

22

Stars from Adolescence to Old Age

Figure 22.1 Ant Nebula. During the later phases of stellar evolution, stars expel some of their mass, which returns to the interstellar medium to form new stars. This Hubble Space Telescope image shows a star losing mass. Known as Menzel 3, or the Ant Nebula, this beautiful region of expelled gas is about 3000 light-years away from the Sun. We see a central star that has ejected mass preferentially in two opposite directions. The object is about 1.6 light-years long. The image is color coded—red corresponds to an emission line of sulfur, green to nitrogen, blue to hydrogen, and blue/violet to oxygen. (credit: modification of work by NASA, ESA and The Hubble Heritage Team (STScI/AURA))

Chapter Outline

- 22.1 Evolution from the Main Sequence to Red Giants
- 22.2 Star Clusters
- 22.3 Checking Out the Theory
- 22.4 Further Evolution of Stars
- 22.5 The Evolution of More Massive Stars



Thinking Ahead

The Sun and other stars cannot last forever. Eventually they will exhaust their nuclear fuel and cease to shine. But how do they change during their long lifetimes? And what do these changes mean for the future of Earth?

We now turn from the birth of stars to the rest of their life stories. This is not an easy task since stars live much longer than astronomers. Thus, we cannot hope to see the life story of any single star unfold before our eyes or telescopes. To learn about their lives, we must survey as many of the stellar inhabitants of the Galaxy as possible. With thoroughness and a little luck, we can catch at least a few of them in each stage of their lives. As you've learned, stars have many different characteristics, with the differences sometimes resulting from their different masses, temperatures, and luminosities, and at other times derived from changes that occur as they age. Through a combination of observation and theory, we can use these differences to piece together the life story of a star.

22.1 Evolution from the Main Sequence to Red Giants

Learning Objectives

By the end of this section, you will be able to:

- › Explain the zero-age main sequence
- › Describe what happens to main-sequence stars of various masses as they exhaust their hydrogen supply

One of the best ways to get a “snapshot” of a group of stars is by plotting their properties on an H–R diagram. We have already used the H–R diagram to follow the evolution of protostars up to the time they reach the main sequence. Now we’ll see what happens next.

Once a star has reached the main-sequence stage of its life, it derives its energy almost entirely from the conversion of hydrogen to helium via the process of nuclear fusion in its core (see [The Sun: A Nuclear Powerhouse](#)). Since hydrogen is the most abundant element in stars, this process can maintain the star’s equilibrium for a long time. Thus, all stars remain on the main sequence for most of their lives. Some astronomers like to call the main-sequence phase the star’s “prolonged adolescence” or “adulthood” (continuing our analogy to the stages in a human life).

The left-hand edge of the main-sequence band in the H–R diagram is called the **zero-age main sequence** (see [Figure 18.15](#)). We use the term *zero-age* to mark the time when a star stops contracting, settles onto the main sequence, and begins to fuse hydrogen in its core. The zero-age main sequence is a continuous line in the H–R diagram that shows where stars of different masses but similar chemical composition can be found when they begin to fuse hydrogen.

Since only 0.7% of the hydrogen used in fusion reactions is converted into energy, fusion does not change the *total* mass of the star appreciably during this long period. It does, however, change the chemical composition in its central regions where nuclear reactions occur: hydrogen is gradually depleted, and helium accumulates. This change of composition changes the luminosity, temperature, size, and interior structure of the star. When a star’s luminosity and temperature begin to change, the point that represents the star on the H–R diagram moves away from the zero-age main sequence.

Calculations show that the temperature and density in the inner region slowly increase as helium accumulates in the center of a star. As the temperature gets hotter, each proton acquires more energy of motion on average; this means it is more likely to interact with other protons, and as a result, the rate of fusion also increases. For the proton-proton cycle described in [The Sun: A Nuclear Powerhouse](#), the rate of fusion goes up roughly as the temperature to the fourth power.

If the rate of fusion goes up, the rate at which energy is being generated also increases, and the luminosity of the star gradually rises. Initially, however, these changes are small, and stars remain within the main-sequence band on the H–R diagram for most of their lifetimes.

EXAMPLE 22.1

Star Temperature and Rate of Fusion

If a star’s temperature were to double, by what factor would its rate of fusion increase?

Solution

Since the rate of fusion (like temperature) goes up to the fourth power, it would increase by a factor of 2^4 , or 16 times.

Check Your Learning

If the rate of fusion of a star increased 256 times, by what factor would the temperature increase?

Answer:

The temperature would increase by a factor of $256^{0.25}$ (that is, the 4th root of 256), or 4 times.

Lifetimes on the Main Sequence

How many years a star remains in the main-sequence band depends on its mass. You might think that a more massive star, having more fuel, would last longer, but it's not that simple. The lifetime of a star in a particular stage of evolution depends on how much nuclear fuel it has and on *how quickly* it uses up that fuel. (In the same way, how long people can keep spending money depends not only on how much money they have but also on how quickly they spend it. This is why many lottery winners who go on spending sprees quickly wind up poor again.) In the case of stars, more massive ones use up their fuel much more quickly than stars of low mass.

The reason massive stars are such spendthrifts is that, as we saw above, the rate of fusion depends *very* strongly on the star's core temperature. And what determines how hot a star's central regions get? It is the *mass* of the star—the weight of the overlying layers determines how high the pressure in the core must be: higher mass requires higher pressure to balance it. Higher pressure, in turn, is produced by higher temperature. The higher the temperature in the central regions, the faster the star races through its storehouse of central hydrogen. Although massive stars have more fuel, they burn it so prodigiously that their lifetimes are much shorter than those of their low-mass counterparts. You can also understand now why the most massive main-sequence stars are also the most luminous. Like new rock stars with their first platinum album, they spend their resources at an astounding rate.

The main-sequence lifetimes of stars of different masses are listed in [Table 22.1](#). This table shows that the most massive stars spend only a few million years on the main sequence. A star of 1 solar mass remains there for roughly 10 billion years, while a star of about 0.4 solar mass has a main-sequence lifetime of some 200 billion years, which is longer than the current age of the universe. (Bear in mind, however, that every star spends *most* of its total lifetime on the main sequence. Stars devote an average of 90% of their lives to peacefully fusing hydrogen into helium.)

Lifetimes of Main-Sequence Stars

| Spectral Type | Surface Temperature (K) | Mass (Mass of Sun = 1) | Lifetime on Main Sequence (years) |
|---------------|-------------------------|---------------------------|-----------------------------------|
| O5 | 54,000 | 40 | 1 million |
| B0 | 29,200 | 16 | 10 million |
| A0 | 9600 | 3.3 | 500 million |
| F0 | 7350 | 1.7 | 2.7 billion |
| G0 | 6050 | 1.1 | 9 billion |
| K0 | 5240 | 0.8 | 14 billion |
| M0 | 3750 | 0.4 | 200 billion |

Table 22.1

These results are not merely of academic interest. Human beings developed on a planet around a G-type star. This means that the Sun's stable main-sequence lifetime is so long that it afforded life on Earth plenty of time to evolve. When searching for intelligent life like our own on planets around other stars, it would be a pretty big waste of time to search around O- or B-type stars. These stars remain stable for such a short time that the development of creatures complicated enough to take astronomy courses is very unlikely.

From Main-Sequence Star to Red Giant

Eventually, all the hydrogen in a star's core, where it is hot enough for fusion reactions, is used up. The core then contains only helium, "contaminated" by whatever small percentage of heavier elements the star had to begin with. The helium in the core can be thought of as the accumulated "ash" from the nuclear "burning" of hydrogen during the main-sequence stage.

Energy can no longer be generated by hydrogen fusion in the stellar core because the hydrogen is all gone and, as we will see, the fusion of helium requires much higher temperatures. Since the central temperature is not yet high enough to fuse helium, there is no nuclear energy source to supply heat to the central region of the star. The long period of stability now ends, gravity again takes over, and the core begins to contract. Once more, the star's energy is partially supplied by gravitational energy, in the way described by Kelvin and Helmholtz (see [Sources of Sunshine: Thermal and Gravitational Energy](#)). As the star's core shrinks, the energy of the inward-falling material is converted to heat.

The heat generated in this way, like all heat, flows outward to where it is a bit cooler. In the process, the heat raises the temperature of a layer of hydrogen that spent the whole long main-sequence time just outside the core. Like an understudy waiting in the wings of a hit Broadway show for a chance at fame and glory, this hydrogen was almost (but not quite) hot enough to undergo fusion and take part in the main action that sustains the star. Now, the additional heat produced by the shrinking core puts this hydrogen "over the limit," and a shell of hydrogen nuclei just outside the core becomes hot enough for hydrogen fusion to begin.

New energy produced by fusion of this hydrogen now pours outward from this shell and begins to heat up layers of the star farther out, causing them to expand. Meanwhile, the helium core continues to contract, producing more heat right around it. This leads to more fusion in the shell of fresh hydrogen outside the core ([Figure 22.2](#)). The additional fusion produces still more energy, which also flows out into the upper layer of the star.

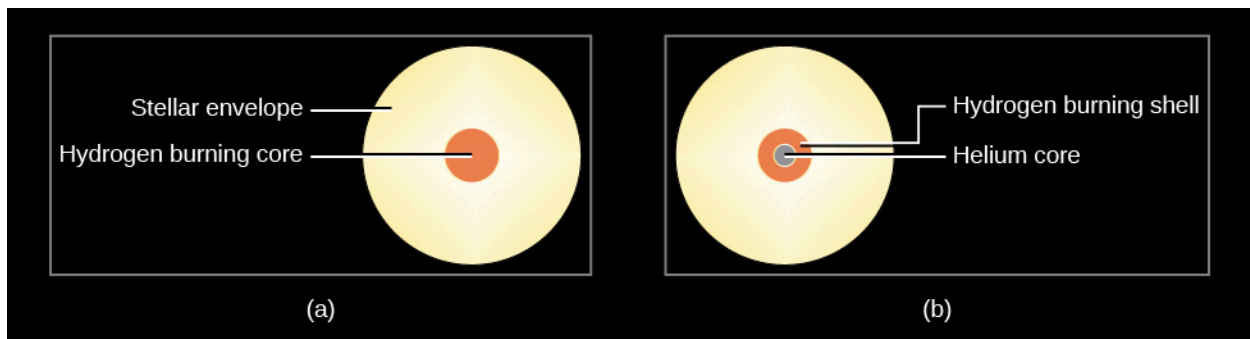


Figure 22.2 Star Layers during and after the Main Sequence. (a) During the main sequence, a star has a core where fusion takes place and a much larger envelope that is too cold for fusion. (b) When the hydrogen in the core is exhausted (made of helium, not hydrogen), the core is compressed by gravity and heats up. The additional heat starts hydrogen fusion in a layer just outside the core. Note that these parts of the Sun are not drawn to scale.

Most stars actually generate more energy each second when they are fusing hydrogen in the shell surrounding the helium core than they did when hydrogen fusion was confined to the central part of the star; thus, they increase in luminosity. With all the new energy pouring outward, the outer layers of the star begin to expand, and the star eventually grows and grows until it reaches enormous proportions ([Figure 22.3](#)).

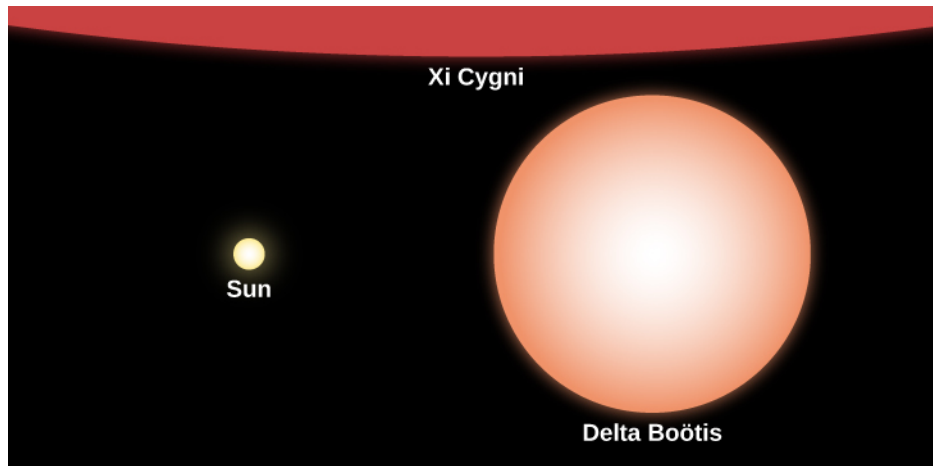


Figure 22.3 Relative Sizes of Stars. This image compares the size of the Sun to that of Delta Boötis, a giant star, and Xi Cygni, a supergiant. Note that Xi Cygni is so large in comparison to the other two stars that only a small portion of it is visible at the top of the frame.

When you take the lid off a pot of boiling water, the steam can expand and it cools down. In the same way, the expansion of a star’s outer layers causes the temperature at the surface to decrease. As it cools, the star’s overall color becomes redder. (We saw in [Radiation and Spectra](#) that a red color corresponds to cooler temperature.)

So the star becomes simultaneously more luminous and cooler. On the H-R diagram, the star therefore leaves the main-sequence band and moves upward (brighter) and to the right (cooler surface temperature). Over time, massive stars become red supergiants, and lower-mass stars like the Sun become red giants. (We first discussed such giant stars in [The Stars: A Celestial Census](#); here we see how such “swollen” stars originate.) You might also say that these stars have “split personalities”: their cores are contracting while their outer layers are expanding. (Note that red giant stars do not actually look deep red; their colors are more like orange or orange-red.)

