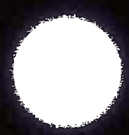
(4) Helium-burning supergiant: Helium fusion begins when the core temperature becomes hot enough to fuse helium into carbon. The core then expands, slowing the rate of hydrogen shell burning and allowing the star's outer layers to shrink.



1 million years

3:14:00 AM → 3:52:00 AM

(5) Multiple shell-burning supergiant: After the core runs out of helium, it shrinks and heats until fusion of heavier elements begins. Late in life, the star fuses many different elements in a series of shells while iron collects in the core.

10,000 years

3:52:00 AM → 3:52:23 AM

(6) Supernova: Iron cannot provide fusion energy, so it accumulates in the core until degeneracy pressure can no longer support it. Then the core collapses, leading to the catastrophic explosion of the star.

a few months

3:52:23 AM

(7) Neutron star or black hole: The core collapse forms a ball of neutrons, which may remain as a neutron star or collapse further to make a black hole.

indefinite

—

(4) Helium-burning star: Helium fusion begins when the core becomes hot enough to fuse helium into carbon. The core then expands, slowing the rate of hydrogen shell burning and allowing the star's outer layers to shrink.

100 million years

December 27 → December 30

(5) Double shell-burning red giant: Helium shell burning begins around the inert carbon core after the core helium is exhausted. The star then enters its second red giant phase, with fusion in both a hydrogen shell and a helium shell.

30 million years

December 30 → December 31

(6) Planetary nebula: The dying star expels its outer layers in a planetary nebula, leaving behind the exposed inert core.

10,000 years

December 31

(7) White dwarf: The remaining white dwarf is made primarily of carbon and oxygen because the core of the low-mass star never grows hot enough to produce heavier elements.

indefinite

—

The lifetime of this $1M_{Sun}$ star is almost 2000 times as long as that of a $25M_{Sun}$ star with a mass 25 times that of our Sun and a low-mass star with the same mass as our Sun. Remember that all types of stars grow larger and redder when they exhaust their core hydrogen, and during these late stages they make the elements necessary for human existence. Much of the carbon in our bodies was made in low- and intermediate-mass stars and then blown into space by their stellar winds and planetary nebulae. Most of the heavier elements that our bodies rely upon were made in high-mass stars and expelled in supernova explosions.

How are the lives of stars with close companions different?

For the most part, stars in binary systems proceed from birth to death as if they were isolated. However, exceptions can occur in close binary star systems. Algol, the "demon star" in the constellation Perseus, is a good example. It appears as a single star to our eyes and telescopes, but it is actually an eclipsing binary star system [Section 15.1] consisting of two stars that orbit each other closely: a $3.7M_{\text{Sun}}$ main-sequence star and a $0.8M_{\text{Sun}}$ subgiant.

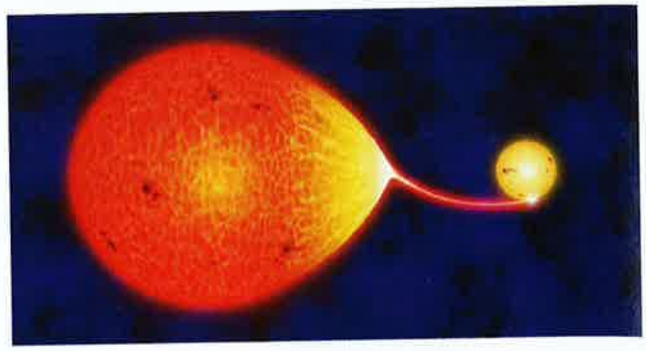
A moment's thought reveals that something quite strange is going on. The stars of a binary system are born at the same time and therefore must both be the same age. We know that more massive stars live shorter lives, and therefore the more massive star must exhaust its core hydrogen and become a subgiant before the less massive star does. How, then, can Algol's less massive star be a subgiant while the more massive star is still burning hydrogen as a main-sequence star?

This so-called *Algol paradox* reveals some of the complications in ordinary stellar life cycles that can arise in close binary systems. The two stars in a close binary are near enough to exert significant tidal forces on each other [Section 4.5]. The gravity of each star attracts the near side of the other star more strongly than it attracts the far side. The stars therefore stretch into elongated shapes rather than remaining spherical. In addition, the stars become *tidally locked* so that they always show the same face to each other, much as the Moon always shows the same face to Earth.

