hydrogen into helium in their cores. Slightly more massive stars have consumed their core hydrogen and are ascending the red-giant branch; even more massive stars have begun helium core fusion and are found on the horizontal branch. The most massive stars (which still have less than 4 $M_\odot$) have consumed all the helium in their cores and are ascending the asymptotic giant branch. (Compare with Figure 21-11.) (Adapted from D. Schade, D. VandenBerg, and F. Hartwick)

A 1-$M_\odot$ AGB star can reach a maximum luminosity of nearly $10^4\ L_\odot$, as compared with approximately $10^3\ L_\odot$ when it reached the helium flash and a relatively paltry 1 $L_\odot$ during its main-sequence lifetime. When the Sun becomes an AGB star some 12.3 billion years from now, this tremendous increase in luminosity will cause Mars and the Jovian planets to largely evaporate away. The Sun's bloated outer layers will reach to the Earth's orbit. Mercury and perhaps Venus will simply be swallowed whole.

20-2 Dredge-ups bring the products of nuclear fusion to a giant star's surface

As we saw in Section 16-2, energy is transported outward from a star's core by one of two processes—radiative diffusion or convection. The first is the passage of energy in the form of electromagnetic radiation, and it dominates only when a star's gases are relatively transparent. The second involves up-and-down movement of the star's gases. Convection plays a very important role in giant stars, because it helps supply the cosmos with the elements essential to life.

Convection, Dredge-ups, and Carbon Stars

In the Sun, convection dominates only the outer layers, from around 0.71 solar radius (measured from the center of the Sun) up to the photosphere (recall Figure 16-4). During the final stages of a star's life, however, the convective zone can become so broad that it extends down to the star's core. At these times, convection can "dredge up" the heavy elements produced in and around the core by thermonuclear fusion, transporting them all the way to the star's surface.

The *first* **dredge-up** takes place after core hydrogen fusion stops, when the star becomes a red giant for the first time. Convection dips so deeply into the star that material processed by the CNO cycle of hydrogen fusion (see Section 16-1) is carried up to the star's surface, changing the relative abundances of carbon, nitrogen, and oxygen. A *second* dredge-up occurs after core helium fusion ceases, further altering the abundances of carbon, nitrogen, and oxygen. Still later, during the AGB stage, a *third* dredge-up can occur if the star has a mass greater than about 2 $M_\odot$. This third dredge-up transports large amounts of freshly synthesized carbon to the star's surface, and the star's spectrum thus exhibits prominent absorption bands of carbon-rich molecules like C_2, CH, and CN. For this reason, an AGB star that has undergone a third dredge-up is called a **carbon star.**

All AGB stars have very strong stellar winds that cause them to lose mass at very high rates, up to $10^{-4}\ M_\odot$ per year (a thousand times greater than that of a red giant, and 10^{10} times greater than the rate at which our present-day Sun loses mass). The surface temperature of AGB stars is relatively low, around 3000 K, so any ejected carbon-rich molecules can condense to form tiny grains of soot. Indeed, carbon stars are commonly found to be obscured in sooty cocoons of ejected matter (Figure 20-4).

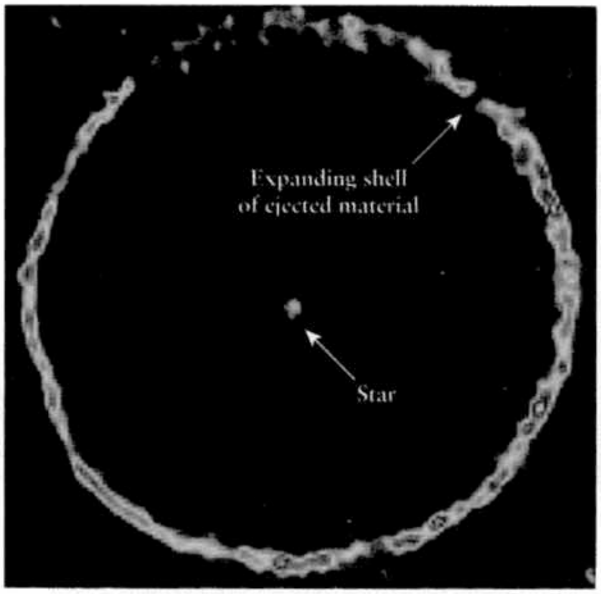


Figure 20-4 R I V U X G

A Carbon Star TT Cygni is an AGB star in the constellation Cygnus that ejects some of its carbon-rich outer layers into space. Some of the ejected carbon combines with oxygen to form molecules of carbon monoxide (CO), whose emissions can be detected with a radio telescope. This radio image shows the CO emissions from a shell of material that TT Cygni ejected some 7000 years ago. Over that time, the shell has expanded to a diameter of about ½ light-year.
(H. Olofsson, Stockholm Observatory, et al./NASA)

The carbon that forms the basis of all life on Earth was ejected billions of years ago from giant stars

Carbon stars are important because they enrich the interstellar medium with carbon and some nitrogen and oxygen. The triple alpha process that occurs in helium fusion is the *only* way that carbon can be made, and carbon stars are the primary avenue by which this element is dispersed into interstellar space. Indeed, most of the carbon in your body was produced long ago inside a star by the triple alpha process (see Section 19-3). This carbon was later dredged up to the star's surface and ejected into space. Some 4.56 billion years ago a clump of the interstellar medium which contained this carbon coalesced into the solar nebula from which our Earth—and all of the life on it—eventually formed. In this sense you can think of your body as containing "recycled" material—substances that were once in the heart of a star that formed and evolved long before our solar system existed.

20-3 Stars of moderately low mass die by gently ejecting their outer layers, creating planetary nebulae

For a star that began with a moderately low mass (between about 0.4 and 4 $M_\odot$), the AGB stage in its evolution is a dramatic turning point. Before this stage, a star loses mass only gradually through steady stellar winds. But as it evolves during its AGB stage, a star divests itself completely of its outer layers. The aging star undergoes a series of bursts in luminosity, and in each burst it ejects a shell of material into space. (The shell around the AGB star TT Cygni, shown in Figure 20-4, was probably created in this way.) Eventually, all that remains of a low-mass star is a fiercely hot, exposed core, surrounded by glowing shells of ejected gas. This late stage in the life of a star is called a **planetary nebula.** The left-hand image on the opening page of this chapter shows one such planetary nebula, called the Ring Nebula for its shape.

Like a human going through a midlife crisis, an aging AGB star casts off much of the mass that it possesses and makes a cosmic spectacle of itself

Making a Planetary Nebula

To understand how an AGB star can eject its outer layers in shells, consider the internal structure of such a star as shown in Figure 20-2. As the helium in the helium-fusing shell is used up, the pressure that holds up the dormant hydrogen-fusing shell decreases. Hence, the dormant hydrogen shell contracts and heats up, and hydrogen fusion begins anew. This revitalized hydrogen fusion creates helium, which rains downward onto the temporarily dormant helium-fusing shell. As the helium shell gains mass, it shrinks and heats up. When the temperature of the helium shell reaches a certain critical value, it reignites in a **helium shell flash** that is similar to (but less intense than) the helium flash that occurred earlier in the evolution of a low-mass star (see Section 19-3). The released energy pushes the hydrogen-fusing shell outward, making it cool off, so that hydrogen fusion ceases and this shell again becomes dormant. The process then starts over again.

When a helium shell flash occurs, the luminosity of an AGB star increases substantially in a relatively short-lived burst called a **thermal pulse.** Figure 20-5, which is based on a theoretical calculation of the evolution of a 1-$M_{\odot}$ star, shows that thermal pulses begin when the star is about 12.365 billion years old. The calculations predict that thermal pulses occur at ever-shorter intervals of about 100,000 years.

During these thermal pulses, the dying star's outer layers can separate completely from its carbon-oxygen core. As the ejected material expands into space, dust grains condense out of the cooling gases. Radiation pressure from the star's hot, burned-out core acts on the specks of dust, propelling them further outward, and the star sheds its outer layers altogether. In this way an aging 1-$M_{\odot}$ star loses as much as 40% of its mass. More massive stars eject even greater fractions of their original mass.

As a dying star ejects its outer layers, the star's hot core becomes exposed. With a surface temperature of about 100,000 K, this exposed core emits ultraviolet radiation intense enough to ionize and excite the expanding shell of ejected gases. These gases therefore glow and emit visible light through the process of fluorescence (see Box 18-1), producing a planetary nebula like those shown in Figure 20-6.

CAUTION! Despite their name, planetary nebulae have nothing to do with planets. This misleading term was introduced in the nineteenth century because these glowing objects looked like distant Jovian planets when viewed through the small telescopes then available. The difference between planets and planetary nebulae became obvious with the advent of spectroscopy: Planets have *absorption* line spectra (see Section 7-3), but the excited gases of planetary nebulae have *emission* line spectra.