Just how different are these red giants and supergiants from a main-sequence star? [Table 22.2](#) compares the Sun with the red supergiant Betelgeuse, which is visible above Orion’s belt as the bright red star that marks the hunter’s armpit. Relative to the Sun, this supergiant has a much larger radius, a much lower average density, a cooler surface, and a much hotter core.

Comparing a Supergiant with the Sun

| Property | Sun | Betelgeuse |
|--------------------------------------------|------------|----------------------|
| Mass (2×10^{33} g) | 1 | 16 |
| Radius (km) | 700,000 | 500,000,000 |
| Surface temperature (K) | 5,800 | 3,600 |
| Core temperature (K) | 15,000,000 | 160,000,000 |
| Luminosity (4×10^{26} W) | 1 | 46,000 |
| Average density (g/cm^3) | 1.4 | 1.3×10^{-7} |

Table 22.2

| Property | Sun | Betelgeuse |
|-------------------------|-------|------------|
| Age (millions of years) | 4,500 | 10 |

Table 22.2

Red giants can become so large that if we were to replace the Sun with one of them, its outer atmosphere would extend to the orbit of Mars or even beyond (Figure 22.4). This is the next stage in the life of a star as it moves (to continue our analogy to human lives) from its long period of “youth” and “adulthood” to “old age.” By considering the relative ages of the Sun and Betelgeuse, we can also see that the idea that “bigger stars die faster” is indeed true here. Betelgeuse is a mere 10 million years old, which is relatively young compared with our Sun’s 4.5 billion years, but it is already nearing its death throes as a red supergiant.

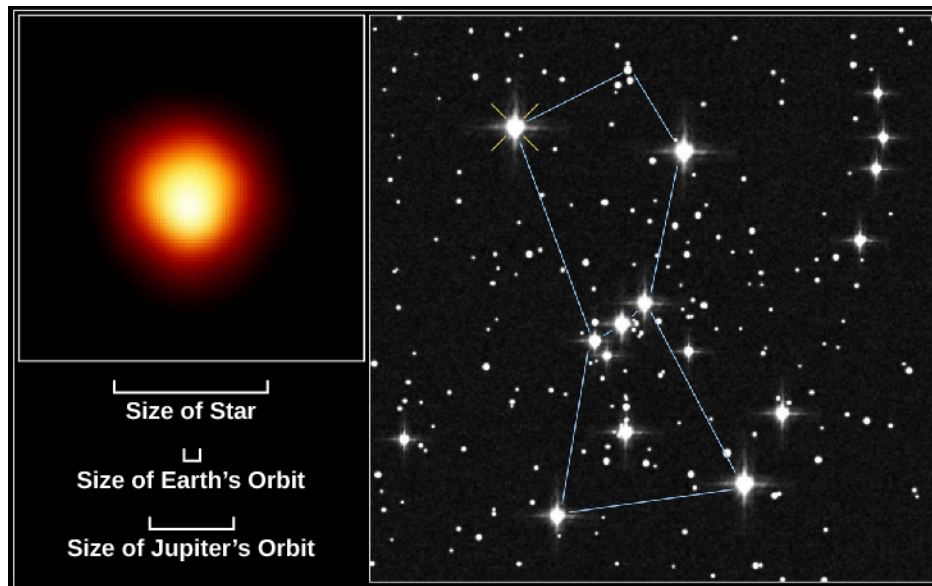


Figure 22.4 Betelgeuse. Betelgeuse is in the constellation Orion, the hunter; in the right image, it is marked with a yellow “X” near the top left. In the left image, we see it in ultraviolet with the Hubble Space Telescope, in the first direct image ever made of the surface of another star. As shown by the scale at the bottom, Betelgeuse has an extended atmosphere so large that, if it were at the center of our solar system, it would stretch past the orbit of Jupiter. (credit: Modification of work by Andrea Dupree (Harvard-Smithsonian CfA), Ronald Gilliland (STScI), NASA and ESA)

Models for Evolution to the Giant Stage

As we discussed earlier, astronomers can construct computer models of stars with different masses and compositions to see how stars change throughout their lives. Figure 22.5, which is based on theoretical calculations by University of Illinois astronomer Icko Iben, shows an H-R diagram with several tracks of evolution from the main sequence to the giant stage. Tracks are shown for stars with different masses (from 0.5 to 15 times the mass of our Sun) and with chemical compositions similar to that of the Sun. The red line is the initial or zero-age main sequence. The numbers along the tracks indicate the time, in years, required for each star to reach those points in their evolution after leaving the main sequence. Once again, you can see that the more massive a star is, the more quickly it goes through each stage in its life.

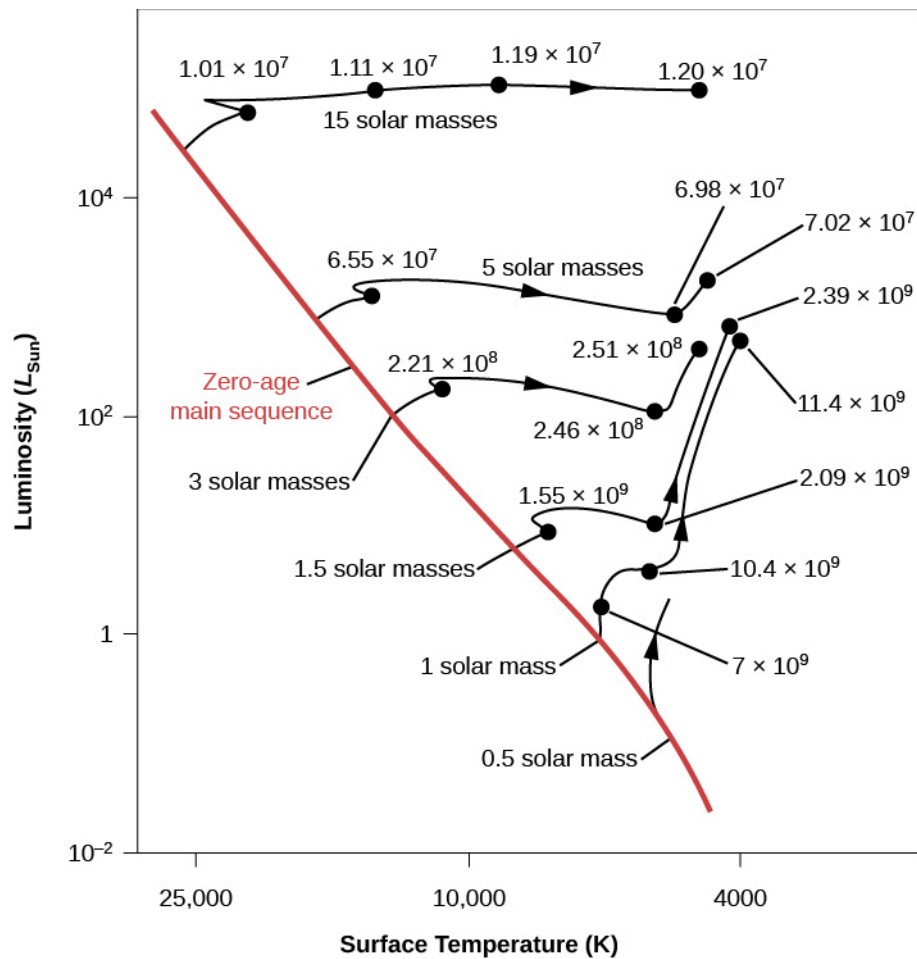


Figure 22.5 Evolutionary Tracks of Stars of Different Masses. The solid black lines show the predicted evolution from the main sequence through the red giant or supergiant stage on the H-R diagram. Each track is labeled with the mass of the star it is describing. The numbers show how many years each star takes to become a giant. The red line is the zero-age main sequence. While theorists debate the exact number of years shown here, our main point should be clear. The more massive the star, the shorter time it takes for each stage in its life.

Note that the most massive star in this diagram has a mass similar to that of Betelgeuse, and so its evolutionary track shows approximately the history of Betelgeuse. The track for a 1-solar-mass star shows that the Sun is still in the main-sequence phase of evolution, since it is only about 4.5 billion years old. It will be billions of years before the Sun begins its own “climb” away from the main sequence—the expansion of its outer layers that will make it a red giant.

LINK TO LEARNING



Use the [Star in a Box simulation \(https://openstax.org/l/30starinbox\)](https://openstax.org/l/30starinbox) to explore the evolution of stars of different masses. Select the star’s mass, and then hit play to see how its luminosity, temperature, and size change during its lifetime.

22.2 Star Clusters

Learning Objectives

By the end of this section, you will be able to:

- › Explain how star clusters help us understand the stages of stellar evolution
- › List the different types of star clusters and describe how they differ in number of stars, structure, and age
- › Explain why the chemical composition of globular clusters is different from that of open clusters

The preceding description of stellar evolution is based on calculations. However, no star completes its main-sequence lifetime or its evolution to a red giant quickly enough for us to observe these structural changes as they happen. Fortunately, nature has provided us with an indirect way to test our calculations.

Instead of observing the evolution of a single star, we can look at a group or *cluster* of stars. We look for a group of stars that is very close together in space, held together by gravity, often moving around a common center. Then it is reasonable to assume that the individual stars in the group all formed at nearly the same time, from the same cloud, and with the same composition. We expect that these stars will differ only in mass. And their masses determine how quickly they go through each stage of their lives.

Since stars with higher masses evolve more quickly, we can find clusters in which massive stars have already completed their main-sequence phase of evolution and become red giants, while stars of lower mass in the same cluster are still on the main sequence, or even—if the cluster is very young—undergoing pre-main-sequence gravitational contraction. We can see many stages of stellar evolution among the members of a single cluster, and we can see whether our models can explain why the H–R diagrams of clusters of different ages look the way they do.

The three basic types of clusters astronomers have discovered are globular clusters, open clusters, and stellar associations. Their properties are summarized in [Table 22.3](#). As we will see in the next section of this chapter, globular clusters contain only very old stars, whereas open clusters and associations contain young stars.

Characteristics of Star Clusters

| Characteristic | Globular Clusters | Open Clusters | Associations |
|---------------------------|------------------------|------------------------|-----------------|
| Number in the Galaxy | 150 | Thousands | Thousands |
| Location in the Galaxy | Halo and central bulge | Disk (and spiral arms) | Spiral arms |
| Diameter (in light-years) | 50–450 | <30 | 100–500 |
| Mass M_{Sun} | 10^4 – 10^6 | 10^2 – 10^3 | 10^2 – 10^3 |
| Number of stars | 10^4 – 10^6 | 50–1000 | 10^2 – 10^4 |

Table 22.3

| Characteristic | Globular Clusters | Open Clusters | Associations |
|--------------------------------------------|-------------------|----------------------------------------------------------------------------------------------------|--------------------------|
| Color of brightest stars | Red | Red or blue | Blue |
| Luminosity of cluster (L_{Sun}) | 10^4 – 10^6 | 10^2 – 10^6 | 10^4 – 10^7 |
| Typical ages | Billions of years | A few hundred million years to, in the case of unusually large clusters, more than a billion years | Up to about 10^7 years |

Table 22.3

Globular Clusters

Globular clusters were given this name because they are nearly symmetrical round systems of, typically, hundreds of thousands of stars. The most massive globular cluster in our own Galaxy is Omega Centauri, which is about 16,000 light-years away and contains several million stars (Figure 22.6). Note that the brightest stars in this cluster, which are red giants that have already completed the main-sequence phase of their evolution, are red-orange in color. These stars have typical surface temperatures around 4000 K. As we will see, globular clusters are among the oldest parts of our Milky Way Galaxy.

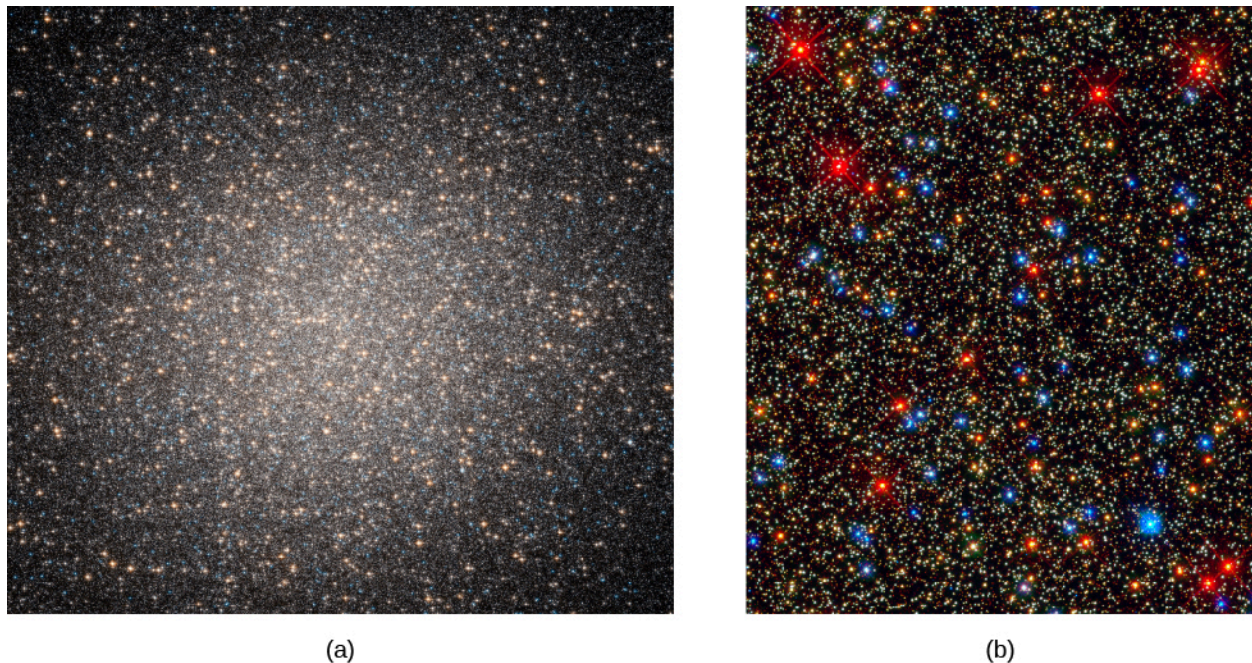


Figure 22.6 Omega Centauri. (a) Located at about 16,000 light-years away, Omega Centauri is the most massive globular cluster in our Galaxy. It contains several million stars. (b) This image, taken with the Hubble Space Telescope, zooms in near the center of Omega Centauri. The image is about 6.3 light-years wide. The most numerous stars in the image, which are yellow-white in color, are main-sequence stars similar to our Sun. The brightest stars are red giants that have begun to exhaust their hydrogen fuel and have expanded to about 100 times the diameter of our Sun. The blue stars have started helium fusion. (credit a: modification of work by NASA, ESA and the Hubble Heritage Team (STScI/AURA); credit b: modification of work by NASA, ESA, and the Hubble SM4 ERO Team)

What would it be like to live inside a globular cluster? In the dense central regions, the stars would be roughly a million times closer together than in our own neighborhood. If Earth orbited one of the inner stars in a globular cluster, the nearest stars would be light-months, not light-years, away. They would still appear as points of light, but would be brighter than any of the stars we see in our own sky. The Milky Way would

probably be difficult to see through the bright haze of starlight produced by the cluster.