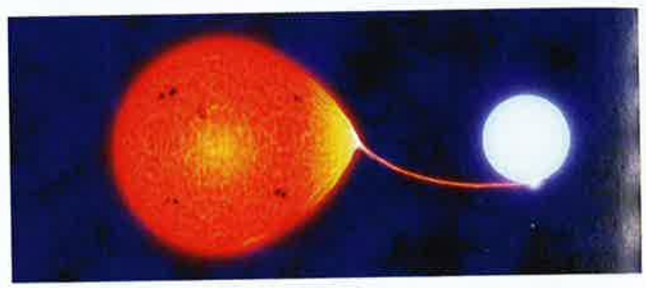
During the time that both stars are main-sequence stars, the tidal forces have little effect on their lives. However, when the more massive star (which exhausts its core hydrogen sooner) begins to expand into a red giant, gas from its outer layers can spill onto its companion. This **mass exchange** occurs when the giant grows so large that its tidally distorted outer layers succumb to the gravitational contraction of the smaller companion star. The companion then begins to gain mass at the giant's expense.

The solution to the Algol paradox should now be clear (Figure 17.20). The $0.8M_{\text{Sun}}$ subgiant *used to be* much more massive. As the more massive star, it was the first to begin expanding into a red giant. As it expanded, however, it transferred so much of its matter onto its companion that it is now the less massive star.

Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen-burning companion.



Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

FIGURE 17.20 Artist's conception of the development of the Algol close binary system.

The future may hold even more interesting events for Algol. The $3.7M_{\text{Sun}}$ star is still gaining mass from its subgiant companion. Its life cycle is therefore accelerating as its increasing gravity raises its core hydrogen fusion rate. Millions of years from now, it will exhaust its hydrogen and begin to expand into a red giant itself. At that point, it can begin to transfer mass *back* to its companion. Even more amazing things can happen in other mass-exchange systems, particularly when one of the stars is a white dwarf or a neutron star. But that is a topic for the next chapter.

THE BIG PICTURE

Putting Chapter 17 into Context

In this chapter, we have seen how the origin of the elements, first discussed in Chapter 1, is intimately linked to the lives and deaths of stars. As you look back over this chapter, remember these "big picture" ideas:

- Virtually all elements besides hydrogen and helium were forged in the nuclear furnaces of stars and released into space as they died. We and our planet are therefore made of stuff produced in stars that lived and died long ago.
- Low-mass stars like our Sun live long lives and die by producing planetary nebulae that leave behind white dwarfs.
- High-mass stars live fast and die young, exploding dramatically as supernovae and leaving behind neutron stars or black holes.
- Close binary stars can exchange mass, altering the usual course of stellar evolution.

SUMMARY OF KEY CONCEPTS

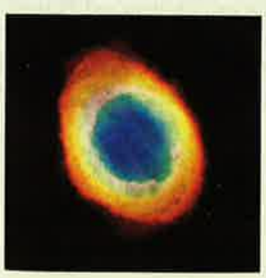
17.1 LIVES IN THE BALANCE

- **How does a star's mass affect nuclear fusion?** Stars of greater mass have hotter core temperatures, causing fusion to proceed more quickly and enabling fusion of heavier elements to take place. A star's *mass* at birth therefore determines almost every aspect of its life and death. To understand the general characteristics of stellar lives, we divide stars into three groups by mass: **low-mass stars**, with masses less than $2M_{Sun}$; **intermediate-mass stars**, with masses between $2M_{Sun}$ and $8M_{Sun}$; and **high-mass stars**, with masses above $8M_{Sun}$.