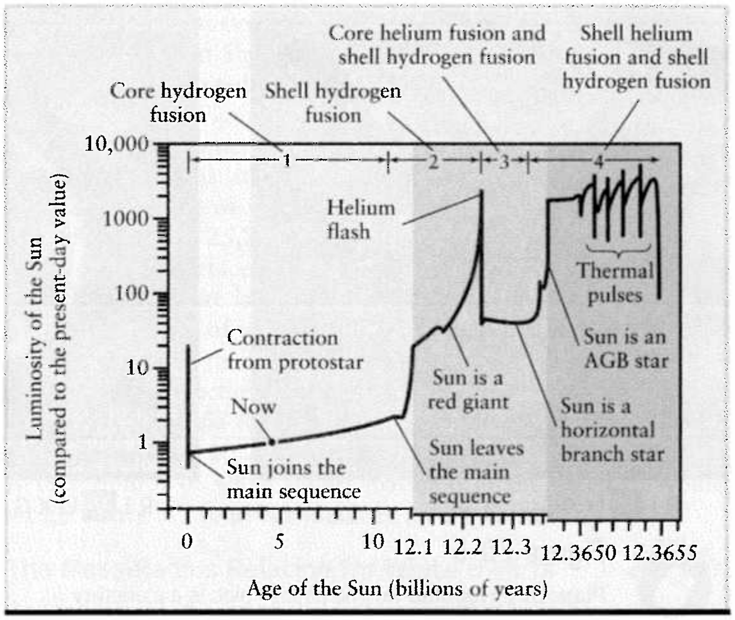


Figure 20-5

Further Stages in the Evolution of the Sun This diagram, which shows how the luminosity of the Sun (a 1-$M_{\odot}$ star) changes over time, is an extension of Figure 19-8. We use different scales for the final stages because the evolution is so rapid. During the AGB stage there are brief periods of runaway helium fusion, causing spikes in luminosity called thermal pulses. (Adapted from Mark A. Garlick, based on calculations by I.-Juliana Sackmann and Kathleen E. Kramer)

The Properties of Planetary Nebulae

Planetary nebulae are quite common. Astronomers estimate that there are 20,000 to 50,000 planetary nebulae in our Galaxy alone. Many planetary nebulae, such as those in Figure 20-6, are more or less spherical in shape. This is a result of the symmetrical way in which the gases were ejected. But if the rate of expansion is not the same in all directions, the resulting nebula takes on an hourglass or dumbbell appearance (**Figure** 20-7).

Spectroscopic observations of planetary nebulae show emission lines of ionized hydrogen, oxygen, and nitrogen. From the Doppler shifts of these lines, astronomers have concluded that the expanding shell of gas moves outward from a dying star at speeds from 10 to 30 km/s. For a shell expanding at such speeds to have attained the typical diameter of a planetary nebula, about 1 light-year, it must have begun expanding about 10,000 years ago. Thus, by astronomical standards, the planetary nebulae we see today were created only very recently.

We do not observe planetary nebulae that are more than about 50,000 years old. After this length of time, the shell has spread out so far from the cooling central star that its gases cease to glow and simply fade from view. The nebula's gases then mix with the surrounding interstellar medium.

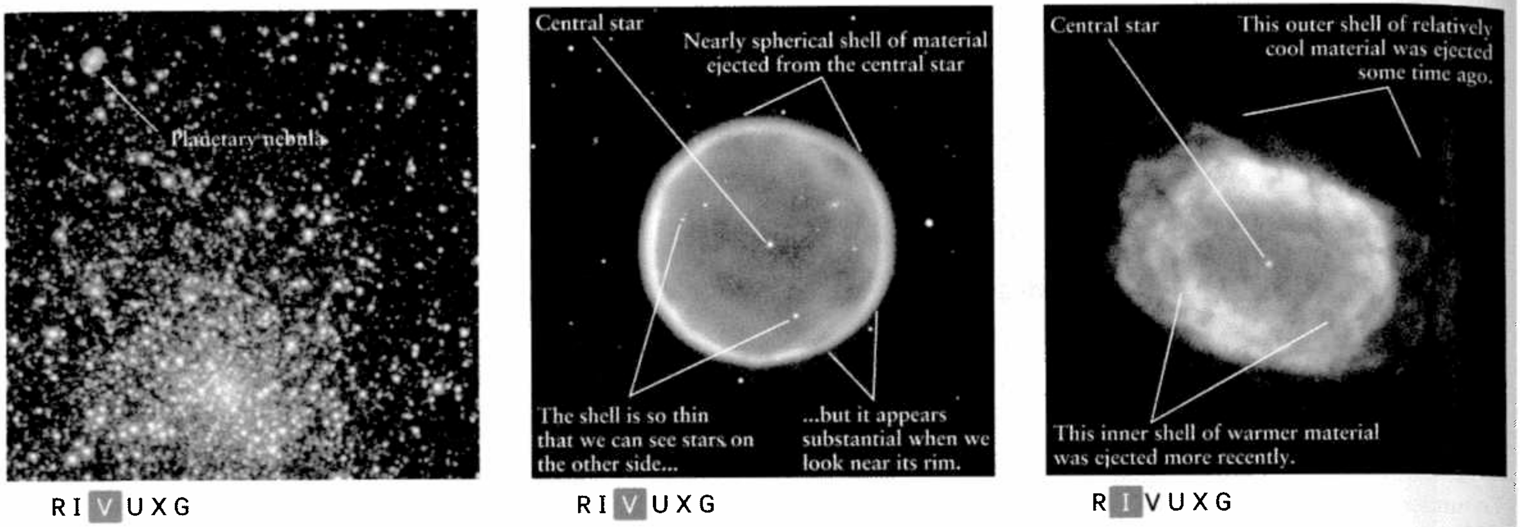


Figure 20-6

Planetary Nebulae (a) The pinkish blob is a planetary nebula surrounding a star in the globular cluster M15, about 10,000 pc (33,000 ly) from Earth in the constellation Pegasus. **(b)** The planetary nebula Abell 39 lies about 2200 pc (7000 ly) from Earth in the constellation Hercules. The almost perfectly spherical shell that comprises the nebula is about 1.5 pc (5 ly) in diameter; the thickness of the shell is only about 0.1 pc (0.3 ly). **(c)** This infrared image of the planetary nebula NGC 7027 suggests a more complex evolutionary history than that of Abell 39. NGC 7027 is about 900 pc (3000 ly) from Earth in the constellation Cygnus and is roughly 14,000 AU across. (a: NASA/Hubble Heritage Team, STScI/AURA; b: WIYN/NOAO/NSF; c: William B. Latter, SIRTF Science Center/Caltech, and NASA)

Astronomers estimate that all the planetary nebulae in the Galaxy return a total of about 5 $M_\odot$ to the interstellar medium each year. This amounts to 15% of all the matter expelled by all the various sorts of stars in the Galaxy each year. Because this contribution is so significant, and because the ejected material includes heavier elements (metals) manufactured within a nebula's central star, planetary nebulae play an important role in the chemical evolution of the Galaxy as a whole.

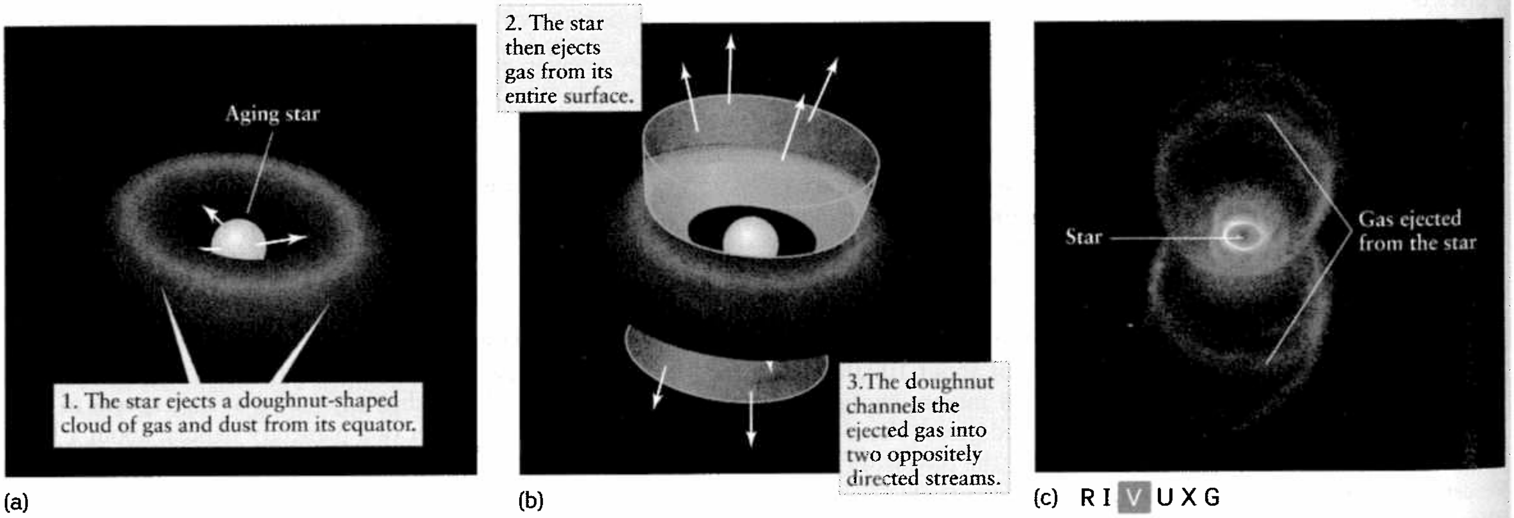


Figure 20-7

Making an Elongated Planetary Nebula (a), (b) These illustrations show one proposed explanation for why many planetary nebulae have an elongated shape. **(c)** The planetary nebula MyCn18, shown here in false color, may have acquired its elongated shape in this way. It lies some 2500 pc (8000 ly) from Earth in the constellation Musca (the Fly). (R. Sahai and J. Trauger, Jet Propulsion Laboratory; the WFPC-2 Science Team; and NASA)