About 150 globular clusters are known in our Galaxy. Most of them are in a spherical halo (or cloud) surrounding the flat disk formed by the majority of our Galaxy's stars. All the globular clusters are very far from the Sun, and some are found at distances of 60,000 light-years or more from the main disk of the Milky Way. The diameters of globular star clusters range from 50 light-years to more than 450 light-years.

Open Clusters

Open clusters are found in the disk of the Galaxy. They have a range of ages, some as old as, or even older than, our Sun. The youngest open clusters are still associated with the interstellar matter from which they formed. Open clusters are smaller than globular clusters, usually having diameters of less than 30 light-years, and they typically contain only several dozen to several hundreds of stars (Figure 22.7). The stars in open clusters usually appear well separated from one another, even in the central regions, which explains why they are called “open.” Our Galaxy contains thousands of open clusters, but we can see only a small fraction of them. Interstellar dust, which is also concentrated in the disk, dims the light of more distant clusters so much that they are undetectable.



Figure 22.7 Jewel Box (NGC 4755). This open cluster of young, bright stars is about 6400 light-years away from the Sun. Note the contrast in color between the bright yellow supergiant and the hot blue main-sequence stars. The name comes from John Herschel's nineteenth-century description of it as “a casket of variously colored precious stones.” (credit: ESO/Y. Beletsky)

Although the individual stars in an open cluster can survive for billions of years, they typically remain together as a cluster for only a few million years, or at most, a few hundred million years. There are several reasons for this. In small open clusters, the average speed of the member stars within the cluster may be higher than the cluster's escape velocity,¹ and the stars will gradually “evaporate” from the cluster. Close encounters of member stars may also increase the velocity of one of the members beyond the escape velocity. Every few hundred million years or so, the cluster may have a close encounter with a giant molecular cloud, and the gravitational force exerted by the cloud may tear the cluster apart.

Several open clusters are visible to the unaided eye. Most famous among them is the Pleiades (Figure 20.13), which appears as a tiny group of six stars (some people can see even more than six, and the Pleiades is sometimes called the Seven Sisters). This cluster is arranged like a small dipping spoon and is seen in the constellation of Taurus, the bull. A good pair of binoculars shows dozens of stars in the cluster, and a telescope

¹ Escape velocity is the speed needed to overcome the gravity of some object or group of objects. The rockets we send up from Earth, for example, must travel faster than the escape velocity of our planet to be able to get to other worlds.

reveals hundreds. (A car company, Subaru, takes its name from the Japanese term for this cluster; you can see the star group on the Subaru logo.)

The Hyades is another famous open cluster in the constellation of Taurus the bull. To the naked eye, it appears as a V-shaped group of faint stars marking the face of the bull. Telescopes show that Hyades actually contains more than 200 stars.

Stellar Associations

An **association** is a group of extremely young stars, typically containing 5 to 50 hot, bright O and B stars scattered over a region of space some 100–500 light-years in diameter. As an example, most of the stars in the constellation Orion form one of the nearest stellar associations. Associations also contain hundreds to thousands of low-mass stars, but these are much fainter and less conspicuous. The presence of really hot, luminous stars indicates that star formation in the association has occurred in the last million years or so. Since O stars go through their entire lives in only about a million years, they would not still be around unless star formation has occurred recently. It is therefore not surprising that associations are found in regions rich in the gas and dust required to form new stars. It's like a brand new building still surrounded by some of the construction materials used to build it and with the landscape still showing signs of construction. On the other hand, because associations, like ordinary open clusters, lie in regions occupied by dusty interstellar matter, many are hidden from our view.

22.3 Checking Out the Theory

Learning Objectives

By the end of this section, you will be able to:

- Explain how the H–R diagram of a star cluster can be related to the cluster's age and the stages of evolution of its stellar members
- Describe how the main-sequence turnoff of a cluster reveals its age

In the previous section, we indicated that open clusters are younger than globular clusters, and associations are typically even younger. In this section, we will show how we determine the ages of these star clusters. The key observation is that the stars in these different types of clusters are found in different places in the H–R diagram, and we can use their locations in the diagram in combination with theoretical calculations to estimate how long they have lived.

H–R Diagrams of Young Clusters

What does theory predict for the H–R diagram of a cluster whose stars have recently condensed from an interstellar cloud? Remember that at every stage of evolution, massive stars evolve more quickly than their lower-mass counterparts. After a few million years (“recently” for astronomers), the most massive stars should have completed their contraction phase and be on the main sequence, while the less massive ones should be off to the right, still on their way to the main sequence. These ideas are illustrated in [Figure 22.8](#), which shows the H–R diagram calculated by R. Kippenhahn and his associates at Munich University for a hypothetical cluster with an age of 3 million years.

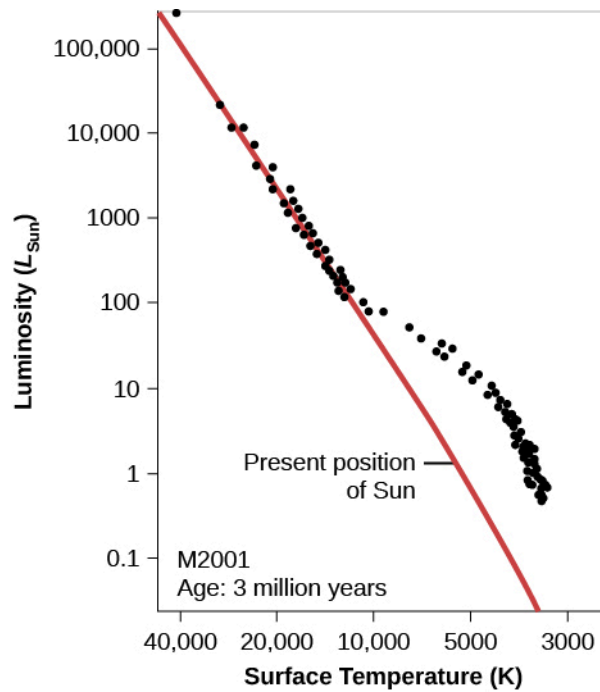


Figure 22.8 Young Cluster H-R Diagram. We see an H-R diagram for a hypothetical young cluster with an age of 3 million years. Note that the high-mass (high-luminosity) stars have already arrived at the main-sequence stage of their lives, while the lower-mass (lower-luminosity) stars are still contracting toward the zero-age main sequence (the red line) and are not yet hot enough to derive all of their energy from the fusion of hydrogen.

There are real star clusters that fit this description. The first to be studied (in about 1950) was NGC 2264, which is still associated with the region of gas and dust from which it was born ([Figure 22.9](#)).



Figure 22.9 Young Cluster NGC 2264. Located about 2600 light-years from us, this region of newly formed stars, known as the Christmas Tree Cluster, is a complex mixture of hydrogen gas (which is ionized by hot embedded stars and shown in red), dark obscuring dust lanes, and brilliant young stars. The image shows a scene about 30 light-years across. (credit: ESO)

The NGC 2264 cluster's H-R diagram is shown in [Figure 22.10](#). The cluster in the middle of the Orion Nebula (shown in [Figure 21.4](#) and [Figure 21.5](#)) is in a similar stage of evolution.

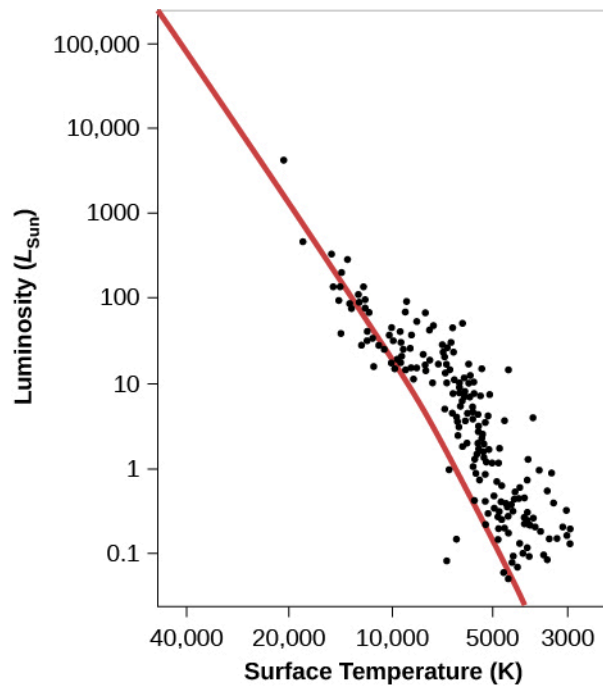


Figure 22.10 NGC 2264 H-R Diagram. Compare this H-R diagram to that in [Figure 22.8](#); although the points scatter a bit more here, the theoretical and observational diagrams are remarkably, and satisfyingly, similar.

As clusters get older, their H-R diagrams begin to change. After a short time (less than a million years after they reach the main sequence), the most massive stars use up the hydrogen in their cores and evolve off the main sequence to become red giants and supergiants. As more time passes, stars of lower mass begin to leave the main sequence and make their way to the upper right of the H-R diagram.

LINK TO LEARNING



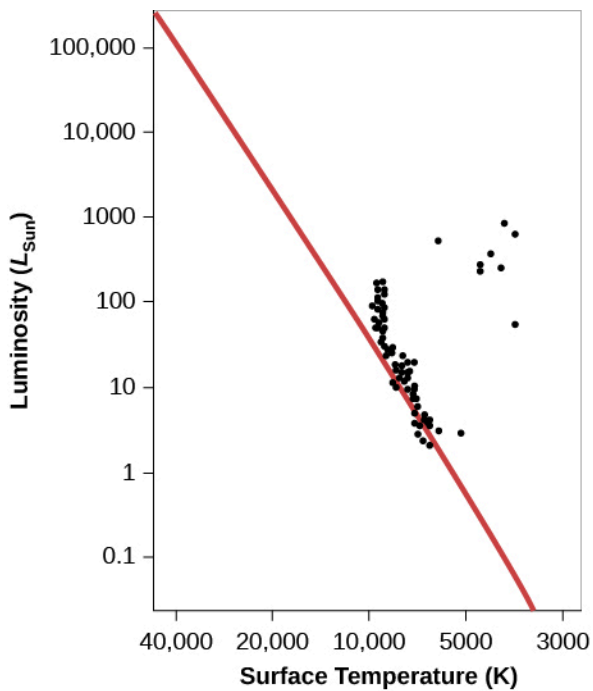
To see the evolution of a star cluster in a dwarf galaxy, you can watch this [brief animation \(https://openstax.org/l/30StarCluster\)](https://openstax.org/l/30StarCluster) of how its H-R diagram changes.

[Figure 22.11](#) is a photograph of NGC 3293, a cluster that is about 10 million years old. The dense clouds of gas and dust are gone. One massive star has evolved to become a red giant and stands out as an especially bright orange member of the cluster.



Figure 22.11 NGC 3293. All the stars in an open star cluster like NGC 3293 form at about the same time. The most massive stars, however, exhaust their nuclear fuel more rapidly and hence evolve more quickly than stars of low mass. As stars evolve, they become redder. The bright orange star in NGC 3293 is the member of the cluster that has evolved most rapidly. (credit: ESO/G. Beccari)

[Figure 22.12](#) shows the H-R diagram of the open cluster M41, which is roughly 100 million years old; by this time, a significant number of stars have moved off to the right and become red giants. Note the gap that appears in this H-R diagram between the stars near the main sequence and the red giants. A gap does not necessarily imply that stars avoid a region of certain temperatures and luminosities. In this case, it simply represents a domain of temperature and luminosity through which stars evolve very quickly. We see a gap for M41 because at this particular moment, we have not caught a star in the process of scurrying across this part of the diagram.



(a)



(b)

Figure 22.12 Cluster M41. (a) Cluster M41 is older than NGC 2264 (see [Figure 22.10](#)) and contains several red giants. Some of its more massive stars are no longer close to the zero-age main sequence (red line). (b) This ground-based photograph shows the open cluster M41. Note that it contains several orange-color stars. These are stars that have exhausted hydrogen in their centers, and

have swelled up to become red giants. (credit b: modification of work by NOAO/AURA/NSF)

H-R Diagrams of Older Clusters

After 4 billion years have passed, many more stars, including stars that are only a few times more massive than the Sun, have left the main sequence (Figure 22.13). This means that no stars are left near the top of the main sequence; only the low-mass stars near the bottom remain. The older the cluster, the lower the point on the main sequence (and the lower the mass of the stars) where stars begin to move toward the red giant region. The location in the H-R diagram where the stars have begun to leave the main sequence is called the **main-sequence turnoff**.

