we sometimes refer to the main-sequence lifetime as simply the "lifetime." Like masses, stellar lifetimes vary in an orderly way as we move up the main sequence: Massive stars near the upper end of the main sequence have *shorter* lives than less massive stars near the lower end (see Figure 15.11).

Why do more massive stars have shorter lives? A star's lifetime depends on both its mass and its luminosity. Its mass determines how much hydrogen fuel the star initially contains in its core. Its luminosity determines how rapidly the star uses up its fuel. Massive stars start their lives with a larger supply of hydrogen, but they fuse this hydrogen into helium so rapidly that they end up with shorter lives. For example, a 10-solar-mass star ($10M_{\text{Sun}}$) is born with 10 times as much hydrogen as the Sun. However, its luminosity of $10{,}000L_{\text{Sun}}$ means that it burns through this hydrogen at a rate 10,000 times as fast as the rate in the Sun. Its lifetime is therefore only $\frac{10}{10{,}000} = \frac{1}{1000}$ as long as the Sun's lifetime because a 10-solar-mass star has only 10 times as much hydrogen and burns through it 10,000 times faster. Since the Sun's core hydrogen-burning lifetime is about 10 billion years [Section 14.1], a 10-solar-mass star must have a lifetime of only about 10 million years. Its actual lifetime is a little longer than this, because it can use more of its core hydrogen for fusion than can the Sun.

Cosmically speaking, the several-million-year lifetimes of very massive stars are a remarkably short time. That is one reason why massive stars are so rare: Most of the massive stars that have ever been born are long since dead. A second reason is that higher-mass stars are born in smaller numbers to begin with [Section 16.3]. Indeed, the fact that massive stars exist at all at the present time tells us that stars must form continuously in our galaxy. The massive, bright O stars in our galaxy today formed only recently and will die long before they have a chance to complete even one orbit around the center of the galaxy.

On the other end of the scale, a 0.3-solar-mass main-sequence star emits a luminosity just 0.01 times that of the Sun and consequently lives roughly $\frac{0.3}{0.01} = 30$ times as long as the Sun, or about 300 billion years. In a universe that is now about 14 billion years old, even the most ancient of these small, dim, red stars of spectral type M still survive and will continue to shine faintly for hundreds of billions of years to come.

Mass: A Star's Most Fundamental Property Astronomers began classifying stars by their spectral type and luminosity class before they understood why stars vary in these properties. Today, we know that the most fundamental property of any star is its *mass*. As we have discussed, a star's mass determines both its surface temperature and luminosity throughout the main-sequence portion of its life, and these properties in turn explain why higher-mass stars have shorter lifetimes. Figure 15.12 compares four main-sequence stars, showing how they differ because of their different masses.

THINK ABOUT IT

Which of the stars labeled in Figure 15.10 has the longest lifetime? Explain.