20-4 The burned-out core of a moderately low-mass star cools and contracts until it becomes a white dwarf

We have seen that after a moderately low-mass star (from about 0.4 to about 4 solar masses) consumes all the hydrogen in its core, it is able to ignite thermonuclear reactions that convert helium to carbon and oxygen. Given sufficiently high temperature and pressure, carbon and oxygen can also undergo fusion reactions that release energy. But for such a moderately low-mass star, the core temperature and pressure never reach the extremely high values needed for these reactions to take place. Instead, as we have seen, the process of mass ejection just strips away the star's outer layers and leaves behind the hot carbon-oxygen core. With no thermonuclear reactions taking place, the core simply cools down like a dying ember. Such a burnt-out relic of a star's former glory is called a **white dwarf.** Such white dwarfs prove to have exotic physical properties that are wholly unlike any object found on Earth.

CAUTION! Unfortunately, the word *dwarf* is used in astronomy for several very different kinds of small objects. Here's a review of the three kinds that we have encountered so far in this book. A *white* dwarf is the relic that remains at the very end of the evolution of a star of initial mass between about 0.4 $M_\odot$ and 4 $M_\odot$. Thermonuclear reactions are no longer taking place in its interior; it emits light simply because it is still hot. A *red* dwarf, discussed in Section 19-1, is a cool main-sequence star with a mass between about 0.08 $M_\odot$ and 0.4 $M_\odot$. The energy emitted by a red dwarf in the form of light comes from its core, where fusion reactions convert hydrogen into helium. Finally, a *brown* dwarf (see Section 8-6 and Section 17-5) is an object like a main-sequence star but with a mass less than about 0.08 $M_\odot$. Because its mass is so small, its internal pressure and temperature are too low to sustain thermonuclear reactions. Instead, a brown dwarf emits light because it is slowly contracting, a process that releases energy (see Section 16-1). White dwarfs are comparable in size to the Earth (see Section 17-7); by contrast, brown dwarfs are larger than the planet Jupiter, and red dwarfs are even larger.

Properties of White Dwarfs

You might think that without thermonuclear reactions to provide internal heat and pressure, a white dwarf should keep on shrinking under the influence of its own gravity as it cools. Actually, however, a cooling white dwarf maintains its size, because the burnt-out stellar core is so dense that most of its electrons are degenerate (see Section 17-3). Thus, degenerate-electron pressure supports the star against further collapse. This pressure does not depend on temperature, so it continues to hold up the star even as the white dwarf cools and its temperature drops.

A white dwarf is kept from collapsing by the pressure of its degenerate electrons

Many white dwarfs are found in the solar neighborhood, but all are too faint to be seen with the naked eye. One of the first white dwarfs to be discovered is a companion to Sirius, the brightest star in the night sky. In 1844 the German astronomer Friedrich Bessel noticed that Sirius was moving back and forth slightly, as if it was being orbited by an unseen object. This companion, designated Sirius B (Figure 20-8), was first glimpsed in 1862 by the American astronomer Alvan Clark. Recent Hubble Space Telescope observations at ultraviolet wavelengths, where hot white dwarfs emit most of their light, show that the surface temperature of Sirius B is 25,200 K. (By contrast, the main-sequence star Sirius A has a surface temperature of 10,500 K, while the Sun's surface temperature is a relatively frosty 5800 K.)

Observations of white dwarfs in binary systems like Sirius allow astronomers to determine the mass, radius, and density of these stars (see Sections 17-9, 17-10, and 17-11). Such observations show that the density of the degenerate matter in a white dwarf is typically 10^9 kg/m^3 (a million times denser than water). A teaspoonful of white dwarf matter brought to Earth would weigh nearly 5.5 tons—as much as an elephant!

The Mass-Radius Relation for White Dwarfs

As we learned in Section 17-3, degenerate matter has a very different relationship between its pressure, density, and temperature

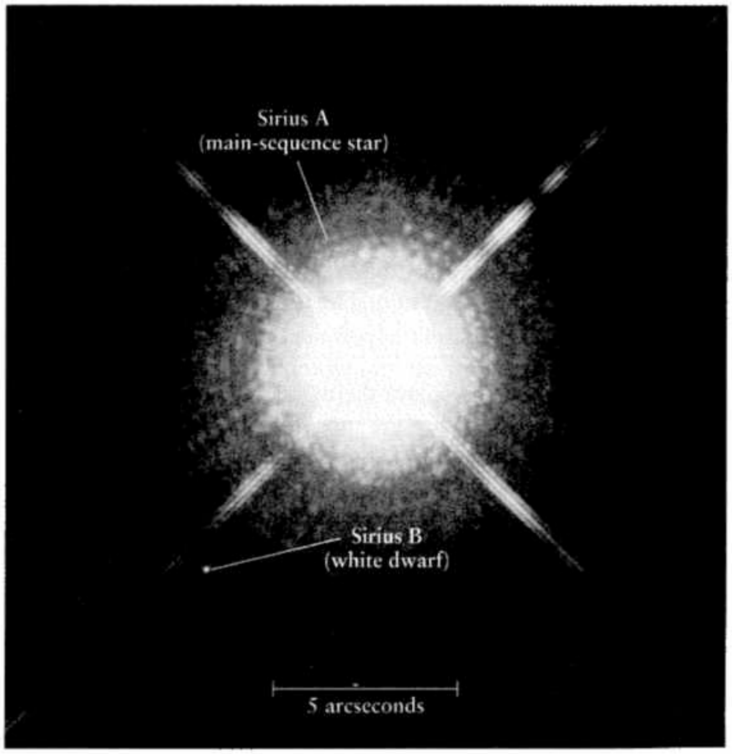


Figure 20-8 R I V U X G

Sirius A and Its White Dwarf Companion Sirius, the brightest-appearing star in the sky, is actually a binary star: The secondary star, called Sirius B, is a white dwarf. In this Hubble Space Telescope image, Sirius B is almost obscured by the glare of the overexposed primary star, Sirius A, which is about 10^4 times more luminous than Sirius B. The halo and rays around Sirius A are the result of optical effects within the telescope. (NASA; H. E. Bond and E. Nelan, STScI; M. Barstow and M. Burleigh, U. of Leicester; and J. B. Holberg, U. of Arizona)

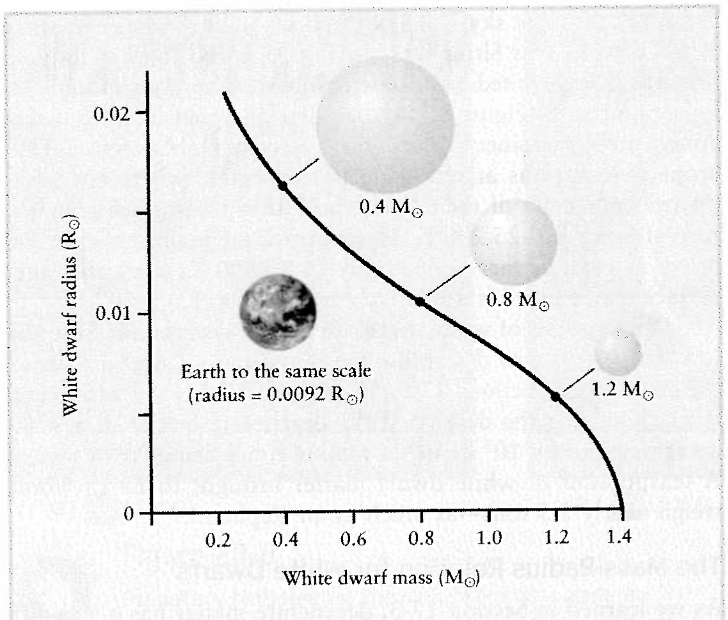


Figure 20-9

The Mass-Radius Relationship for White Dwarfs The more massive a white dwarf is, the smaller its radius. (The drawings of white dwarfs of different mass are drawn to the same scale as the image of the Earth.) This unusual relationship is a result of the degenerate-electron pressure that supports the star. The maximum mass of a white dwarf, called the Chandrasekhar limit, is 1.4 M⊙.