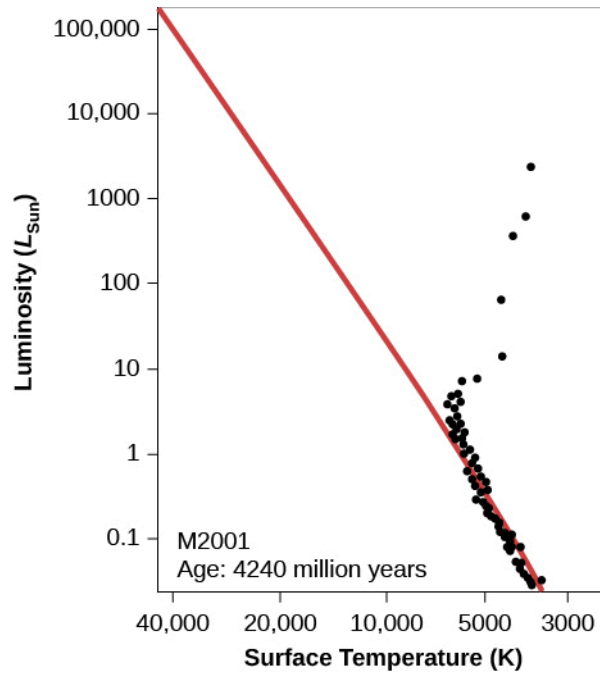


Figure 22.13 H-R Diagram for an Older Cluster. We see the H-R diagram for a hypothetical older cluster at an age of 4.24 billion years. Note that most of the stars on the upper part of the main sequence have turned off toward the red-giant region. And the most massive stars in the cluster have already died and are no longer on the diagram.

The oldest clusters of all are the globular clusters. Figure 22.14 shows the H-R diagram of globular cluster 47 Tucanae. Notice that the luminosity and temperature scales are different from those of the other H-R diagrams in this chapter. In Figure 22.13, for example, the luminosity scale on the left side of the diagram goes from 0.1 to 100,000 times the Sun's luminosity. But in Figure 22.14, the luminosity scale has been significantly reduced in extent. So many stars in this old cluster have had time to turn off the main sequence that only the very bottom of the main sequence remains.

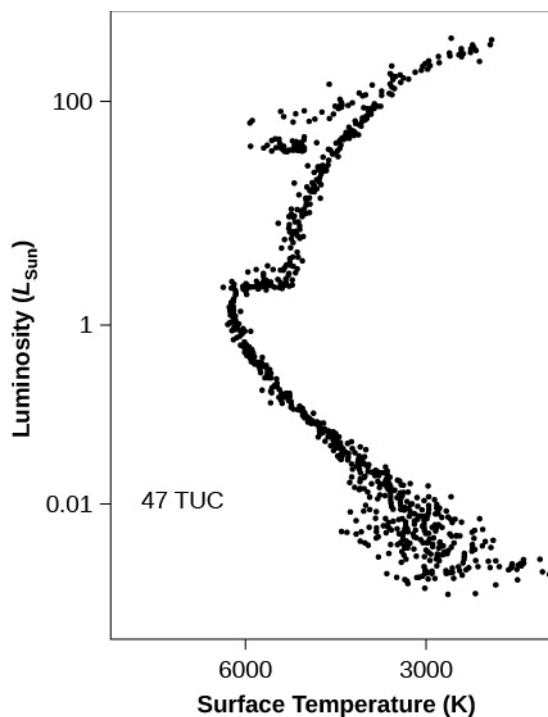


Figure 22.14 Cluster 47 Tucanae. This H-R diagram is for the globular cluster 47. Note that the scale of luminosity differs from that of the other H-R diagrams in this chapter. We are only focusing on the lower portion of the main sequence, the only part where stars still remain in this old cluster.

LINK TO LEARNING



Check out this brief NASA video with a [3-D visualization \(https://openstax.org/l/30HRDiagram\)](https://openstax.org/l/30HRDiagram) of how an H-R diagram is created for the globular cluster Omega Centauri.

Just how old are the different clusters we have been discussing? To get their actual ages (in years), we must compare the appearances of our *calculated* H-R diagrams of different ages to *observed* H-R diagrams of real clusters. In practice, astronomers use the position at the top of the main sequence (that is, the luminosity at which stars begin to move off the main sequence to become red giants) as a measure of the age of a cluster (the main-sequence turnoff we discussed previously). For example, we can compare the luminosities of the brightest stars that are still on the main sequence in [Figure 22.10](#) and [Figure 22.13](#).

Using this method, some associations and open clusters turn out to be as young as 1 million years old, while others are several hundred million years old. Once all of the interstellar matter surrounding a cluster has been used to form stars or has dispersed and moved away from the cluster, star formation ceases, and stars of progressively lower mass move off the main sequence, as shown in [Figure 22.10](#), [Figure 22.12](#), and [Figure 22.13](#).

To our surprise, even the youngest of the globular clusters in our Galaxy are found to be older than the oldest open cluster. All of the globular clusters have main sequences that turn off at a luminosity less than that of the Sun. Star formation in these crowded systems ceased billions of years ago, and no new stars are coming on to the main sequence to replace the ones that have turned off (see [Figure 22.15](#)).

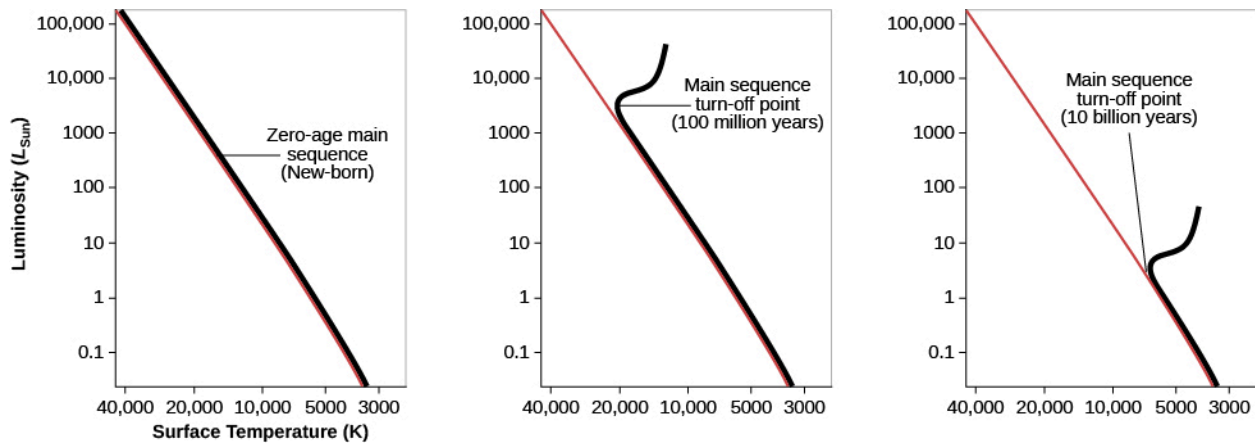


Figure 22.15 H-R Diagrams for Clusters of Different Ages. This sketch shows how the turn-off point from the main sequence gets lower as we make H-R diagrams for clusters that are older and older.

Indeed, the globular clusters are the oldest structures in our Galaxy (and in other galaxies as well). The youngest have ages of about 11 billion years and some appear to be even older. Since these are the oldest objects we know of, this estimate is one of the best limits we have on the age of the universe itself—it must be at least 11 billion years old. We will return to the fascinating question of determining the age of the entire universe in the chapter on [The Big Bang](#).

22.4 Further Evolution of Stars

Learning Objectives

By the end of this section, you will be able to:

- Explain what happens in a star’s core when all of the hydrogen has been used up
- Define “planetary nebulae” and discuss their origin
- Discuss the creation of new chemical elements during the late stages of stellar evolution

The “life story” we have related so far applies to almost all stars: each starts as a contracting protostar, then lives most of its life as a stable main-sequence star, and eventually moves off the main sequence toward the red-giant region.

As we have seen, the pace at which each star goes through these stages depends on its mass, with more massive stars evolving more quickly. But after this point, the life stories of stars of different masses diverge, with a wider range of possible behavior according to their masses, their compositions, and the presence of any nearby companion stars.

Because we have written this book for students taking their first astronomy course, we will recount a simplified version of what happens to stars as they move toward the final stages in their lives. We will (perhaps to your heartfelt relief) not delve into all the possible ways aging stars can behave and the strange things that happen when a star is orbited by a second star in a binary system. Instead, we will focus only on the key stages in the evolution of single stars and show how the evolution of high-mass stars differs from that of low-mass stars (such as our Sun).

Helium Fusion

Let’s begin by considering stars with composition like that of the Sun and whose *initial* masses are comparatively low—no more than about twice the mass of our Sun. (Such mass may not seem too low, but stars with masses less than this all behave in a fairly similar fashion. We will see what happens to more massive stars in the next section.) Because there are many more low-mass stars than high-mass stars in the Milky Way, the vast majority of stars—including our Sun—follow the scenario we are about to relate. By the way, we carefully used the term *initial masses* of stars because, as we will see, stars can lose quite a bit of mass

in the process of aging and dying.

Remember that red giants start out with a helium core where no energy generation is taking place, surrounded by a shell where hydrogen is undergoing fusion. The core, having no source of energy to oppose the inward pull of gravity, is shrinking and growing hotter. As time goes on, the temperature in the core can rise to much hotter values than it had in its main-sequence days. Once it reaches a temperature of 100 million K (but not before such point), three helium atoms can begin to fuse to form a single carbon nucleus. This process is called the **triple-alpha process**, so named because physicists call the nucleus of the helium atom an alpha particle.

When the triple-alpha process begins in low-mass (about 0.8 to 2.0 solar masses) stars, calculations show that the entire core is ignited in a quick burst of fusion called a **helium flash**. (More massive stars also ignite helium but more gradually and not with a flash.) As soon as the temperature at the center of the star becomes high enough to start the triple-alpha process, the extra energy released is transmitted quickly through the entire helium core, producing very rapid heating. The heating speeds up the nuclear reactions, which provide more heating, and which accelerates the nuclear reactions even more. We have runaway generation of energy, which reignites the entire helium core in a flash.

You might wonder why the next major step in nuclear fusion in stars involves three helium nuclei and not just two. Although it is a lot easier to get two helium nuclei to collide, the product of this collision is not stable and falls apart very quickly. It takes three helium nuclei coming together simultaneously to make a stable nuclear structure. Given that each helium nucleus has two positive protons and that such protons repel one another, you can begin to see the problem. It takes a temperature of 100 million K to slam three helium nuclei (six protons) together and make them stick. But when that happens, the star produces a carbon nucleus.

ASTRONOMY BASICS



Stars in Your Little Finger

Stop reading for a moment and look at your little finger. It's full of carbon atoms because carbon is a fundamental chemical building block for life on Earth. Each of those carbon atoms was once inside a red giant star and was fused from helium nuclei in the triple-alpha process. All the carbon on Earth—in you, in the charcoal you use for barbecuing, and in the diamonds you might exchange with a loved one—was “cooked up” by previous generations of stars. How the carbon atoms (and other elements) made their way from inside some of those stars to become part of Earth is something we will discuss in the next chapter. For now, we want to emphasize that our description of stellar evolution is, in a very real sense, the story of our own cosmic “roots”—the history of how our own atoms originated among the stars. We are made of “star-stuff.”

Becoming a Giant Again

After the helium flash, the star, having survived the “energy crisis” that followed the end of the main-sequence stage and the exhaustion of the hydrogen fuel at its center, finds its balance again. As the star readjusts to the release of energy from the triple-alpha process in its core, its internal structure changes once more: its surface temperature increases and its overall luminosity decreases. The point that represents the star on the H-R diagram thus moves to a new position to the left of and somewhat below its place as a red giant ([Figure 22.16](#)). The star then continues to fuse the helium in its core for a while, returning to the kind of equilibrium between pressure and gravity that characterized the main-sequence stage. During this time, a newly formed carbon nucleus at the center of the star can sometimes be joined by another helium nucleus to produce a nucleus of oxygen—another building block of life.

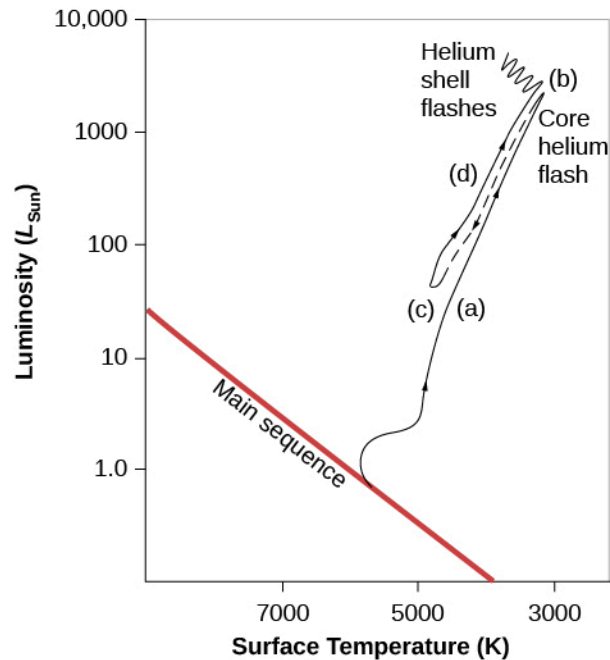


Figure 22.16 Evolution of a Star Like the Sun on an H-R Diagram. Each stage in the star's life is labeled. (a) The star evolves from the main sequence to be a red giant, decreasing in surface temperature and increasing in luminosity. (b) A helium flash occurs, leading to a readjustment of the star's internal structure and to (c) a brief period of stability during which helium is fused to carbon and oxygen in the core (in the process the star becomes hotter and less luminous than it was as a red giant). (d) After the central helium is exhausted, the star becomes a giant again and moves to higher luminosity and lower temperature. By this time, however, the star has exhausted its inner resources and will soon begin to die. Where the evolutionary track becomes a dashed line, the changes are so rapid that they are difficult to model.