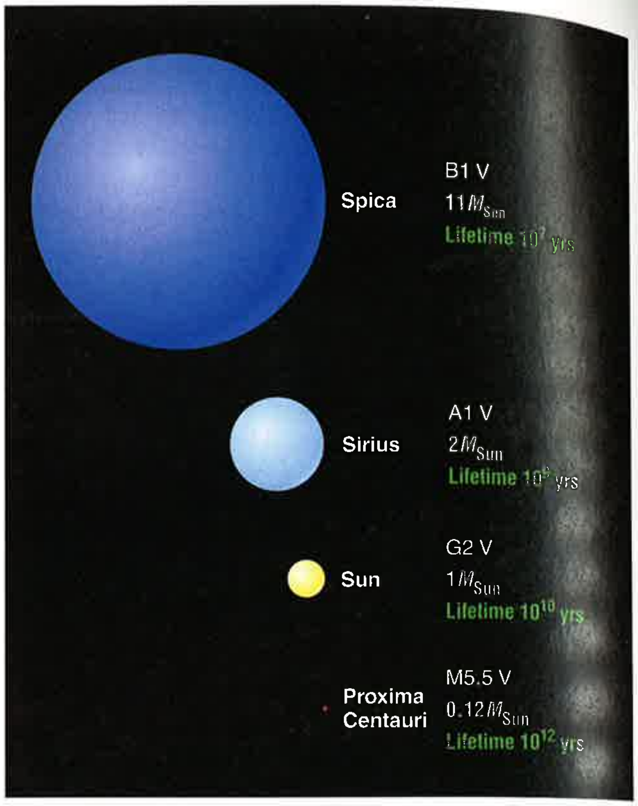

FIGURE 15.12 Four main-sequence stars shown to scale. The mass of a main-sequence star determines its fundamental properties of luminosity, surface temperature, radius, and lifetime. More massive main-sequence stars are hotter and brighter than less massive ones but have shorter lifetimes.

What are giants, supergiants, and white dwarfs?

Main-sequence stars fuse hydrogen into helium in their cores, but what about the other classes of stars on the H-R diagram? These other classes all represent stars that have exhausted the supply of hydrogen in their central cores, so that they can no longer generate energy in the same way as our Sun.

Giants and Supergiants The bright red stars in Figure 15.4 are giants and supergiants whose properties place them to the upper right of the main sequence in an H-R diagram. The fact that these stars are cooler but much more luminous than the Sun tells us that they must be much larger in radius than the Sun. Remember that a star's surface temperature determines the amount of light it emits per unit surface area [Section 5.4]: Hotter stars emit much more light per unit surface area than cooler stars. For example, a blue star would emit far more total light than a red star of the same size. A star that is red and cool can be bright only if it has a very large surface area, which means it must be enormous in size.

As we'll discuss in Chapter 17, we now know that giants and supergiants are stars nearing the ends of their lives. They have already exhausted the supply of hydrogen fuel in their central cores and are in essence facing an energy crisis