17.2 LIFE AS A LOW-MASS STAR

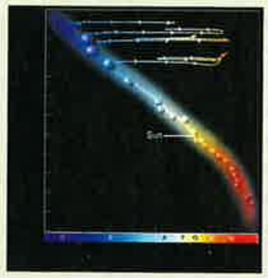
- **What are the life stages of a low-mass star?** A low-mass star spends most of its life generating energy by fusing hydrogen in its core via the proton-proton chain. When core hydrogen is exhausted, the core begins to shrink while the star as a whole expands to become a **red giant**, with **hydrogen shell burning** around an inert helium core. When the core becomes hot enough, a **helium flash** initiates **helium fusion** in the core, which fuses helium into carbon. This phase lasts until core helium is exhausted. Low-mass stars never become hot enough for carbon fusion, so at this point their lives must come to an end.

- **How does a low-mass star die?** The core again shrinks after core helium burning ceases. Helium shell burning begins around the inert carbon core beneath the hydrogen-burning shell. The outer layers expand again, making the star into a double shell–burning red giant. The star's energy generation never reaches equilibrium during this time; instead, the star experiences a series of **thermal pulses** and ultimately expels its outer layers into space as a **planetary nebula**. The remaining "dead" stellar core is a **white dwarf**.

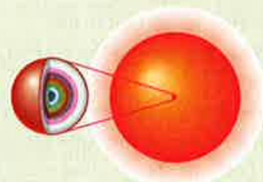


17.3 LIFE AS A HIGH-MASS STAR

- **What are the life stages of a high-mass star?** A high-mass star lives a much shorter life than a low-mass star, fusing hydrogen into helium via the **CNO cycle**. After exhausting its core hydrogen, a high-mass star begins hydrogen shell burning and then goes through a series of stages, burning successively heavier elements. The furious rate of fusion makes the star swell in size to become a supergiant.



- **How do high-mass stars make the elements necessary for life?** In its final stages of life, a high-mass star's core becomes hot enough to fuse carbon and other heavy elements. The variety of different fusion reactions produces a wide range of elements—including all the elements necessary for life—that are then released into space when the star dies.



- **How does a high-mass star die?** A high-mass star dies in the cataclysmic explosion of a **supernova**, scattering newly produced elements into space and leaving a neutron star or a black hole behind. The supernova occurs after fusion begins to pile up iron in the high-mass star's core. Because iron fusion cannot release energy, the core cannot hold off the crush of gravity for long. In the instant that gravity overcomes degeneracy pressure, the core collapses and the star explodes. The expelled gas may be visible for a few thousand years as a **supernova remnant**.

17.4 THE ROLES OF MASS AND MASS EXCHANGE

- **How does a star's mass determine its life story?** A star's mass determines how it lives its life. Low-mass stars never get hot enough to fuse carbon into heavier elements in their cores, and they end their lives by expelling their outer layers and leaving white dwarfs behind. High-mass stars live short but brilliant lives, ultimately dying in supernova explosions.

- **How are the lives of stars with close companions different?** When one star in a close binary system begins to swell in size at the end of its hydrogen-burning life, it can begin to transfer mass to its companion. This **mass exchange** can change the remaining life histories of both stars.

EXERCISES AND PROBLEMS

For instructor-assigned homework go to www.masteringastronomy.com.

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REVIEW QUESTIONS

Short-Answer Questions Based on the Reading

1. Why is mass so important to a star's life? How and why do we divide stars into groups by mass?
2. What do all *low-mass stars* share in common? Why do they differ in their levels of surface activity? What are *flare stars*?
3. When a star exhausts its core hydrogen fuel, the core contracts but the star as a whole expands. Why?
4. What is the *helium fusion* reaction, and why does it require much higher temperatures than hydrogen fusion? Why will helium fusion in the Sun begin with a *helium flash?*
5. Why does the H-R diagram of a globular cluster show a *horizontal branch*? What are the characteristics of the stars on the horizontal branch?
6. What happens to a low-mass star after it exhausts its core helium? Why can't it fuse carbon into heavier elements?
7. What are *carbon stars*? How are they important to life?
8. What is a *planetary nebula?* What happens to the core of a star after a planetary nebula occurs?
9. What will happen to Earth as the Sun changes in the future?
10. Summarize the stages of life that we see on the Sun's life track in Figure 17.8. Be sure to explain both the changes that occur in the Sun's core with each stage and the changes that are observable from outside the Sun.
11. In broad terms, explain how the life of a *high-mass star* differs from that of a low-mass star. How do *intermediate-mass stars* fit into this picture?
12. Describe some of the nuclear reactions that can occur in high-mass stars after they exhaust their core helium. Why does this continued nuclear burning occur in high-mass stars but not in low-mass stars?
13. Why can't iron be fused to release energy?
14. Summarize some of the observational evidence supporting our ideas about how heavy elements form in massive stars.
15. What event initiates a *supernova*? Explain what happens during the explosion and why a neutron star or a black hole is left behind. What observational evidence supports our understanding of supernovae?
16. What is the *Algol paradox* and its resolution? Why can the lives of close binary stars differ from those of single stars?