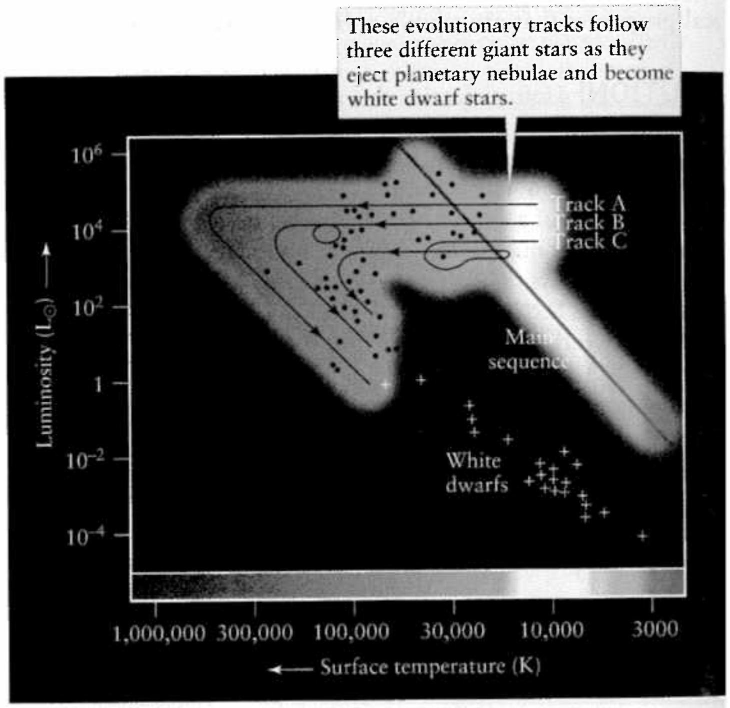
than that of ordinary gases. Consequently, white dwarf stars have an unusual **mass-radius relation:** The more massive a white dwarf star, the *smaller* it is.

Figure 20-9 displays the mass-radius relation for white dwarfs. Note that the more degenerate matter you pile onto a white dwarf, the smaller it becomes. However, there is a limit to how much pressure degenerate electrons can produce. As a result, there is an upper limit to the mass that a white dwarf can have. This maximum mass is called the **Chandrasekhar limit,** after the Indian-American scientist Subrahmanyan Chandrasekhar, who pioneered theoretical studies of white dwarfs in the 1930s. (The orbiting Chandra X-ray Observatory, described in Section 6-7, is named in his honor.) The Chandrasekhar limit is equal to 1.4 M⊙, meaning that all white dwarfs must have masses less than 1.4 M⊙.

The material inside a white dwarf consists mostly of ionized carbon and oxygen atoms floating in a sea of degenerate electrons. As the dead star cools, the carbon and oxygen ions slow down, and electric forces between the ions begin to prevail over the random thermal motions. About 5×10^9 years after the star first becomes a white dwarf, when its luminosity has dropped to about 10^{-4} L⊙ and its surface temperature is a mere 4000 K, the ions no longer move freely. Instead, they arrange themselves in orderly rows, like an immense crystal lattice. From this time on, you could say that the star is "solid." The degenerate electrons move around freely in this crystal material, just as electrons move freely through an electrically conducting metal like copper or silver. A diamond is also crystallized carbon, so a cool carbon-oxygen white dwarf resembles an immense spherical diamond!

From Red Giant to Planetary Nebula to White Dwarf

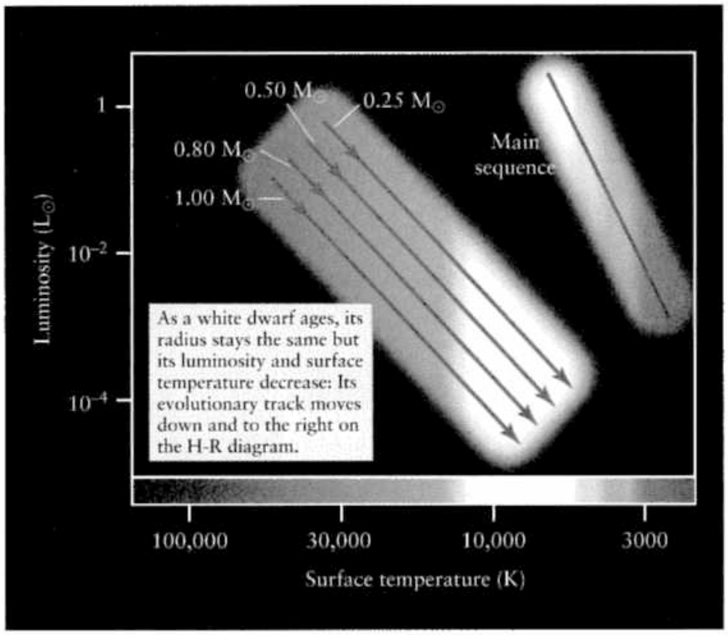
Figure 20-10 shows the evolutionary tracks followed by three burned-out stellar cores as they pass through the planetary nebula stage and become white dwarfs. When these three stars were red giants, they had masses of 0.8, 1.5, and 3.0 M⊙. Mass ejection strips these dying stars of up to 60% of their matter. During their final spasms, the luminosity and surface temperature of these stars change quite rapidly. The points representing these stars on an H-R diagram race along their evolutionary tracks, sometimes executing loops corresponding to thermal pulses (see


These evolutionary tracks follow three different giant stars as they eject planetary nebulae and become white dwarf stars.

Evolutionary track	Mass (M⊙)		
	Giant star	Ejected nebula	White dwarf
A	3.0	1.8	1.2
B	1.5	0.7	0.8
C	0.8	0.2	0.6

Figure 20-10

Evolution from Giants to White Dwarfs This H-R diagram shows the evolutionary tracks of three low-mass giant stars as they eject planetary nebulae. The table gives the extent of mass loss in each case. The dots represent the central stars of planetary nebulae whose surface temperatures and luminosities have been determined; the crosses represent white dwarfs of known temperature and luminosity. (Adapted from B. Paczynski)



As a white dwarf ages, its radius stays the same but its luminosity and surface temperature decrease: Its evolutionary track moves down and to the right on the H-R diagram.

Figure 20-11

White Dwarf "Cooling Curves" As white dwarf stars radiate their internal energy into space, they become dimmer and cooler. The blue lines show the evolutionary tracks of four white dwarfs of different mass: The more massive a white dwarf, the smaller and hence fainter it is. Compare these "cooling curves" with the lines of constant radius in Figure 17-15*b*.

Track B and Track C in Figure 20-10). Finally, as the ejected nebulae fade and the stellar cores cool, the evolutionary tracks of these dying stars take a sharp turn toward the white dwarf region of the H-R diagram. As the table accompanying Figure 20-10 shows, the final white dwarf has only a fraction of the mass of the giant star from which it evolved.

Although a white dwarf maintains the same size as it cools, its luminosity and surface temperature both decrease with time. Consequently, the evolutionary tracks of aging white dwarfs point toward the lower right corner of the H-R diagram. You can see this in Figure 20-10; Figure 20-11 shows it in more detail. The energy that the white dwarf radiates into space comes only from the star's internal heat, which is a relic from the white dwarf's past existence as a stellar core. Over billions of years, white dwarfs grow dimmer and dimmer as their surface temperatures drop toward absolute zero.

After ejecting much of its mass into space, our own Sun will eventually evolve into a white dwarf star about the size of the Earth and with perhaps one-tenth of its present luminosity. It will become even dimmer as it cools. After 5 billion years as a white dwarf, the Sun will radiate with no more than one ten-thousandth of its present brilliance. With the passage of eons, our Sun will simply fade into obscurity. The *Cosmic Connections* figure summarizes the full evolutionary cycle of a 1-$M_\odot$ star like the Sun, from its birth as a main-sequence star to its demise as a white dwarf.

20-5 High-mass stars create heavy elements in their cores

During the entire lifetime of a low-mass red dwarf star (with an initial mass less than about 0.4 $M_\odot$), the only thermonuclear reaction that takes place is the fusion of hydrogen nuclei to form helium nuclei. In stars with initial masses from about 0.4 $M_\odot$ to about 4 $M_\odot$, a second kind of thermonuclear reaction takes place—helium fusion. The heaviest elements manufactured by helium fusion are carbon and oxygen.

The life story of a *high-mass* star (with an initial, zero-age mass greater than about 4 $M_\odot$) begins with these same reactions. But theoretical calculations show that high-mass stars can also go through several additional stages of thermonuclear reactions involving the fusion of carbon, oxygen, and other heavy nuclei. As a result, high-mass stars end their lives quite differently from low-mass stars.

Heavy-Element Fusion in Massive Stars

Why is fusion of heavy nuclei possible only in a high-mass star? The reason is that heavy nuclei have large electric charges: For example, a nucleus of carbon has 6 positively charged protons and hence 6 times the charge of a hydrogen nucleus (which has a single proton). This means that there are strong electric forces that tend to keep these nuclei apart. Only at the great speeds associated with extremely high temperatures can the nuclei travel fast enough to overcome their mutual electric repulsion and fuse together. To produce these very high temperatures at a star's center, the pressure must also be very high. Hence, the star must have a very large mass, because only such a star has strong enough gravity trying to pull it together and thus strong enough pressure at its center.