However, at a temperature of 100 million K, the inner core is converting its helium fuel to carbon (and a bit of oxygen) at a rapid rate. Thus, the new period of stability cannot last very long: it is far shorter than the main-sequence stage. Soon, all the helium hot enough for fusion will be used up, just like the hot hydrogen that was used up earlier in the star's evolution. Once again, the inner core will not be able to generate energy via fusion. Once more, gravity will take over, and the core will start to shrink again. We can think of stellar evolution as a story of a constant struggle against gravitational collapse. A star can avoid collapsing as long as it can tap energy sources, but once any particular fuel is used up, it starts to collapse again.

The star's situation is analogous to the end of the main-sequence stage (when the central hydrogen got used up), but the star now has a somewhat more complicated structure. Again, the star's core begins to collapse under its own weight. Heat released by the shrinking of the carbon and oxygen core flows into a shell of helium just above the core. This helium, which had not been hot enough for fusion into carbon earlier, is heated just enough for fusion to begin and to generate a new flow of energy.

Farther out in the star, there is also a shell where fresh hydrogen has been heated enough to fuse helium. The star now has a multi-layered structure like an onion: a carbon-oxygen core, surrounded by a shell of helium fusion, a layer of helium, a shell of hydrogen fusion, and finally, the extended outer layers of the star (see [Figure 22.17](#)). As energy flows outward from the two fusion shells, once again the outer regions of the star begin to expand. Its brief period of stability is over; the star moves back to the red-giant domain on the H-R diagram for a short time (see [Figure 22.16](#)). But this is a brief and final burst of glory.

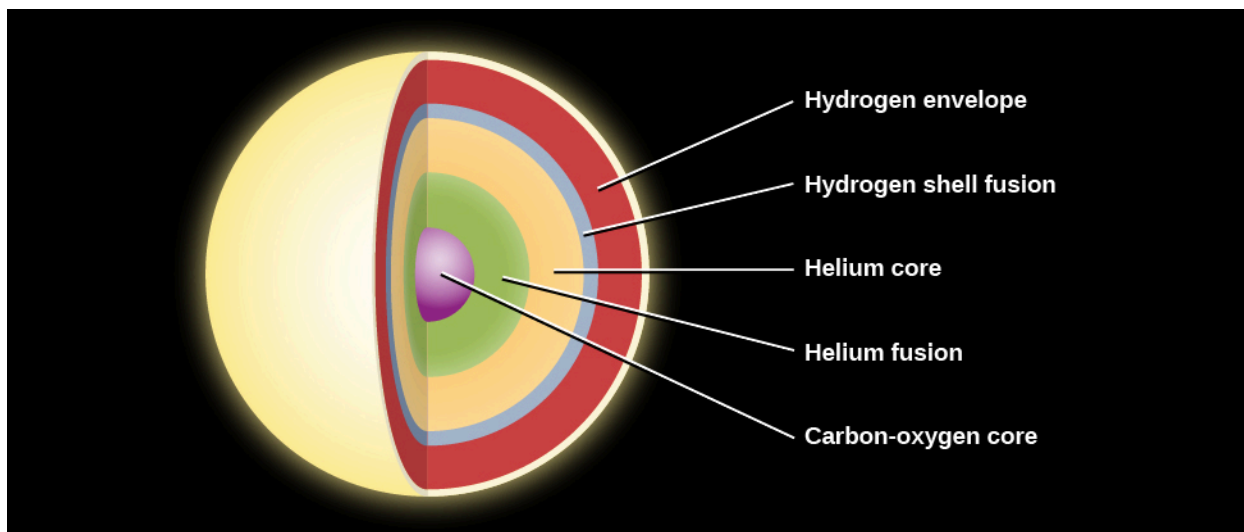


Figure 22.17 Layers inside a Low-Mass Star before Death. Here we see the layers inside a star with an initial mass that is less than twice the mass of the Sun. These include, from the center outward, the carbon-oxygen core, a layer of helium hot enough to fuse, a layer of cooler helium, a layer of hydrogen hot enough to fuse, and then cooler hydrogen beyond.

Recall that the last time the star was in this predicament, helium fusion came to its rescue. The temperature at the star's center eventually became hot enough for the *product* of the previous step of fusion (helium) to become the *fuel* for the next step (helium fusing into carbon). But the step after the fusion of helium nuclei requires a temperature so hot that the kinds of lower-mass stars (less than 2 solar masses) we are discussing simply cannot compress their cores to reach it. No further types of fusion are possible for such a star.

In a star with a mass similar to that of the Sun, the formation of a carbon-oxygen core thus marks the end of the generation of nuclear energy at the center of the star. The star must now confront the fact that its death is near. We will discuss how stars like this end their lives in [The Death of Stars](#), but in the meantime, [Table 22.4](#) summarizes the stages discussed so far in the life of a star with the same mass as that of the Sun. One thing that gives us confidence in our calculations of stellar evolution is that when we make H-R diagrams of older clusters, we actually see stars in each of the stages that we have been discussing.

The Evolution of a Star with the Sun's Mass

| Stage | Time in This Stage (years) | Surface Temperature (K) | Luminosity (L_{Sun}) | Diameter (Sun = 1) |
|-------------------|----------------------------|-------------------------|---------------------------------|--------------------|
| Main sequence | 11 billion | 6000 | 1 | 1 |
| Becomes red giant | 1.3 billion | 3100 at minimum | 2300 at maximum | 165 |
| Helium fusion | 100 million | 4800 | 50 | 10 |
| Giant again | 20 million | 3100 | 5200 | 180 |

Table 22.4

Mass Loss from Red-Giant Stars and the Formation of Planetary Nebulae

When stars swell up to become red giants, they have very large radii and therefore a low escape velocity.² Radiation pressure, stellar pulsations, and violent events like the helium flash can all drive atoms in the outer atmosphere away from the star, and cause it to lose a substantial fraction of its mass into space. Astronomers estimate that by the time a star like the Sun reaches the point of the helium flash, for example, it will have lost as much as 25% of its mass. And it can lose still more mass when it ascends the red-giant branch for the second time. As a result, aging stars are surrounded by one or more expanding shells of gas, each containing as much as 10–20% of the Sun’s mass (or 0.1–0.2 M_{Sun}).

When nuclear energy generation in the carbon-oxygen core ceases, the star’s core begins to shrink again and to heat up as it gets more and more compressed. (Remember that this compression will not be halted by another type of fusion in these low-mass stars.) The whole star follows along, shrinking and also becoming very hot—reaching surface temperatures as high as 100,000 K. Such hot stars are very strong sources of stellar winds and ultraviolet radiation, which sweep outward into the shells of material ejected when the star was a red giant. The winds and the ultraviolet radiation heat the shells, ionize them, and set them aglow (just as ultraviolet radiation from hot, young stars produces H II regions; see [Between the Stars: Gas and Dust in Space](#)).

The result is the creation of some of the most beautiful objects in the cosmos (see the gallery in [Figure 22.18](#) and [Figure 22.1](#)). These objects were given an extremely misleading name when first found in the eighteenth century: **planetary nebulae**. The name is derived from the fact that a few planetary nebulae, when viewed through a small telescope, have a round shape bearing a superficial resemblance to planets. Actually, they have nothing to do with planets, but once names are put into regular use in astronomy, it is extremely difficult to change them. There are tens of thousands of planetary nebulae in our own Galaxy, although many are hidden from view because their light is absorbed by interstellar dust.

² Recall that the force of gravity depends not only on the mass doing the pulling, but also on our distance from the center of gravity. As a red giant star gets a lot bigger, a point on the surface of the star is now farther from the center, and thus has less gravity. That’s why the speed needed to escape the star goes down.

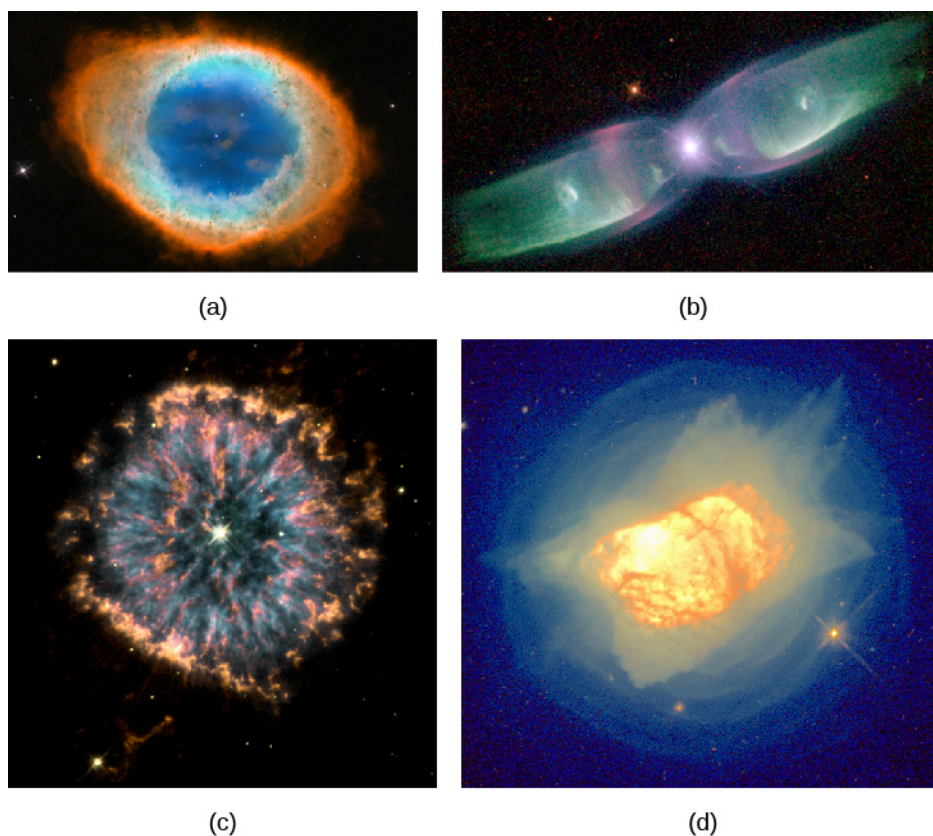


Figure 22.18 Gallery of Planetary Nebulae. This series of beautiful images depicting some intriguing planetary nebulae highlights the capabilities of the Hubble Space Telescope. (a) Perhaps the best known planetary nebula is the Ring Nebula (M57), located about 2000 light-years away in the constellation of Lyra. The ring is about 1 light-year in diameter, and the central star has a temperature of about 120,000 °C. Careful study of this image has shown scientists that, instead of looking at a spherical shell around this dying star, we may be looking down the barrel of a tube or cone. The blue region shows emission from very hot helium, which is located very close to the star; the red region isolates emission from ionized nitrogen, which is radiated by the coolest gas farthest from the star; and the green region represents oxygen emission, which is produced at intermediate temperatures and is at an intermediate distance from the star. (b) This planetary nebula, M2-9, is an example of a butterfly nebula. The central star (which is part of a binary system) has ejected mass preferentially in two opposite directions. In other images, a disk, perpendicular to the two long streams of gas, can be seen around the two stars in the middle. The stellar outburst that resulted in the expulsion of matter occurred about 1200 years ago. Neutral oxygen is shown in red, once-ionized nitrogen in green, and twice-ionized oxygen in blue. The planetary nebula is about 2100 light-years away in the constellation of Ophiuchus. (c) In this image of the planetary nebula NGC 6751, the blue regions mark the hottest gas, which forms a ring around the central star. The orange and red regions show the locations of cooler gas. The origin of these cool streamers is not known, but their shapes indicate that they are affected by radiation and stellar winds from the hot star at the center. The temperature of the star is about 140,000 °C. The diameter of the nebula is about 600 times larger than the diameter of our solar system. The nebula is about 6500 light-years away in the constellation of Aquila. (d) This image of the planetary nebula NGC 7027 shows several stages of mass loss. The faint blue concentric shells surrounding the central region identify the mass that was shed slowly from the surface of the star when it became a red giant. Somewhat later, the remaining outer layers were ejected but not in a spherically symmetric way. The dense clouds formed by this late ejection produce the bright inner regions. The hot central star can be seen faintly near the center of the nebulosity. NGC 7027 is about 3000 light-years away in the direction of the constellation of Cygnus. (credit a: modification of work by NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration; credit b: modification of work by Bruce Balick (University of Washington), Vincent Icke (Leiden University, The Netherlands), Garrelt Mellema (Stockholm University), and NASA; credit c: modification of work by NASA, The Hubble Heritage Team (STScI/AURA); credit d: modification of work by H. Bond (STScI) and NASA)

As [Figure 22.18](#) shows, sometimes a planetary nebula appears to be a simple ring. Others have faint shells surrounding the bright ring, which is evidence that there were multiple episodes of mass loss when the star was a red giant (see image (d) in [Figure 22.18](#)). In a few cases, we see two lobes of matter flowing in opposite directions. Many astronomers think that a considerable number of planetary nebulae basically consist of the same structure, but that the shape we see depends on the viewing angle ([Figure 22.19](#)). According to this idea, the dying star is surrounded by a very dense, doughnut-shaped disk of gas. (Theorists do not yet have a definite explanation for why the dying star should produce this ring, but many believe that binary stars, which are common, are involved.)