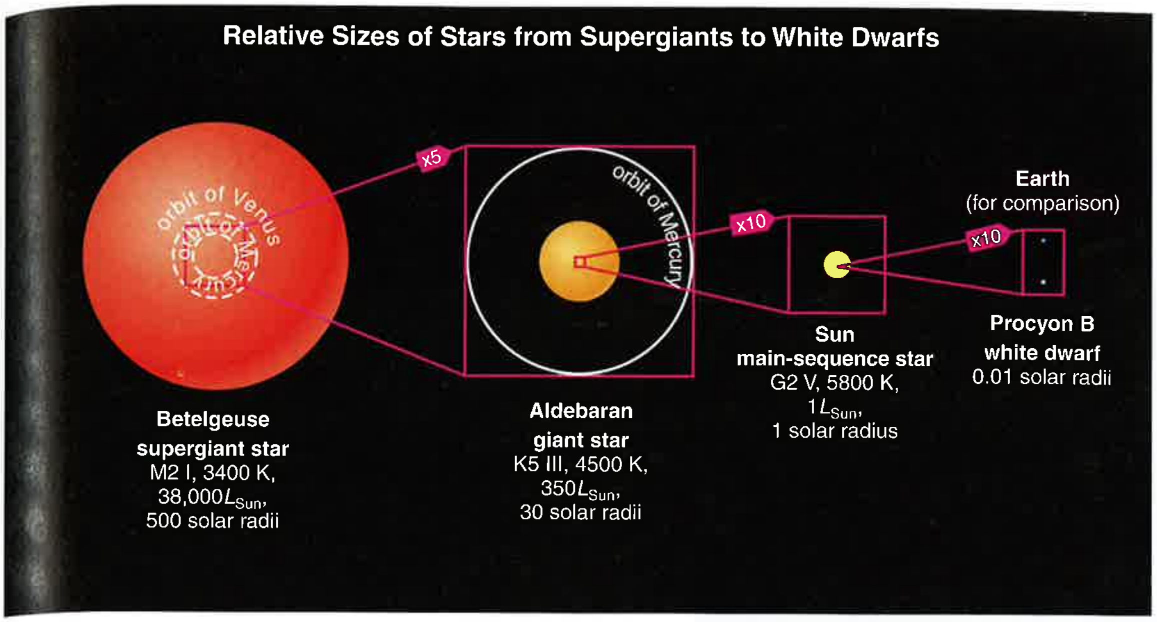

FIGURE 15.13 The relative sizes of stars. A supergiant like Betelgeuse would fill the inner solar system. A giant like Aldebaran would fill the inner third of Mercury's orbit. The Sun is a hundred times larger in radius than a white dwarf, which is roughly the same size as Earth.

as they try to stave off the inevitable crushing force of gravity. This crisis causes these stars to release fusion energy at a furious rate, which explains their high luminosities, while the need to radiate away this huge amount of energy causes them to expand to enormous size (Figure 15.13). For example, Arcturus and Aldebaran (the eye of the bull in the constellation Taurus) are giant stars more than 10 times as large in radius as our Sun. Betelgeuse, the left shoulder in the constellation Orion, is an enormous supergiant with a radius roughly 500 times that of the Sun, equivalent to more than twice the Earth-Sun distance, placing it in the upper-right corner of the H-R diagram.

Because giants and supergiants are so bright, we can see them even if they are not especially close to us. Many of the brightest stars in our sky are giants or supergiants, often identifiable by their reddish colors. Overall, however, giants and supergiants are considerably rarer than main-sequence stars. In our snapshot of the heavens, we catch most stars in the act of hydrogen burning and relatively few in a later stage of life.

White Dwarfs Giants and supergiants eventually run out of fuel entirely. A giant with a mass similar to that of our Sun ultimately ejects its outer layers, leaving behind a "dead" core in which all nuclear fusion has ceased. White dwarfs are these remaining embers of former giants. They are hot because they are essentially exposed stellar cores, but they are dim because they lack an energy source and radiate only their leftover heat into space. A typical white dwarf is no larger in size than Earth, but has a mass similar to that of our Sun. Clearly, white dwarfs must be made of matter compressed to an extremely high density, unlike anything found on Earth. We'll discuss the nature of white dwarfs and other stellar corpses in Chapter 18.

Why do the properties of some stars vary?

Not all stars shine steadily like our Sun. Any star that varies significantly in brightness with time is called a *variable star*. Certain types of variable stars cannot achieve balance between the power welling up from the core and the power being radiated from the surface. Sometimes the upper layers of such a star are too opaque to allow much energy to escape, so pressure builds up beneath the photosphere and the star expands in size. This expansion puffs up the outer layers until they become transparent enough for the trapped energy to escape. The underlying pressure then drops, allowing the star to contract until the trapping of energy resumes.

In a futile quest for a steady equilibrium, the atmosphere of such a **pulsating variable star** alternately expands and contracts, causing the star to rise and fall in luminosity. Figure 15.14 shows a typical light curve for a pulsating variable star,

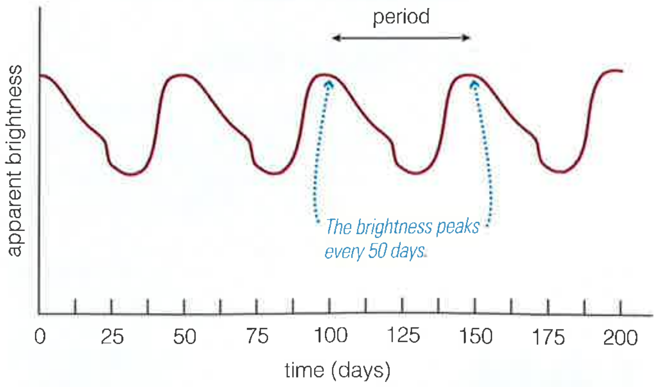

FIGURE 15.14 A typical light curve for a pulsating variable star. This particular star is a Cepheid variable star with a pulsation period of about 50 days.