As we discussed in Section 19-2, when a main-sequence star with a mass greater than about 0.4 $M_\odot$ uses up its core hydrogen, it begins shell hydrogen fusion and enters a red-giant phase. Such a star then begins core helium fusion when the core temperature becomes high enough. The differences between moderately low-mass (from about 0.4 $M_\odot$ to about 4 $M_\odot$) and high-mass stars (more than about 4 $M_\odot$) become pronounced after helium core fusion ends, when the core is composed primarily of carbon and oxygen.

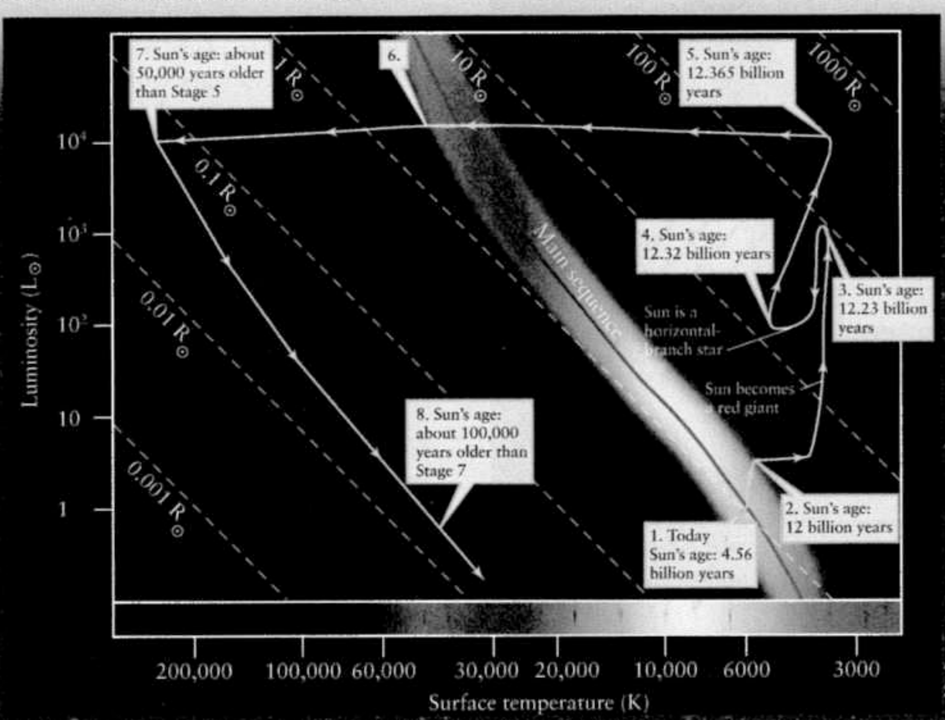
Let us consider how the late stages in the evolution of a high-mass star differ from those of a low-mass star. In low-mass stars, as we saw in Section 20-4, the carbon-oxygen core eventually becomes exposed and becomes a white dwarf. But in stars whose overall mass is more than about 4 $M_\odot$, the carbon-oxygen core is more massive than the Chandrasekhar limit of 1.4 $M_\odot$, so degenerate-electron pressure cannot prevent the core from contracting and heating. Hence, a high-mass star is able to enter a new round of core thermonuclear reactions. When the central temperature of such a high-mass star reaches 600 million kelvins (6×10^8 K), the first of the new thermonuclear reactions, **carbon fusion**, begins. Carbon fusion consumes carbon nuclei (^{12}C, with 6 protons in each nucleus) and produces oxygen (^{16}O, 8 protons), neon (^{20}Ne, 10 protons), sodium (^{23}Na, 11 protons), and magnesium (^{23}Mg and ^{24}Mg, each with 12 protons).

If a star has an even larger main-sequence mass of about 8 $M_\odot$ or so (before mass ejection), even more thermonuclear

COSMIC CONNECTIONS

Our Sun: The Next Eight Billion Years

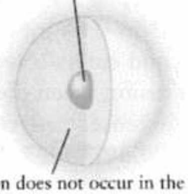
The Sun is presently less than halfway through its lifetime as a main-sequence star. The H-R diagram and cross-sections on this page summarize the dramatic changes that will take place when the Sun's main-sequence lifetime comes to an end.



NOTE: The illustrations below do *not* show the dramatic changes in the Sun's radius as it evolves. The sizes of the various layers are not shown to scale.

1. On the main sequence

The present-day Sun is a main-sequence star – in its core, hydrogen fuses to produce helium.



Fusion does not occur in the outer layers (which contain predominantly hydrogen and helium).

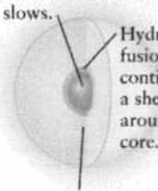
2. Becoming a red giant

At the end of the Sun's main-sequence lifetime, fusion stops in the core (which has been converted to helium).

Fusion of hydrogen into helium continues in a shell around the core. The core shrinks, accelerating the fusion reactions in the shell and making the outer layers expand and cool.

3. The helium flash

As the core contracts and heats, the core helium begins to fuse to make carbon and oxygen. The core expands and the rate of energy release slows.

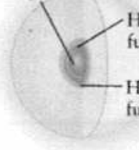


Hydrogen fusion continues in a shell around the core.

The outer layers (where there are still no fusion reactions) contract and get hotter due to the slower rate of energy release.

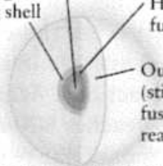
4. Beginning the second red giant phase

Once the core helium is consumed, what remains is an inert core of carbon and oxygen. The core again shrinks and gets hotter.



The shrinkage of the core again accelerates fusion reactions in the shells, making the inert outer layers expand and cool.

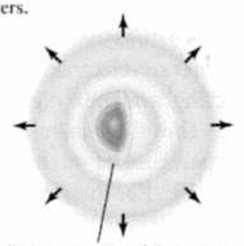
5. The Sun reaches its maximum size



The Sun is more than 100 times larger in radius than when it was a main-sequence star. Part of the outer layers escapes into space in a stellar wind.

6. A planetary nebula

Thermal pulses cause spikes in luminosity that eject the star's outer layers.



As the hot interior of the star is exposed, we observe an increase in the star's surface temperature.

7. The end of nuclear reactions

With the outer layers gone, the pressure on the shells around the core is too little to sustain nuclear reactions.

The star still glows intensely because of its high temperature. As energy is lost in the form of electromagnetic radiation, the star slowly cools.

8. A white dwarf

The core is now a white dwarf star, and the former shells around the core become its thin atmosphere.

The carbon-oxygen interior of the white dwarf is degenerate, so it does not contract as it cools. Hence the white dwarf's radius no longer changes.

▢	Hydrogen and helium, no fusion
▢	Hydrogen fusion producing helium
▢	Helium, no fusion
▢	Helium fusion producing carbon and oxygen
▢	Carbon and oxygen, no fusion

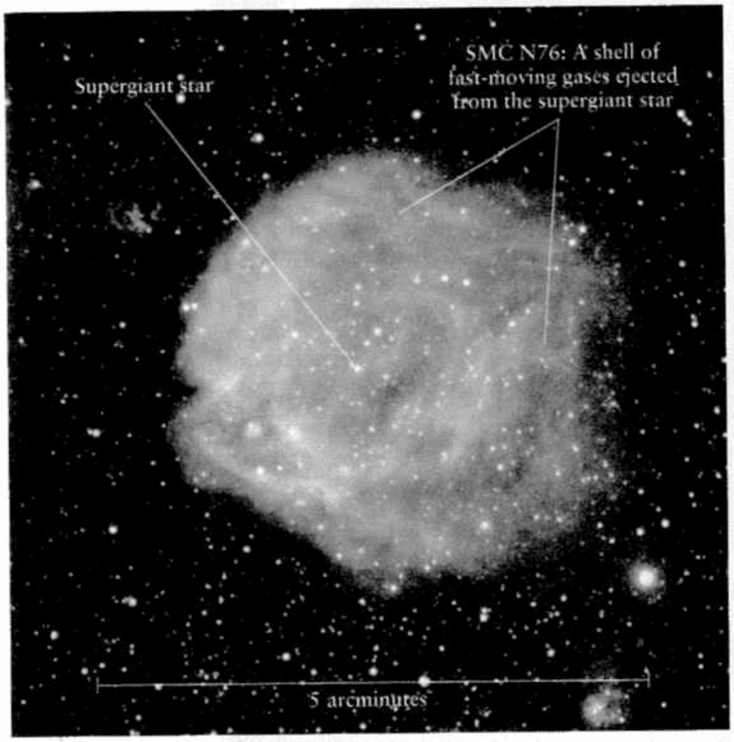


Figure 20-12 RIVUXG

Mass Loss from a Supergiant Star At the heart of this nebulosity, called SMC N76, lies a supergiant star with a mass of at least 18 $M_\odot$. This star is losing mass at a rapid rate in a strong stellar wind. As this wind collides with the surrounding interstellar gas and dust, it creates the "bubble" shown here. SMC N76, which has an angular diameter of 130 arcsec, lies within the Small Magellanic Cloud, a small galaxy that orbits our Milky Way. It is about 60,600 pc (198,000 ly) distant. (Y. Nazé, G. Rauw, J. Manfroid, and J.-M. Vreux, Liège Institute; Y.-H. Chu, U. of Illinois; and ESO)

reactions can take place. After the cessation of carbon fusion, the core will again contract, and the star's central temperature can rise to 1 billion kelvins (10^9 K). At this temperature **neon fusion** begins. This uses up the neon accumulated from carbon fusion and further increases the concentrations of oxygen and magnesium in the star's core.