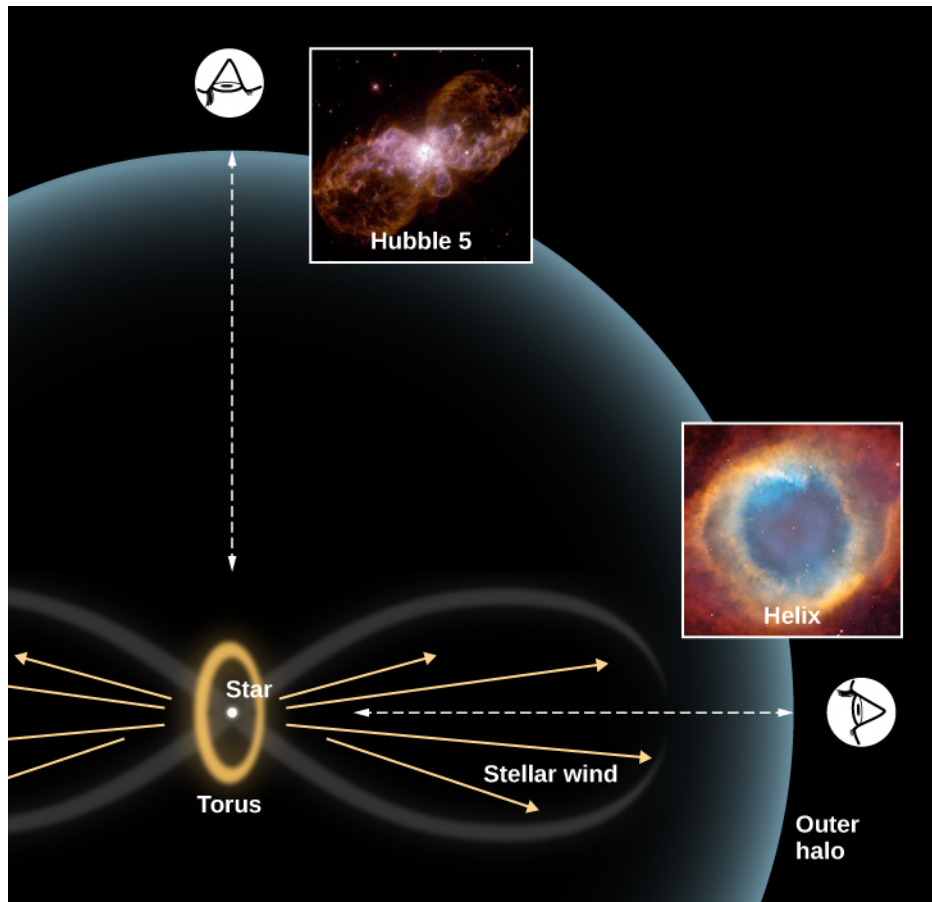


Figure 22.19 Model to Explain the Different Shapes of Planetary Nebulae. The range of different shapes that we see among planetary nebulae may, in many cases, arise from the same geometric shape, but seen from a variety of viewing directions. The basic shape is a hot central star surrounded by a thick torus (or doughnut-shaped disk) of gas. The star's wind cannot flow out into space very easily in the direction of the torus, but can escape more freely in the two directions perpendicular to it. If we view the nebula along the direction of the flow (Helix Nebula), it will appear nearly circular (like looking directly down into an empty ice-cream cone). If we look along the equator of the torus, we see both outflows and a very elongated shape (Hubble 5). Current research on planetary nebulae focuses on the reasons for having a torus around the star in the first place. Many astronomers suggest that the basic cause may be that many of the central stars are actually close binary stars, rather than single stars. (credit "Hubble 5": modification of work by Bruce Balick (University of Washington), Vincent Icke (Leiden University, The Netherlands), Garrelt Mellema (Stockholm University), and NASA/ESA; credit "Helix": modification of work by NASA, ESA, C.R. O'Dell (Vanderbilt University), and M. Meixner, P. McCullough)

As the star continues to lose mass, any less dense gas that leaves the star cannot penetrate the torus, but the gas *can* flow outward in directions perpendicular to the disk. If we look perpendicular to the direction of outflow, we see the disk and both of the outward flows. If we look "down the barrel" and into the flows, we see a ring. At intermediate angles, we may see wonderfully complex structures. Compare the viewpoints in [Figure 22.19](#) with the images in [Figure 22.18](#).

Planetary nebula shells usually expand at speeds of 20–30 km/s, and a typical planetary nebula has a diameter of about 1 light-year. If we assume that the gas shell has expanded at a constant speed, we can calculate that the shells of all the planetary nebulae visible to us were ejected within the past 50,000 years at most. After this amount of time, the shells have expanded so much that they are too thin and tenuous to be seen. That's a pretty short time that each planetary nebula can be observed (when compared to the whole lifetime of the star). Given the number of such nebulae we nevertheless see, we must conclude that a large fraction of all stars evolve through the planetary nebula phase. Since we saw that low-mass stars are much more common than high-mass stars, this confirms our view of planetary nebulae as sort of "last gasp" of low-mass star evolution.

Cosmic Recycling

The loss of mass by dying stars is a key step in the gigantic cosmic recycling scheme we discussed in [Between the Stars: Gas and Dust in Space](#). Remember that stars form from vast clouds of gas and dust. As they end their lives, stars return part of their gas to the galactic reservoirs of raw material. Eventually, some of the expelled material from aging stars will participate in the formation of new star systems.

However, the atoms returned to the Galaxy by an aging star are not necessarily the same ones it received initially. The star, after all, has fused hydrogen and helium to form new elements over the course of its life. And during the red-giant stage, material from the star's central regions is dredged up and mixed with its outer layers, which can cause further nuclear reactions and the creation of still more new elements. As a result, the winds that blow outward from such stars include atoms that were "newly minted" inside the stars' cores. (As we will see, this mechanism is even more effective for high-mass stars, but it does work for stars with masses like that of the Sun.) In this way, the raw material of the Galaxy is not only resupplied but also receives infusions of new elements. You might say this cosmic recycling plan allows the universe to get more "interesting" all the time.

MAKING CONNECTIONS



The Red Giant Sun and the Fate of Earth

How will the evolution of the Sun affect conditions on Earth in the future? Although the Sun has appeared reasonably steady in size and luminosity over recorded human history, that brief span means nothing compared with the timescales we have been discussing. Let's examine the long-term prospects for our planet.

The Sun took its place on the zero-age main sequence approximately 4.5 billion years ago. At that time, it emitted only about 70% of the energy that it radiates today. One might expect that Earth would have been a lot colder than it is now, with the oceans frozen solid. But if this were the case, it would be hard to explain why simple life forms existed when Earth was less than a billion years old. Scientists now think that the explanation may be that much more carbon dioxide was present in Earth's atmosphere when it was young, and that a much stronger greenhouse effect kept Earth warm. (In the greenhouse effect, gases like carbon dioxide or water vapor allow the Sun's light to come in but do not allow the infrared radiation from the ground to escape back into space, so the temperature near Earth's surface increases.)

Carbon dioxide in Earth's atmosphere has steadily declined as the Sun has increased in luminosity. As the brighter Sun increases the temperature of Earth, rocks weather faster and react with carbon dioxide, removing it from the atmosphere. The warmer Sun and the weaker greenhouse effect have kept Earth at a nearly constant temperature for most of its life. This remarkable coincidence, which has resulted in fairly stable climatic conditions, has been the key in the development of complex life-forms on our planet.

As a result of changes caused by the buildup of helium in its core, the Sun will continue to increase in luminosity as it grows older, and more and more radiation will reach Earth. For a while, the amount of carbon dioxide will continue to decrease. (Note that this effect counteracts increases in carbon dioxide from human activities, but on a much-too-slow timescale to undo the changes in climate that are likely to occur in the next 100 years.)

Eventually, the heating of Earth will melt the polar caps and increase the evaporation of the oceans. Water vapor is also an efficient greenhouse gas and will more than compensate for the decrease in carbon dioxide. Sooner or later (atmospheric models are not yet good enough to say exactly when, but estimates range from 500 million to 2 billion years), the increased water vapor will cause a runaway greenhouse effect.

About 1 billion years from now, Earth will lose its water vapor. In the upper atmosphere, sunlight will break down water vapor into hydrogen, and the fast-moving hydrogen atoms will escape into outer space. Like Humpty Dumpty, the water molecules cannot be put back together again. Earth will start to resemble the Venus of today, and temperatures will become much too high for life as we know it.

All of this will happen before the Sun even becomes a red giant. Then the bad news really starts. The Sun, as it expands, will swallow Mercury and Venus, and friction with our star's outer atmosphere will make these planets spiral inward until they are completely vaporized. It is not completely clear whether Earth will escape a similar fate. As described in this chapter, the Sun will lose some of its mass as it becomes a red giant. The gravitational pull of the Sun decreases when it loses mass. The result would be that the diameter of Earth's orbit would increase (remember Kepler's third law). However, recent calculations also show that forces due to the tides raised on the Sun by Earth will act in the opposite direction, causing Earth's orbit to shrink. Thus, many astrophysicists conclude that Earth will be vaporized along with Mercury and Venus. Whether or not this dire prediction is true, there is little doubt that all life on Earth will surely be incinerated. But don't lose any sleep over this—we are talking about events that will occur billions of years from now.

What then are the prospects for preserving Earth life as we know it? The first strategy you might think of would be to move humanity to a more distant and cooler planet. However, calculations indicate that there are long periods of time (several hundred million years) when no planet is habitable. For example, Earth becomes far too warm for life long before Mars warms up enough.

A better alternative may be to move the entire Earth progressively farther from the Sun. The idea is to use gravity in the same way NASA has used it to send spacecraft to distant planets. When a spacecraft flies near a planet, the planet's motion can be used to speed up the spacecraft, slow it down, or redirect it. Calculations show that if we were to redirect an asteroid so that it follows just the right orbit between Earth and Jupiter, it could transfer orbital energy from Jupiter to Earth and move Earth slowly outward, pulling us away from the expanding Sun on each flyby. Since we have hundreds of millions of years to change Earth's orbit, the effect of each flyby need not be large. (Of course, the people directing the asteroid had better get the orbit exactly right and not cause the asteroid to hit Earth.)

It may seem crazy to think about projects to move an entire planet to a different orbit. But remember that we are talking about the distant future. If, by some miracle, human beings are able to get along for all that time and don't blow ourselves to bits, our technology is likely to be far more sophisticated than it is today. It may also be that if humans survive for hundreds of millions of years, we may spread to planets or habitats around other stars. Indeed, Earth, by then, might be a museum world to which youngsters from other planets return to learn about the origin of our species. It is also possible that evolution will by then have changed us in ways that allow us to survive in very different environments. Wouldn't it be exciting to see how the story of the human race turns out after all those billions of years?

22.5 The Evolution of More Massive Stars

Learning Objectives

By the end of this section, you will be able to:

- Explain how and why massive stars evolve much more rapidly than lower-mass stars like our Sun
- Discuss the origin of the elements heavier than carbon within stars

If what we have described so far were the whole story of the evolution of stars and elements, we would have a big problem on our hands. We will see in later chapters that in our best models of the first few minutes of the universe, everything starts with the two simplest elements—hydrogen and helium (plus a tiny bit of lithium). All the predictions of the models imply that no heavier elements were produced at the beginning of the universe. Yet when we look around us on Earth, we see lots of other elements besides hydrogen and helium.

These elements must have been made (fused) somewhere in the universe, *and the only place hot enough to make them is inside stars*. One of the fundamental discoveries of twentieth-century astronomy is that the stars are the source of most of the chemical richness that characterizes our world and our lives.

We have already seen that carbon, oxygen, and some other elements are made inside lower-mass stars during the red-giant stage. But where do the heavier elements we know and love (such as the silicon and iron inside Earth, and the gold and silver in our jewelry) come from? The kinds of stars we have been discussing so far never get hot enough at their centers to make these elements. It turns out that these heavier elements are formed later in the lives *more massive stars*, as well as during explosions that can mark the end of the lives of some stars.

Making New Elements in Massive Stars

Massive stars evolve in much the same way that the Sun does (but always more quickly)—up to the formation of a carbon-oxygen core. One difference is that for stars with more than about twice the mass of the Sun, helium begins fusion more gradually, rather than with a sudden flash. Also, when more massive stars become red giants, they become so bright and large that we call them *supergiants*. Such stars can expand until their outer regions become as large as the orbit of Jupiter, which is precisely what the Hubble Space Telescope has shown for the star Betelgeuse (see [Figure 22.4](#)). They also lose mass very effectively, producing dramatic winds and outbursts as they age. [Figure 22.20](#) shows a wonderful image of the very massive star Eta Carinae, with a great deal of ejected material clearly visible.