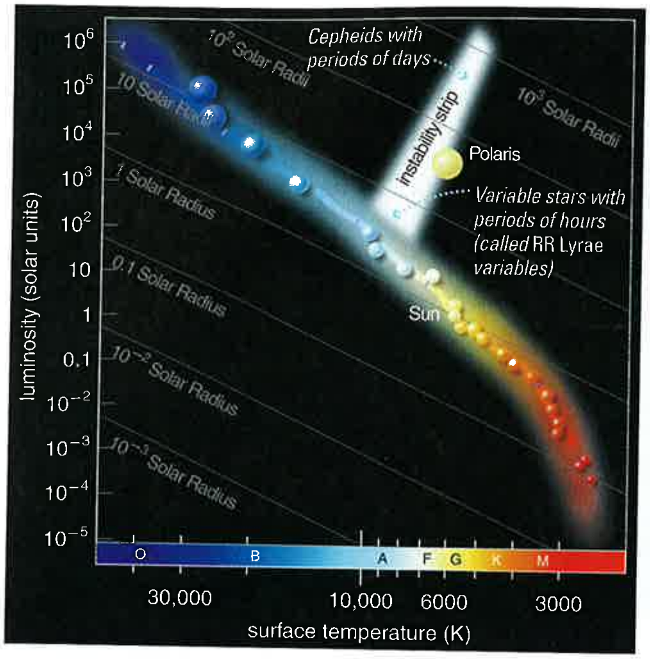

FIGURE 15.15 An H-R diagram with the instability strip highlighted. Notice that Polaris, the North Star, is a Cepheid variable star.

with the star's brightness graphed against time. Any pulsating variable star has its own particular period between peaks and valleys in luminosity, which we can discover easily from its light curve. These periods can range from as short as several hours to as long as several years.

Most pulsating variable stars inhabit a strip (called the *instability strip*) on the H-R diagram that lies between the main sequence and the red giants (Figure 15.15). A special category of very luminous pulsating variable stars lies in the upper portion of this strip. They are known as *Cepheid variable stars,* and they are significant both because they are so bright and because their pulsation periods turn out to be closely related to their luminosities. As a result, Cepheids have played a key role in helping us establish the distances to many galaxies beyond the Milky Way, thereby revealing the overall scale of the cosmos. We will discuss the cosmic distance scale further in Chapter 20.

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15.3 STAR CLUSTERS

All stars are born from giant clouds of gas. Because a single interstellar cloud can contain enough material to form many stars, stars usually form in groups [Section 16.1]. In our snapshot of the heavens, many stars still congregate in the groups in which they formed.

These groups are known as *star clusters,* and they are extremely useful to astronomers for two key reasons:

1. All the stars in a cluster lie at about the same distance from Earth.

2. All the stars in a cluster formed at about the same time (within a few million years of one another).

FIGURE 15.16 A photo of the Pleiades, a nearby open cluster of stars. The most prominent stars in this open cluster are of spectral type B, indicating that the stars of the Pleiades are no more than 100 million years old, relatively young for a star cluster. The region shown is about 11 light-years across.

Astronomers can therefore use star clusters as laboratories for comparing the properties of stars that all have similar ages, and we shall see that these features of star clusters enable us to use them as cosmic clocks.

What are the two types of star clusters?

Star clusters come in two basic types: modest-size **open clusters** and densely packed **globular clusters.** The two types differ not only in how densely they are packed with stars but also in their locations and ages. Recall that most of the stars, gas, and dust in the Milky Way Galaxy, including our Sun, lie in the relatively flat *galactic disk;* the region above and below the disk is called the *halo* of the galaxy (see Figure 1.15). Open clusters are always found in the disk of the galaxy and tend to be young in age. They can contain up to several thousand stars and typically are about 30 light-years across. The most famous open cluster is the *Pleiades,* a prominent clump of stars in the constellation Taurus (Figure 15.16). The Pleiades are often called the *Seven Sisters,* although only six of the cluster's several thousand stars are easily visible to the naked eye. Other cultures have other names for this beautiful group of stars. In Japan it is called *Subaru,* which is why the logo for Subaru automobiles is a diagram of the Pleiades.