After neon fusion ends, the core will again contract, and **oxygen fusion** will begin when the central temperature of the star reaches about 1.5 billion kelvins (1.5×10^9 K). The principal product of oxygen fusion is silicon (^{28}Si, 14 protons). Once oxygen fusion is over, the core will contract yet again. If the central temperature reaches about 2.7 billion kelvins (2.7×10^9 K), **silicon fusion** begins, producing a variety of nuclei from sulfur (^{32}S, 16 protons) to iron (^{56}Fe, 26 protons) and nickel (^{56}Ni, 28 protons). While all of this is going on in the star's interior, at the surface the star is losing mass at a rapid rate (Figure 20-12).

As a high-mass star consumes increasingly heavier nuclei, the thermonuclear reactions produce a wider variety of products. For example, oxygen fusion produces not only silicon but also magnesium (^{24}Mg, with 12 protons), phosphorus (^{31}P, with 15 protons), and sulfur (^{31}S and ^{32}S, each with 16 protons). Some thermonuclear reactions that create heavy elements also release neutrons. A neutron is like a proton except that it carries no electric charge. Therefore, neutrons are not repelled by positively charged nuclei, and so can easily collide and combine with them. This absorption of neutrons by nuclei, called **neutron capture**, creates many elements and isotopes that are not produced directly in fusion reactions.

Each stage of thermonuclear reactions in a high-mass star helps to trigger the succeeding stage. In each stage, when the star exhausts a given variety of nuclear fuel in its core, gravitational contraction takes the core to ever-higher densities and temperatures, thereby igniting the "ash" of the previous fusion stage—and possibly the outlying shell of unburned fuel as well.

Supergiant Stars and Their Evolution

The increasing density and temperature of the core make each successive thermonuclear reaction more rapid than the one that preceded it. As an example, Table 20-1 shows a theoretical calculation of the evolutionary stages for a star with a zero-age mass of 25 $M_\odot$. This calculation indicates that carbon fusion in such a star lasts for 600 years, neon fusion for 1 year, and oxygen fusion for only 6 months. The last, and briefest, stage of nuclear reactions is silicon fusion. The entire core supply of silicon in a 25-$M_\odot$ star is used up in only one day!

Table 20-1 Evolutionary Stages of a 25-$M_\odot$ Star

Stage	Core temperature (K)	Core density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	¼ second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosive (supernova)	about 10^9	varies	10 seconds

Based on calculations by Stanford Woosley (University of California, Santa Cruz) and Thomas Weaver (Lawrence Livermore National Laboratory).

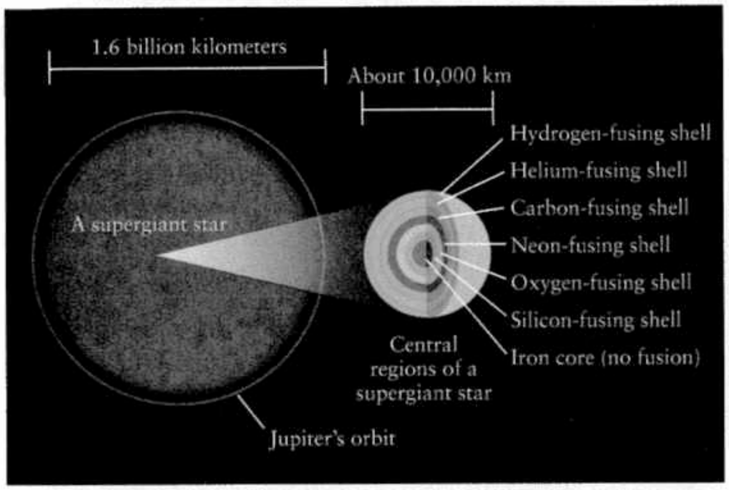


Figure 20-13

The Structure of an Old High-Mass Star Near the end of its life, a star with an initial mass greater than about 8 $M_\odot$ becomes a red supergiant. The star's overall size can be as large as Jupiter's orbit around the Sun. The stars energy comes from a series of concentric fusing shells, all combined within a volume roughly the same size as the Earth. Thermonuclear reactions do not occur within the iron core, because fusion reactions that involve iron absorb energy rather than release it.

Each stage of core fusion in a high-mass star generates a new shell of material around the core. After several such stages, the internal structure of a truly massive star—say, 25 to 30 $M_\odot$ or greater—resembles that of an onion (see Figure 20-13). Because thermonuclear reactions can take place simultaneously in several shells, energy is released at such a rapid rate that the star's outer layers expand tremendously. The result is a **supergiant** star, whose luminosity and radius are much larger than those of a giant (see Section 17-7).

A star of 8 or more solar masses evolves into a supergiant 100 times (or more) larger than the Sun

Several of the brightest stars in the sky are supergiants, including Betelgeuse and Rigel in the constellation Orion and Antares in the constellation Scorpius. (Figure 17-15 shows the locations of these stars on an H-R diagram.) They appear bright not because they are particularly close, but because they are extraordinarily luminous.

A supergiant star cannot keep adding shells to its "onion" structure forever, because the sequence of thermonuclear reactions cannot go on indefinitely. In order for an element to serve as a thermonuclear fuel, energy must be given off when its nuclei collide and fuse. This released energy is a result of the strong nuclear force of attraction that draws nucleons (neutrons and protons) together. However, protons also repel one another by the weaker electric force. As a result of this electric repulsion, adding extra protons to nuclei larger than iron, which has 26 protons, requires an *input* of energy rather than causing energy to be released. Nuclei of this size or larger cannot act as fuel for thermonuclear reactions. Hence, the sequence of fusion stages ends with silicon fusion. One of the products of silicon fusion is iron, and the result is a star with an iron-rich core in which no thermonuclear reactions take place (see Figure 20-13).

Shell fusion in the layers surrounding the iron-rich core consumes the star's remaining reserves of fuel. At this stage the entire energy-producing region of the star is contained in a volume no bigger than the Earth, some 10^6 times smaller in radius than the overall size of the star. This state of affairs will soon come to an end, because the buildup of an inert, iron-rich core signals the impending violent death of a massive supergiant star.

20-6 High-mass stars violently blow apart in core-collapse supernova explosions

Our present understanding is that all stars of about 8 $M_\odot$ or less divest most of their mass in the form of planetary nebulae. The burned-out core that remains settles down to become a white dwarf star. But the truly massive stars—stellar heavyweights that begin their lives with more than 8 solar masses of material—do not pass through a planetary nebula phase. Instead, they die in spectacular *core-collapse supernova explosions.*