TEST YOUR UNDERSTANDING

Does It Make Sense?

Decide whether the statement makes sense (or is clearly true) or does not make sense (or is clearly false). Explain clearly; not all these have definitive answers, so your explanation is more important than your chosen answer.

17. The iron in my blood came from a star that blew up more than 4 billion years ago.
18. Humanity will eventually have to find another planet to live on, because one day the Sun will blow up as a supernova.
19. I sure am glad hydrogen has a higher mass per nuclear particle than many other elements. If it had the lowest mass per nuclear particle, none of us would be here.
20. I just discovered a $3.5M_{\text{Sun}}$ main-sequence star orbiting a $2.5M_{\text{Sun}}$ red giant. I'll bet that red giant was more massive than $3M_{\text{Sun}}$ when it was a main-sequence star.
21. If the Sun had been born as a high-mass star $4\frac{1}{2}$ billion years ago rather than as a low-mass star, the planet Jupiter would probably have Earth-like conditions today, while Earth would be hot like Venus.
22. If you could look inside the Sun today, you'd find that its core contains a much higher proportion of helium and a lower proportion of hydrogen than it did when the Sun was born.
23. Most of the supernova explosions that occur in a star cluster happen during its first 100 million years.

24. Globular clusters generally contain lots of white dwarfs.
25. After hydrogen fusion stops in a low-mass star, its core cools off until the star becomes a red giant.
26. The gold in my new ring came from a supernova explosion.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

27. Which of these stars has the hottest core? (a) a white main-sequence star (b) an orange main-sequence star (c) a red main-sequence star
28. Which of these stars has the hottest core? (a) a blue main-sequence star (b) a red supergiant (c) a red main-sequence star
29. Which of these stars does not have fusion occurring in its core? (a) a red giant (b) a red main-sequence star (c) a blue main-sequence star
30. What happens to a low-mass star after its helium flash? (a) Its luminosity goes up. (b) Its luminosity goes down. (c) Its luminosity stays the same.
31. What would stars be like if hydrogen had the smallest mass per nuclear particle? (a) Stars would be brighter. (b) All stars would be red giants. (c) Nuclear fusion would not occur in stars of any mass.
32. What would stars be like if carbon had the smallest mass per nuclear particle? (a) Supernovae would be more common. (b) Supernovae would never occur. (c) High-mass stars would be hotter.
33. What would you be most likely to find if you returned to the solar system in 10 billion years? (a) a neutron star (b) a white dwarf (c) a black hole
34. Which of these stars has the shortest life expectancy? (a) an isolated $1M_{\text{Sun}}$ star (b) a $1M_{\text{Sun}}$ star in a close binary system with a $0.8M_{\text{Sun}}$ star (c) a $1M_{\text{Sun}}$ star in a close binary system with a $2M_{\text{Sun}}$ star
35. What happens to the core of a high-mass star after it runs out of hydrogen? (a) It shrinks and heats up. (b) It shrinks and cools down. (c) Helium fusion begins right away.
36. Which of these elements had to be made in a supernova explosion? (a) calcium (b) uranium (c) oxygen

PROCESS OF SCIENCE

Examining How Science Works

37. *Predicting the Sun's Future.* Models of stellar evolution make detailed predictions about the fate of the Sun. Describe a piece of evidence that supports each of the following model predictions:
a. The Sun cannot continue supplying Earth with light and heat forever. b. The Sun will become a red giant before the end of its life. c. The Sun will leave behind a white dwarf after it dies.
38. *Blue Stragglers.* Notice in Figure 17.6b the small number of stars that appear to be on the main sequence but above the cluster's main-sequence turnoff point. These stars are known as *blue stragglers*, because they are bluer and more massive than the stars we expect to find on the cluster's main sequence. (a) Why is the presence of blue stragglers surprising? (b) One possible explanation for blue stragglers is that there is something wrong with our theory of stellar evolution, but astronomers instead suspect that a blue straggler forms through the merger of two smaller stars. Why do astronomers prefer the merger explanation? Can you think of a way in which the merger explanation could be tested?