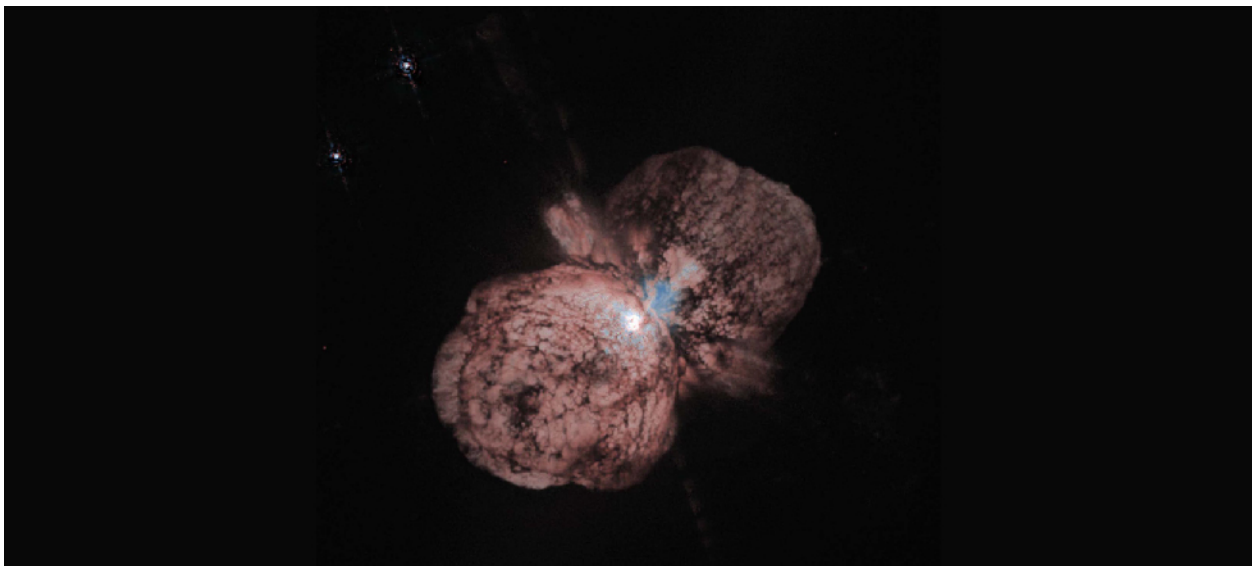


Figure 22.20 Eta Carinae. With a mass at least 100 times that of the Sun, the hot supergiant Eta Carinae is one of the most massive stars known. This Hubble Space Telescope image records the two giant lobes and equatorial disk of material it has ejected in the course of its evolution. The pink outer region is material ejected in an outburst seen in 1843, the largest of such mass loss event that any star is known to have survived. Moving away from the star at a speed of about 1000 km/s, the material is rich in nitrogen and other elements formed in the interior of the star. The inner blue-white region is the material ejected at lower speeds and is thus still closer to the star. It appears blue-white because it contains dust and reflects the light of Eta Carinae, whose luminosity is 4 million times that of our Sun. (credit: modification of work by Jon Morse (University of Colorado) & NASA)

But the crucial way that massive stars diverge from the story we have outlined is that they can start additional kinds of fusion in their centers and in the shells surrounding their central regions. The outer layers of a star with a mass greater than about 8 solar masses have a weight that is enough to compress the carbon-oxygen core until it becomes hot enough to ignite fusion of carbon nuclei. Carbon can fuse into still more oxygen, and at still higher temperatures, oxygen and then neon, magnesium, and finally silicon can build even heavier elements. Iron is, however, the endpoint of this process. The fusion of iron atoms produces products that are *more massive* than the nuclei that are being fused and therefore the process *requires* energy, as opposed to releasing energy, which all fusion reactions up to this point have done. This required energy comes at the

expense of the star itself, which is now on the brink of death (Figure 22.21). What happens next will be described in the chapter on [The Death of Stars](#).

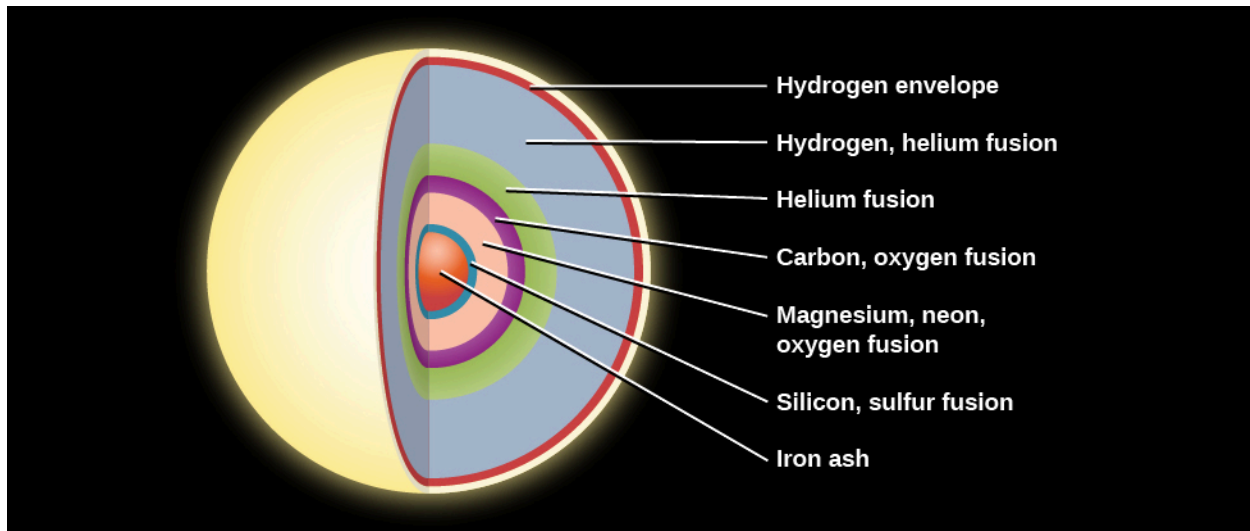


Figure 22.21 Interior Structure of a Massive Star Just before It Exhausts Its Nuclear Fuel. High-mass stars can fuse elements heavier than carbon. As a massive star nears the end of its evolution, its interior resembles an onion. Hydrogen fusion is taking place in an outer shell, and progressively heavier elements are undergoing fusion in the higher-temperature layers closer to the center. All of these fusion reactions generate energy and enable the star to continue shining. Iron is different. The fusion of iron requires energy, and when iron is finally created in the core, the star has only minutes to live.

Physicists have now found nuclear pathways whereby virtually all chemical elements of atomic weights up to that of iron can be built up by this **nucleosynthesis** (the making of new atomic nuclei) in the centers of the more massive red giant stars. This still leaves the question of where elements *heavier* than iron come from. We will see in the next chapter that when massive stars finally exhaust their nuclear fuel, they most often die in a spectacular explosion—a supernova. Heavier elements can be synthesized in the stunning violence of such explosions.

Not only can we explain in this way where the elements that make up our world and others come from, but our theories of nucleosynthesis inside stars are even able to predict the *relative abundances* with which the elements occur in nature. The way stars build up elements during various nuclear reactions really can explain why some elements (oxygen, carbon, and iron) are common and others are quite rare (gold, silver, and uranium).

Elements in Globular Clusters and Open Clusters Are Not the Same

The fact that the elements are made in stars over time explains an important difference between globular and open clusters. Hydrogen and helium, which are the most abundant elements in stars in the solar neighborhood, are also the most abundant constituents of stars in both kinds of clusters. However, the abundances of the elements *heavier* than helium are very different.

In the Sun and most of its neighboring stars, the combined abundance (by mass) of the elements heavier than hydrogen and helium is 1–4% of the star’s mass. Spectra show that most open-cluster stars also have 1–4% of their matter in the form of heavy elements. Globular clusters, however, are a different story. The heavy-element abundance of stars in typical globular clusters is found to be only 1/10 to 1/100 that of the Sun. A few very old stars not in clusters have been discovered with even lower abundances of heavy elements.

The differences in chemical composition are a direct consequence of the formation of a cluster of stars. The very first generation of stars initially contained only hydrogen and helium. We have seen that these stars, in order to generate energy, created heavier elements in their interiors. In the last stages of their lives, they ejected matter, now enriched in heavy elements, into the reservoirs of raw material between the stars. Such matter was then incorporated into a new generation of stars.

This means that the relative abundance of the heavy elements must be less and less as we look further into the past. We saw that the globular clusters are much older than the open clusters. Since globular-cluster stars formed much earlier (that is, they are an earlier generation of stars) than those in open clusters, they have only a relatively small abundance of elements heavier than hydrogen and helium.

As time passes, the proportion of heavier elements in the “raw material” that makes new stars and planets increases. This means that the first generation of stars that formed in our Galaxy would not have been accompanied by a planet like Earth, full of silicon, iron, and many other heavy elements. Earth (and the astronomy students who live on it) was possible only after generations of stars had a chance to make and recycle their heavier elements.

Now the search is on for true *first*-generation stars, made only of hydrogen and helium. Theories predict that such stars should be very massive, live fast, and die quickly. They should have lived and died long ago. The place to look for them is in very distant galaxies that formed when the universe was only a few hundred million years old, but whose light is only arriving at Earth now.

Approaching Death

Compared with the main-sequence lifetimes of stars, the events that characterize the last stages of stellar evolution pass very quickly (especially for massive stars). As the star’s luminosity increases, its rate of nuclear fuel consumption goes up rapidly—just at that point in its life when its fuel supply is beginning to run down.

After the prime fuel—hydrogen—is exhausted in a star’s core, we saw that other sources of nuclear energy are available to the star in the fusion of, first, helium, and then of other more complex elements. But the energy yield of these reactions is much less than that of the fusion of hydrogen to helium. And to trigger these reactions, the central temperature must be higher than that required for the fusion of hydrogen to helium, leading to even more rapid consumption of fuel. Clearly this is a losing game, and very quickly the star reaches its end. As it does so, however, some remarkable things can happen, as we will see in [The Death of Stars](#).

 Key Terms

- association** a loose group of young stars whose spectral types, motions, and positions in the sky indicate a common origin
- globular cluster** one of about 150 large, spherical star clusters (each with hundreds of thousands of stars) that form a spherical halo around the center of our Galaxy
- helium flash** a nearly explosive ignition of helium in the triple-alpha process in the dense core of a red giant star
- main-sequence turnoff** location in the H-R diagram where stars begin to leave the main sequence
- nucleosynthesis** the building up of heavy elements from lighter ones by nuclear fusion
- open cluster** a comparatively loose cluster of stars, containing from a few dozen to a few thousand members, located in the spiral arms or disk of our Galaxy; sometimes referred to as a galactic cluster
- planetary nebula** a shell of gas ejected by and expanding away from an extremely hot low-mass star that is nearing the end of its life (the nebulae glow because of the ultra-violet energy of the central star)
- triple-alpha process** a nuclear reaction by which three helium nuclei are built up (fused) into one carbon nucleus
- zero-age main sequence** a line denoting the main sequence on the H-R diagram for a system of stars that have completed their contraction from interstellar matter and are now deriving all their energy from nuclear reactions, but whose chemical composition has not yet been altered substantially by nuclear reactions

 Summary

22.1 Evolution from the Main Sequence to Red Giants

When stars first begin to fuse hydrogen to helium, they lie on the zero-age main sequence. The amount of time a star spends in the main-sequence stage depends on its mass. More massive stars complete each stage of evolution more quickly than lower-mass stars. The fusion of hydrogen to form helium changes the interior composition of a star, which in turn results in changes in its temperature, luminosity, and radius. Eventually, as stars age, they evolve away from the main sequence to become red giants or supergiants. The core of a red giant is contracting, but the outer layers are expanding as a result of hydrogen fusion in a shell outside the core. The star gets larger, redder, and more luminous as it expands and cools.

22.2 Star Clusters

Star clusters provide one of the best tests of our calculations of what happens as stars age. The stars in a given cluster were formed at about the same time and have the same composition, so they differ mainly in mass, and thus, in their life stage. There are three types of star clusters: globular, open, and associations. Globular clusters have diameters of 50–450 light-years, contain hundreds of thousands of stars, and are distributed in a halo around the Galaxy. Open clusters typically contain hundreds of stars, are located in the plane of the Galaxy, and have diameters less than 30 light-years. Associations are found in regions of gas and dust and contain extremely young stars.

22.3 Checking Out the Theory

The H-R diagram of stars in a cluster changes systematically as the cluster grows older. The most massive stars evolve most rapidly. In the youngest clusters and associations, highly luminous blue stars are on the main sequence; the stars with the lowest masses lie to the right of the main sequence and are still contracting toward it. With passing time, stars of progressively lower masses evolve away from (or turn off) the main sequence. In globular clusters, which are all at least 11 billion years old, there are no luminous blue stars at all. Astronomers can use the turnoff point from the main sequence to determine the age of a cluster.

22.4 Further Evolution of Stars

After stars become red giants, their cores eventually become hot enough to produce energy by fusing helium to form carbon (and sometimes a bit of oxygen.) The fusion of three helium nuclei produces carbon through the triple-alpha process. The rapid onset of helium fusion in the core of a low-mass star is called the helium flash. After this, the star becomes stable and reduces its luminosity and size briefly. In stars with masses about twice the mass of the Sun or less, fusion stops after the helium in the core has been exhausted. Fusion of hydrogen and helium in shells around the contracting core makes the star a bright red giant again, but only temporarily. When the star is a red giant, it can shed its outer layers and thereby expose hot inner layers. Planetary nebulae (which have nothing to do with planets) are shells of gas ejected by such stars, set glowing by the ultraviolet radiation of the dying central star.

22.5 The Evolution of More Massive Stars

In stars with masses higher than about 8 solar masses, nuclear reactions involving carbon, oxygen, and still heavier elements can build up nuclei as heavy as iron. The creation of new chemical elements is called nucleosynthesis. The late stages of evolution occur very quickly. Ultimately, all stars must use up all of their available energy supplies. In the process of dying, most stars eject some matter, enriched in heavy elements, into interstellar space where it can be used to form new stars. Each succeeding generation of stars therefore contains a larger proportion of elements heavier than hydrogen and helium. This progressive enrichment explains why the stars in open clusters (which formed more recently) contain more heavy elements than do those in ancient globular clusters, and it tells us where most of the atoms on Earth and in our bodies come from.