The Violent End of a High-Mass Star

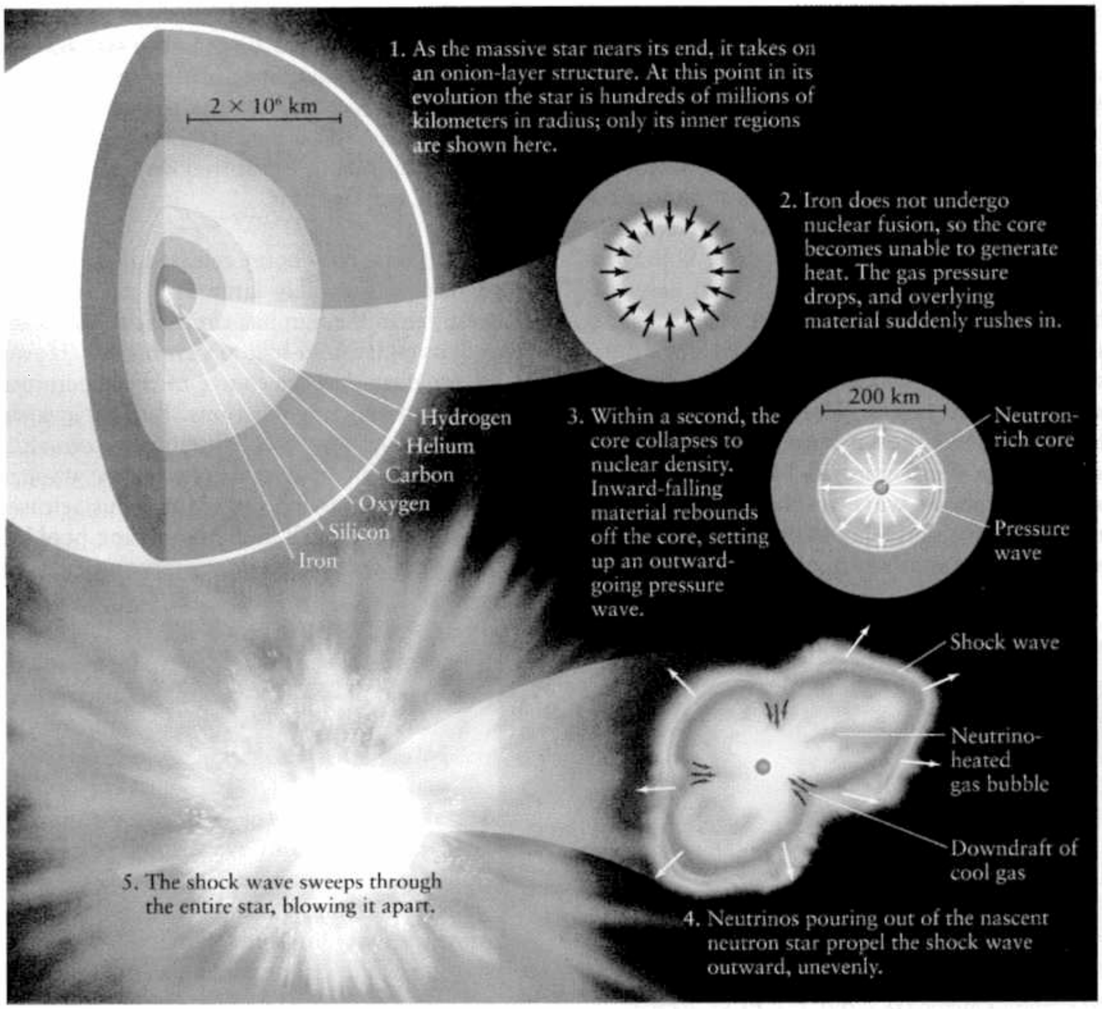
To understand what happens in a core-collapse supernova explosion, we must look deep inside a massive star at the end of its life. Of course, we cannot do this in actuality, because the interiors of stars are opaque. But astronomers have developed theoretical models based on what we know about the behavior of gases and atomic nuclei. The story that follows, while largely theoretical, describes our observations of supernovae fairly well. And, as we will see in Section 20-8, a special kind of "telescope" has allowed us to glimpse the interior of at least one relatively nearby supernova.

The core of an aging, massive star gets progressively hotter as it contracts to ignite successive stages of thermonuclear fusion (see Stage 1 in Figure 20-14). Wien's law (Section 5-4) and Planck's law (Section 5-5) together tell us that as the temperature of an object like a star increases, so does the energy of the photons it emits. When the temperature in the core of a massive star reaches a few hundred million kelvins, the photons are energetic enough to initiate a host of nuclear reactions that create neutrinos. These neutrinos, which carry off energy, escape from the star's core, just as solar neutrinos flow freely out of the Sun (see Section 16-4).

To compensate for the energy drained by the neutrinos, the star must provide energy either by consuming more thermonuclear fuel, by contracting, or both. But when the star's core is converted into iron, no more energy-producing thermonuclear reactions are possible, and the only source of energy is contraction and rapid heating (see Stage 2 in Figure 20-14).

By forming a dense core of iron, a massive star sows the seeds of its own destruction

Once a star with an original mass of about 8 $M_\odot$ or more develops an iron-rich core, the core contracts very rapidly, so that the core temperature skyrockets to 5×10^9 K within a tenth of a second. The gamma-ray photons emitted by the intensely hot core have so much energy that when they collide with iron nuclei, they begin to break the iron nuclei down into much smaller helium nuclei (^{4}He). This process is called



1. As the massive star nears its end, it takes on an onion-layer structure. At this point in its evolution the star is hundreds of millions of kilometers in radius; only its inner regions are shown here.

2. Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in.

3. Within a second, the core collapses to nuclear density. Inward-falling material rebounds off the core, setting up an outward-going pressure wave.

4. Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly.

5. The shock wave sweeps through the entire star, blowing it apart.

Figure 20-14

A Core-Collapse Supernova This series of illustrations depicts our understanding of the last day in the life of a star of more than about 8 $M_\odot$. (Illustration by Don Dixon, adapted from Wolfgang Hillebrandt, Hans-Thomas Janka, and Ewald Müller, "How to Blow Up a Star," *Scientific American*, October 2006)

photodisintegration. As Table 20-1 shows, it takes a high-mass star millions of years and several stages of thermonuclear reactions to build up an iron core; within a fraction of a second, photodisintegration undoes the result of those millions of years of reactions.

Within another tenth of a second, the core becomes so dense that the negatively charged electrons within it are forced to combine with the positively charged protons to produce electrically neutral neutrons. This process also releases a flood of neutrinos, denoted by the Greek letter ν (nu):

$$e^- + p \rightarrow n + \nu$$

Although neutrinos interact only very weakly with matter (see Section 16-4), the core is now so dense that even neutrinos cannot escape from it immediately. But because these neutrinos carry away a substantial amount of energy as they escape from the core, the core cools down and condenses even further.

At about 0.25 second after its rapid contraction begins, the core is less than 20 km in diameter and its density is in excess of 4×10^{17} kg/m^3. This is **nuclear density**, the density with which neutrons and protons are packed together inside nuclei. (If the Earth were compressed to this density, it would be only 300 meters, or 1000 feet, in diameter.)

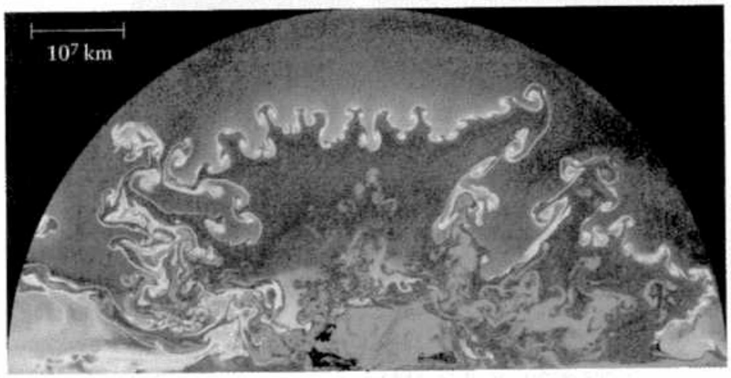
Matter at nuclear density or higher is extraordinarily difficult to compress. Thus, when the density of the neutron-rich core begins to exceed nuclear density, the core suddenly becomes very stiff and rigid. The core's contraction comes to a sudden halt, and the innermost part of the core actually bounces back and expands somewhat. This *core bounce* sends a powerful wave of pressure, like an unimaginably intense sound wave, outward into the outer core (see Stage 3 in Figure 20-14).

During this critical stage, the cooling of the core has caused the pressure to decrease profoundly in the regions surrounding the core. Without pressure to hold it up against gravity, the material from these regions plunges inward at speeds up to 15% of the speed of light. When this inward-moving material crashes down onto the rigid core, it encounters the outward-moving pressure wave. In just a fraction of a second, the material that fell onto the core begins to move back out toward the star's surface, propelled in part by the flood of neutrinos trying to escape from the star's core.

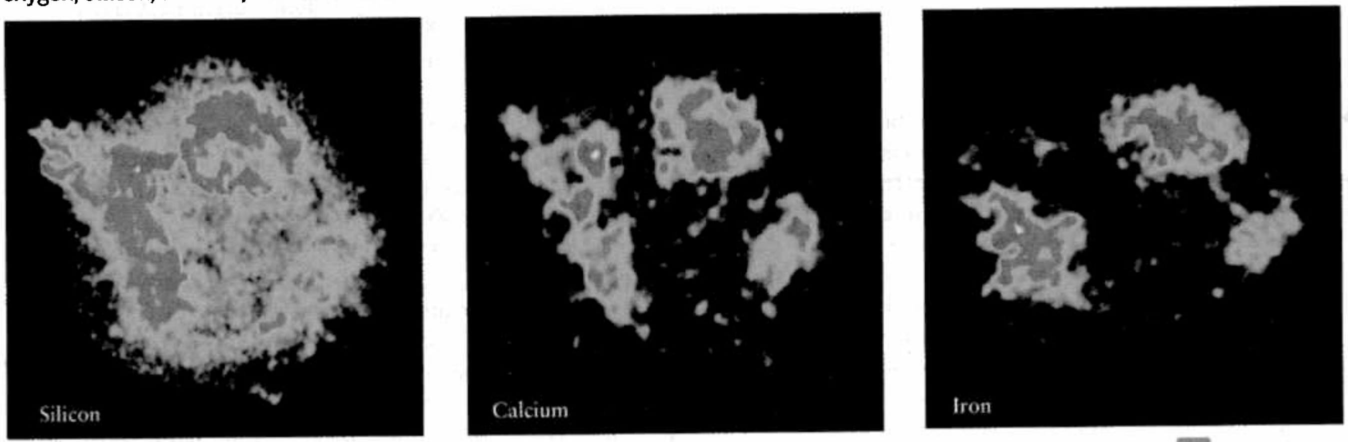
Supercomputer simulations of this complex process show that if the pressure wave were to spread outward at precisely the same speed in all directions, its energy would be absorbed by the gas around the core and the wave would fizzle out. But when the simulations allow for the presence of convection and turbulence in the dying star's gases, the result is quite different: The material surrounding the core behaves more like water boiling furiously in a heated pot. Rising bubbles of superheated gases deliver extra energy to the pressure wave, sustaining it and making it accelerate as it plows outward through the doomed star's outer layers. The wave soon reaches a speed greater than the speed of sound waves in the star's outer layers. When this happens, the wave becomes a *shock wave*, like the sonic boom produced by a supersonic airplane (see Stage 4 in Figure 20-14).