INVESTIGATE FURTHER

In-Depth Questions to Increase Your Understanding

Short-Answer/Essay Questions

Homes to Civilization? We do not yet know how many stars have Earth-like planets, nor do we know the likelihood that such planets might harbor advanced civilizations like our own. However, some stars can probably be ruled out as candidates for advanced civilizations. For example, given that it took a few billion years for humans to evolve from the first life forms on Earth, it seems unlikely that advanced life would have had time to evolve around a star that is only a few million years old. For each of the following stars, decide whether you think it is possible that it could harbor an advanced civilization. Explain your reasoning in one or two paragraphs.

39. A $10M_{\text{Sun}}$ main-sequence star
40. A $1.5M_{\text{Sun}}$ main-sequence star
41. A $1.5M_{\text{Sun}}$ red giant
42. A $1M_{\text{Sun}}$ helium-burning star
43. A red supergiant
44. A flare star
45. A carbon star
46. *Rare Elements.* Lithium, beryllium, and boron are elements with atomic numbers 3, 4, and 5, respectively. Despite their being three of the five simplest elements, Figure 17.15 shows that they are rare compared to many heavier elements. Suggest a reason for their rarity. (*Hint:* Consider the process by which helium fuses into carbon.)
47. *Future Skies.* As a red giant, the Sun will have an angular size in Earth's sky of about 30°. What will sunset and sunrise be like? About how long will they take? Do you think the color of the sky will be different from what it is today? Explain.
48. *Research: Historical Supernovae.* Historical accounts describe supernovae in the years 1006, 1054, 1572, and 1604. Choose one of these supernovae and learn more about historical records of the event. Did the supernova influence human history in any way? Write a two- to three-page summary of your research findings.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

49. *Density of a Red Giant.* Near the end of its life, the Sun's radius will extend nearly to the distance of Earth's orbit. Estimate the

volume of the Sun at that time using the formula for the volume of a sphere ($4\pi r^3/3$). Using that result, estimate the average matter density of the Sun at that time. How does that density compare with the density of water ($1\ g/cm^3$)? How does it compare with the density of Earth's atmosphere at sea level (about $10^{-3}\ g/cm^3$)?

50. *Escape Velocity from a Red Giant.* What is the escape velocity from a red giant with a mass of $1M_{Sun}$ and a radius of $100R_{Sun}$? How does that velocity compare with the escape velocity from the Sun? Describe how your results help account for the fact that red giants have strong stellar winds.

51. *Roasting the Earth.* During its final days as a red giant, the Sun will reach a peak luminosity of about $3000L_{Sun}$. Earth will therefore absorb about 3000 times as much solar energy as it does now, and it will need to radiate 3000 times as much thermal energy to keep its surface temperature in balance. Estimate the temperature Earth's surface will need to attain in order to radiate that much thermal energy. You will need to use the formula for emitted power per unit area in Mathematical Insight 15.5.

52. *Supernova Betelgeuse.* The distance of the red supergiant Betelgeuse is approximately 427 light-years. If it were to explode as a supernova, it would be one of the brightest stars in the sky. Right now, the brightest star other than the Sun is Sirius, with a luminosity of $26L_{Sun}$ and a distance of 8.6 light-years. How much brighter than Sirius would the Betelgeuse supernova be in our sky if it reached a maximum luminosity of $10^{10}L_{Sun}$?