For Further Exploration

Articles

Balick, B. & Frank, A. "The Extraordinary Deaths of Ordinary Stars." *Scientific American* (July 2004): 50. About planetary nebulae, the last gasps of low-mass stars, and the future of our own Sun.

Djorgovsky, G. "The Dynamic Lives of Globular Clusters." *Sky & Telescope* (October 1998): 38. Cluster evolution and blue straggler stars.

Frank, A. "Angry Giants of the Universe." *Astronomy* (October 1997): 32. On luminous blue variables like Eta Carinae.

Garlick, M. "The Fate of the Earth." *Sky & Telescope* (October 2002): 30. What will happen when our Sun becomes a red giant.

Harris, W. & Webb, J. "Life Inside a Globular Cluster." *Astronomy* (July 2014): 18. What would night sky be like there?

Iben, I. & Tutokov, A. "The Lives of the Stars: From Birth to Death and Beyond." *Sky & Telescope* (December 1997): 36.

Kaler, J. "The Largest Stars in the Galaxy." *Astronomy* (October 1990): 30. On red supergiants.

Kalirai, J. "New Light on Our Sun's Fate." *Astronomy* (February 2014): 44. What will happen to stars like our Sun between the main sequence and the white dwarf stages.

Kwok, S. "What Is the Real Shape of the Ring Nebula?" *Sky & Telescope* (July 2000): 33. On seeing planetary nebulae from different angles.

Kwok, S. "Stellar Metamorphosis." *Sky & Telescope* (October 1998): 30. How planetary nebulae form.

Stahler, S. "The Inner Life of Star Clusters." *Scientific American* (March 2013): 44-49. How all stars are born in clusters, but different clusters evolve differently.

Subinsky, R. "All About 47 Tucanae." *Astronomy* (September 2014): 66. What we know about this globular cluster and how to see it.

Websites

Encyclopedia Britannica Article on Star Clusters: <http://www.britannica.com/topic/star-cluster> (<http://www.britannica.com/topic/star-cluster>). Written by astronomer Helen Sawyer Hogg-Priestley.

Hubble Image Gallery: Planetary Nebulae: Go to <https://www.spacetelescope.org/images/> (<https://www.spacetelescope.org/images/>) and in the search box enter "planetary nebulae". See also a similar gallery from NOIRLab: <https://noirlab.edu/public/images/> (<https://noirlab.edu/public/images/>). (Again, enter "planetary nebulae" in the search box.)

"Hubble Image Gallery: Star Clusters: Go to <https://www.spacetelescope.org/images/> (<https://www.spacetelescope.org/images/>) and in the search box enter "star clusters". (See also a similar European Southern Observatory Gallery at: <https://www.eso.org/public/images/archive/category/starclusters/> (<https://www.eso.org/public/images/archive/category/starclusters/>)).

Measuring the Age of a Star Cluster: https://www.e-education.psu.edu/astro801/content/l7_p6.html (https://www.e-education.psu.edu/astro801/content/l7_p6.html). From Penn State.

Videos

Life Cycle of Stars: <https://www.youtube.com/watch?v=PM9CQDIQI0A> (<https://www.youtube.com/watch?v=PM9CQDIQI0A>). Short summary of stellar evolution from the Institute of Physics in Great Britain, with astronomer Tim O'Brien (4:58).

Missions Take an Unparalleled Look into Superstar Eta Carinae: <https://www.youtube.com/watch?v=0rJQi6oaZf0> (<https://www.youtube.com/watch?v=0rJQi6oaZf0>). NASA Goddard video about observations in 2014 and what we know about the pair of stars in this complicated system (4:00).

Star Clusters: Open and Globular Clusters: <https://www.youtube.com/watch?v=rGPRLxrYbYA> (<https://www.youtube.com/watch?v=rGPRLxrYbYA>). Three Short Hubblecast Videos from 2007–2008 on discoveries involving star clusters (12:24).

Tour of Planetary Nebula NGC 5189: <https://www.youtube.com/watch?v=1D2cwiZld0o> (<https://www.youtube.com/watch?v=1D2cwiZld0o>). Brief Hubblecast episode with Joe Liske, explaining planetary nebulae in general and one example in particular (5:22).

Collaborative Group Activities

- A. Have your group take a look at the list of the brightest stars in the sky in [Appendix J](#). What fraction of them are past the main-sequence phase of evolution? The text says that stars spend 90% of their lifetimes in the main-sequence phase of evolution. This suggests that if we have a fair (or representative) sample of stars, 90% of them should be main-sequence stars. Your group should brainstorm why 90% of the brightest stars are not in the main-sequence phase of evolution.
- B. Reading an H–R diagram can be tricky. Suppose your group is given the H–R diagram of a star cluster. Stars above and to the right of the main sequence could be either red giants that had evolved away from the main sequence or very young stars that are still evolving toward the main sequence. Discuss how you would decide which they are.
- C. In the chapter on [Life in the Universe](#), we discuss some of the efforts now underway to search for radio signals from possible intelligent civilizations around other stars. Our present resources for carrying out such searches are very limited and there are many stars in our Galaxy. Your group is a committee set up by the International Astronomical Union to come up with a list of the best possible stars with which such a

search should begin. Make a list of criteria for choosing the stars on the list, and explain the reasons behind each entry (keeping in mind some of the ideas about the life story of stars and timescales that we discuss in the present chapter.)

- D. Have your group make a list of the reasons why a star that formed at the very beginning of the universe (soon after the Big Bang) could not have a planet with astronomy students reading astronomy textbooks (even if the star has the same mass as that of our Sun).
- E. Since we are pretty sure that when the Sun becomes a giant star, all life on Earth will be wiped out, does your group think that we should start making preparations of any kind? Let's suppose that a political leader who fell asleep during large parts of his astronomy class suddenly hears about this problem from a large donor and appoints your group as a task force to make suggestions on how to prepare for the end of Earth. Make a list of arguments for why such a task force is not really necessary.
- F. Use star charts to identify at least one open cluster visible at this time of the year. (Such charts can be found in *Sky & Telescope* and *Astronomy* magazines each month and their websites; see [Appendix B](#).) The Pleiades and Hyades are good autumn subjects, and Praesepe is good for springtime viewing. Go out and look at these clusters with binoculars and describe what you see.
- G. Many astronomers think that planetary nebulae are among the most attractive and interesting objects we can see in the Galaxy. In this chapter, we could only show you a few examples of the pictures of these objects taken with the Hubble or large telescopes on the ground. Have members of your group search further for planetary nebula images online, and make a "top ten" list of your favorite ones (do not include more than three that were featured in this chapter.) Make a report (with images) for the whole class and explain why you found your top five especially interesting. (You may want to check [Figure 22.19](#) in the process.)

Exercises

Review Questions

1. Compare the following stages in the lives of a human being and a star: prenatal, birth, adolescence/adulthood, middle age, old age, and death. What does a star with the mass of our Sun do in each of these stages?
2. What is the first event that happens to a star with roughly the mass of our Sun that exhausts the hydrogen in its core and stops the generation of energy by the nuclear fusion of hydrogen to helium? Describe the sequence of events that the star undergoes.
3. Astronomers find that 90% of the stars observed in the sky are on the main sequence of an H-R diagram; why does this make sense? Why are there far fewer stars in the giant and supergiant region?
4. Describe the evolution of a star with a mass similar to that of the Sun, from the protostar stage to the time it first becomes a red giant. Give the description in words and then sketch the evolution on an H-R diagram.
5. Describe the evolution of a star with a mass similar to that of the Sun, from just after it first becomes a red giant to the time it exhausts the last type of fuel its core is capable of fusing.
6. A star is often described as "moving" on an H-R diagram; why is this description used and what is actually happening with the star?
7. On which edge of the main sequence band on an H-R diagram would the zero-age main sequence be?
8. How do stars typically "move" through the main sequence band on an H-R diagram? Why?
9. Certain stars, like Betelgeuse, have a lower surface temperature than the Sun and yet are more luminous. How do these stars produce so much more energy than the Sun?

10. Gravity always tries to collapse the mass of a star toward its center. What mechanism can oppose this gravitational collapse for a star? During what stages of a star's life would there be a "balance" between them?
11. Why are star clusters so useful for astronomers who want to study the evolution of stars?
12. Would the Sun more likely have been a member of a globular cluster or open cluster in the past?
13. Suppose you were handed two H-R diagrams for two different clusters: diagram A has a majority of its stars plotted on the upper left part of the main sequence with the rest of the stars off the main sequence; and diagram B has a majority of its stars plotted on the lower right part of the main sequence with the rest of the stars off the main sequence. Which diagram would be for the older cluster? Why?
14. Referring to the H-R diagrams in [Exercise 22.13](#), which diagram would more likely be the H-R diagram for an association?
15. The nuclear process for fusing helium into carbon is often called the "triple-alpha process." Why is it called as such, and why must it occur at a much higher temperature than the nuclear process for fusing hydrogen into helium?
16. Pictures of various planetary nebulae show a variety of shapes, but astronomers believe a majority of planetary nebulae have the same basic shape. How can this paradox be explained?
17. Describe the two "recycling" mechanisms that are associated with stars (one during each star's life and the other connecting generations of stars).
18. In which of these star groups would you mostly likely find the least heavy-element abundance for the stars within them: open clusters, globular clusters, or associations?
19. Explain how an H-R diagram of the stars in a cluster can be used to determine the age of the cluster.
20. Where did the carbon atoms in the trunk of a tree on your college campus come from originally? Where did the neon in the fabled "neon lights of Broadway" come from originally?
21. What is a planetary nebula? Will we have one around the Sun?

Thought Questions

22. Is the Sun on the zero-age main sequence? Explain your answer.
23. How are planetary nebulae comparable to a fluorescent light bulb in your classroom?
24. Which of the planets in our solar system have orbits that are smaller than the photospheric radius of Betelgeuse listed in [Table 22.2](#)?
25. Would you expect to find an earthlike planet (with a solid surface) around a very low-mass star that formed right at the beginning of a globular cluster's life? Explain.
26. In the H-R diagrams for some young clusters, stars of both very low and very high luminosity are off to the right of the main sequence, whereas those of intermediate luminosity are on the main sequence. Can you offer an explanation for that? Sketch an H-R diagram for such a cluster.
27. If the Sun were a member of the cluster NGC 2264, would it be on the main sequence yet? Why or why not?
28. If all the stars in a cluster have nearly the same age, why are clusters useful in studying evolutionary effects (different stages in the lives of stars)?

29. Suppose a star cluster were at such a large distance that it appeared as an unresolved spot of light through the telescope. What would you expect the overall color of the spot to be if it were the image of the cluster immediately after it was formed? How would the color differ after 10^{10} years? Why?
30. Suppose an astronomer known for joking around told you she had found a type-O main-sequence star in our Milky Way Galaxy that contained no elements heavier than helium. Would you believe her? Why?
31. Stars that have masses approximately 0.8 times the mass of the Sun take about 18 billion years to turn into red giants. How does this compare to the current age of the universe? Would you expect to find a globular cluster with a main-sequence turnoff for stars of 0.8 solar mass or less? Why or why not?
32. Automobiles are often used as an analogy to help people better understand how more massive stars have much shorter main-sequence lifetimes compared to less massive stars. Can you explain such an analogy using automobiles?

Figuring for Yourself

33. The text says a star does not change its mass very much during the course of its main-sequence lifetime. While it is on the main sequence, a star converts about 10% of the hydrogen initially present into helium (remember it's only the core of the star that is hot enough for fusion). Look in earlier chapters to find out what percentage of the hydrogen mass involved in fusion is lost because it is converted to energy. By how much does the mass of the whole star change as a result of fusion? Were we correct to say that the mass of a star does not change significantly while it is on the main sequence?
34. The text explains that massive stars have shorter lifetimes than low-mass stars. Even though massive stars have more fuel to burn, they use it up faster than low-mass stars. You can check and see whether this statement is true. The lifetime of a star is directly proportional to the amount of mass (fuel) it contains and inversely proportional to the rate at which it uses up that fuel (i.e., to its luminosity). Since the lifetime of the Sun is about 10^{10} y, we have the following relationship:
- $$T = 10^{10} \frac{M}{L} \text{ y}$$
- where T is the lifetime of a main-sequence star, M is its mass measured in terms of the mass of the Sun, and L is its luminosity measured in terms of the Sun's luminosity.
- A. Explain in words why this equation works.
- B. Use the data in [Table 18.3](#) to calculate the ages of the main-sequence stars listed.
- C. Do low-mass stars have longer main-sequence lifetimes?
- D. Do you get the same answers as those in [Table 22.1](#)?
35. You can use the equation in [Exercise 22.34](#) to estimate the approximate ages of the clusters in [Figure 22.10](#), [Figure 22.12](#), and [Figure 22.13](#). Use the information in the figures to determine the luminosity of the most massive star still on the main sequence. Now use the data in [Table 18.3](#) to estimate the mass of this star. Then calculate the age of the cluster. This method is similar to the procedure used by astronomers to obtain the ages of clusters, except that they use actual data and model calculations rather than simply making estimates from a drawing. How do your ages compare with the ages in the text?
36. You can estimate the age of the planetary nebula in image (c) in [Figure 22.18](#). The diameter of the nebula is 600 times the diameter of our own solar system, or about 0.8 light-year. The gas is expanding away from the star at a rate of about 25 mi/s. Considering that distance = velocity \times time, calculate how long ago the gas left the star if its speed has been constant the whole time. Make sure you use consistent units for time, speed, and distance.
37. If star A has a core temperature T , and star B has a core temperature $3T$, how does the rate of fusion of star A compare to the rate of fusion of star B?