After a few hours, the shock wave reaches the star's surface, by which time the star's outer layers have begun to lift away from the core. When the star's outer layers thin out sufficiently, a portion of this energy escapes in a torrent of light (see Stage 5 in Figure 20-14). The star has become a **supernova** (plural **supernovae**). Specifically, what we have described is the formation of a **core-collapse supernova.** We use this term because, as we will see in Section 20-9, it is possible for supernova explosions to occur that do not involve the collapse of the core of a massive star.

CAUTION! The energy released in a core-collapse supernova is an incomprehensibly large 10^{46} joules—a hundred times more energy than the Sun has emitted due to thermonuclear reactions over its entire 4.56-billion year history. However, it is important to recognize that the source of the supernova's energy release is *not* thermonuclear reactions. Rather, it is the *gravitational* energy released by the collapse of the core and by the inward fall of the star's outer layers. (You release gravitational energy when you fall off a diving board, and this released energy goes into making a big splash in the swimming pool.) The energy released by the collapse of the core reappears in the form of neutrinos;



(a) A simulated supernova 5½ hours after the core "bounce" (red = hydrogen, green = helium, turquoise and blue = carbon, oxygen, silicon, and iron)



(b) Material was ejected in "blobs" from the supernova that produced the Cassiopeia A supernova remnant R I V U X G

ANIMATION 20.3
WEBLINK 20.8

Figure 20-15

Turbulence in a Core-Collapse Supernova **(a)** This image from a supercomputer simulation show a cross section of a massive star several hours into the supernova explosion. The colors show the turbulent mixing of material from the star's inner regions (turquoise and blue) with hydrogen and helium from the outer layers (green and red). **(b)** Turbulence causes material to be ejected from the supernova in irregular "blobs," as shown by these images of the supernova remnant Cassiopeia A. Each image was made using an X-ray wavelength emitted by a particular element. (Figure 18-24 shows a false-color image of Cassiopeia A made using visible, infrared, and X-ray wavelengths.) (a: Konstantinos Kifonidis, Max-Planck-Institut für Astrophysik; b: U. Hwang et al., NASA/GSFC) the fall of the outer layers provides the energy to power the nuclear reactions that generate the supernova's electromagnetic radiation. The amount of energy release from the supernova is so great because the star is so massive; hence, the amount of material that falls inward is immense, it falls a great distance, and is acted on by a strong gravitational pull as it falls.

The Wreckage of a Core-Collapse Supernova

Supercomputer simulations provide many insights into the violent, complex, and rapidly changing conditions deep inside a star as it is torn apart by a supernova explosion (Figure 20-15). For example, Figure 20-15*a* shows a snapshot of the interior of a high-mass star $5\frac{1}{2}$ hours after the stiffening of the core. The simulation predicts turbulent swirls and eddies that grow behind the shock wave as it moves outward from the star's core. Evidence in favor of such turbulence comes from images of the remnants of long-ago supernovae (Figure 20-15*b*). Such images show that material is ejected from the supernova not in uniform shells but in irregular clumps. This is just what would be expected from a turbulent explosion. (We discuss supernova remnants further in Section 20-10.)

Detailed computer calculations suggest that a 25-$M_\odot$ star ejects about 96% of its material to the interstellar medium for use in producing future generations of stars. Less massive stars eject a smaller percentage of their mass into space when they become core-collapse supernovae.

Before this material is ejected into space, it is compressed so much by the passage of the shock wave through the star's outer layers that a new wave of thermonuclear reactions sets in. These reactions can produce many more chemical elements, including elements heavier than iron. Reactions of this kind require a tremendous input of energy, and thus cannot take place during the star's pre-supernova lifetime.

The energy-rich environment of a supernova shock wave is almost the only place in the universe where such heavy elements as zinc, silver, tin, gold, mercury, lead, and uranium can be produced. (In Chapter 21 we will see another, even more exotic mechanism for producing these heaviest elements.) Remarkably, all of these elements are found on the Earth. Hence, some of the material that makes up our solar system, our Earth, and our bodies must long ago have been part of a star that lived, evolved, and died as a supernova.

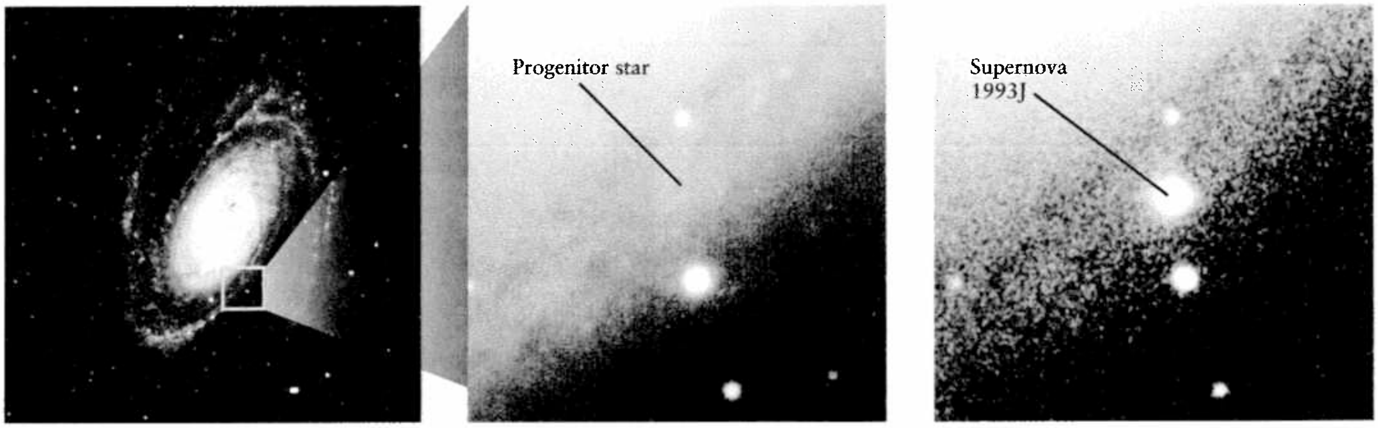
20-7 In 1987 a nearby supernova gave us a close-up look at the death of a massive star

Supernovae have peak luminosities as great as 10^9 $L_\odot$, rivaling the light output of an entire galaxy. This makes it possible to see supernovae in galaxies far beyond our own Milky Way Galaxy, and indeed hundreds of these distant supernovae are observed each year (Figure 20-16). In a handful of cases, images made before the explosion have allowed astronomers to identify the star that subsequently exploded into a supernova, called the **progenitor star.** For example, the progenitor star shown in Figure 20-16*b* was a red supergiant star whose internal structure probably resembled that shown in cross section in Figure 20-13.

One frustrating aspect of these distant supernovae is simply that they *are* distant, and so cannot be studied in as much detail as astronomers would like. But one recent and unusually close supernova has provided astronomers with a unique opportunity to check the theoretical ideas presented in Section 20-6.

A Supernova in the Galaxy Next Door

On February 23, 1987, a supernova was discovered in the Large Magellanic Cloud (LMC), a companion galaxy to our Milky Way some 51,500 pc (168,000 ly) from Earth. The supernova, designated SN 1987A because it was the first discovered that year, occurred near an enormous H II region in the LMC called the



(a) Spiral galaxy M81 **(b) Before the explosion** **(c) After the explosion**

Figure 20-16 R I **V** U X G

A Supernova in a Distant Galaxy On the night of March 28, 1993, Francisco Garcia Diaz, a Spanish amateur astronomer, discovered supernova SN 1993J in the galaxy M81 in Ursa Major. **(a)** M81 lies some 3.6 million pc (12 million ly) from Earth. Its angular size is about half that of the full moon. **(b)** The progenitor star that later exploded into SN 1993J was a K0 red supergiant. **(c)** This image shows the same part of the sky as (b). Like SN 1987A, SN 1993J resulted from the core collapse and subsequent explosion of a massive star. (a: Palomar Observatory; b, c: D. Jones and E. Telles, Isaac Newton Telescope)