53. *Construction of Elements.* Using the periodic table in Appendix D, determine which elements are made by the following nuclear fusion reactions. (You can assume the total number of protons in the reaction remains constant.)

    a. Fusion of a carbon nucleus with another carbon nucleus b. Fusion of a carbon nucleus with a neon nucleus c. Fusion of an iron nucleus with a helium nucleus

54. *Expansion of the Crab Nebula.* Observations of the Crab Nebula taken over several decades show that gas blobs that are now 100 arcseconds from the center of the nebula are moving away from the center by about 0.11 arcsecond per year. Use that information to estimate the year in which the explosion ought to have been observed. How does that year compare with the year in which the supernova that produced the nebula was actually observed?

55. *Algol's Orbital Separation.* The Algol binary system consists of a $3.7M_{Sun}$ star and a $0.8M_{Sun}$ star with an orbital period of 2.87 days. Use Newton's version of Kepler's third law to calculate the orbital separation of the system. How does that separation compare with the typical size of a red giant star?

56. *The Speed of Supernova Debris.* Compute the speed of the debris that was seen hitting the inner ring around Supernova 1987A in the year 2001. Assume that the radius of the inner ring is 0.7 light-year. How does the speed you find compare with the speed of light?

Discussion Questions

57. *Connections to the Stars.* In ancient times, many people believed that our lives were somehow influenced by the patterns of the stars in the sky. Modern science has not found any evidence to support this belief, but instead has found that we have a connection to the stars on a much deeper level: We are "star stuff." Discuss in some detail our real connections to the stars as established by modern astronomy. Do you think these connections have any philosophical implications in terms of how we view our lives and our civilization? Explain.

58. *Humanity in A.D. 5,000,000,000.* Do you think it is likely that humanity will survive until the Sun begins to expand into a red giant 5 billion years from now? Why or why not?

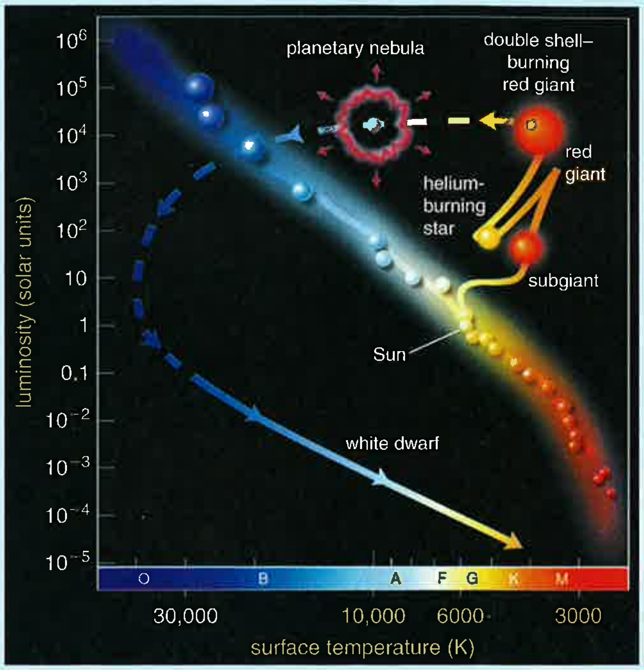
Web Projects

59. *Fireworks in Supernova 1987A.* The light show from Supernova 1987A is still continuing. Learn more about how Supernova 1987A is changing and what we might expect to see from it in the future. Summarize your findings in a one- to two-page report.

60. *Picturing Star Birth and Death.* Photographs of stellar birthplaces (i.e., molecular clouds) and death places (e.g., planetary nebulae and supernova remnants) can be strikingly beautiful, but only a few such photographs are included in this chapter. Search the Web for additional images. Look not only for photos taken in visible light, but also for those taken in other wavelengths. Put the photographs you find into a personal online journal, along with a one-paragraph description of what each photograph shows. Include at least 20 images.

VISUAL SKILLS CHECK

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 17 Visual Quiz at www.masteringastronomy.com.



This figure, similar to the left side of Figure 17.8, shows the future life stages of the Sun on the H-R diagram. Answer the following questions, using the information provided in the figure.

1. What will the Sun's approximate luminosity be during the subgiant stage?
2. When the Sun is a red giant, what will its approximate surface temperature be?
3. Just before the Sun produces a planetary nebula, what will its approximate luminosity be?
4. When the Sun becomes a white dwarf with a surface temperature similar to its current surface temperature, what will its luminosity be?