In contrast, most globular clusters are found in the halo, and their stars are among the oldest in the universe. A globular cluster can contain more than a million stars concentrated in the shape of a ball typically from 60 to 150 light-years across. Its central region can have 10,000 stars packed into a space just a few light-years across (Figure 15.17). The view from a planet in a globular cluster would be marvelous, with thousands of stars lying closer to that planet than Alpha Centauri is to the Sun.

Because a globular cluster's stars nestle so closely together, they engage in an intricate and complex dance choreographed

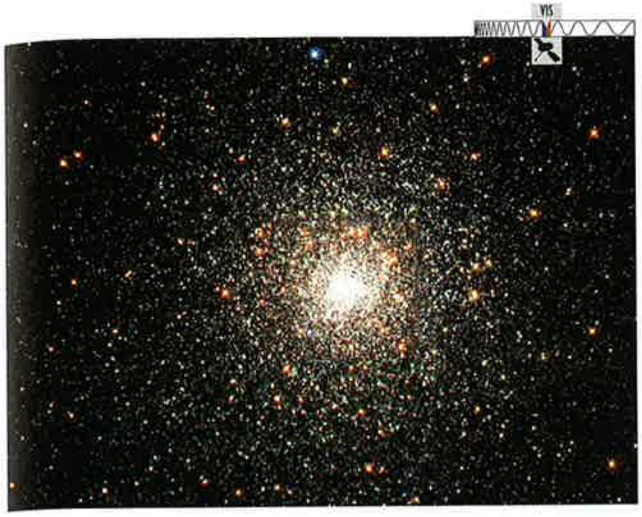


FIGURE 15.17 The globular cluster M80 is more than 12 billion years old. The prominent reddish stars in this Hubble Space Telescope photo are red giant stars nearing the ends of their lives. The central region pictured here is about 15 light-years across.

by gravity. Some stars zoom from the cluster's core to its outskirts and back again at speeds approaching escape velocity from the cluster, while others orbit the dense core more closely. When two stars pass especially close to each other, the gravitational pull between them deflects their trajectories, altering their speeds and sending them careening off in new directions. Occasionally, a close encounter boosts one star's velocity enough to eject it from the cluster. Through such ejections, globular clusters gradually lose stars and grow more compact.

How do we measure the age of a star cluster?

We can use clusters as clocks, because we can determine their ages by plotting their stars in an H-R diagram. To understand how the process works, look at Figure 15.18, which shows an H-R diagram for the Pleiades. Most of the stars in the Pleiades fall along the main sequence, with one important exception: The Pleiades' stars trail away to the right of the main sequence at the upper end. That is, the hot, short-lived stars of spectral type O are missing from the main sequence. Apparently, the Pleiades cluster is old enough for its main-sequence O stars to have already ended their hydrogen-burning lives. At the same time, the cluster is young enough that some of its stars of spectral type B still survive as hydrogen-burning stars on the main sequence.

The precise point on the H-R diagram at which the Pleiades' stars diverge from the main sequence is called its **main-sequence turnoff** point. In this cluster, it occurs around spectral type B6. The main-sequence lifetime of a B6 star is roughly 100 million years, so this must be the age of the Pleiades. Any star in the Pleiades that was born with a main-sequence spectral type hotter than B6 had a lifetime shorter than 100 million years and is no longer found on the main sequence. Stars with lifetimes longer than 100 million years are still fusing hydrogen in their cores and remain as main-sequence stars. Over the next few billion years, the B stars in the Pleiades will die out, followed by the A stars and the F stars. If we could make an H-R diagram for the Pleiades every few million years, we would find that the main sequence gradually grows shorter.

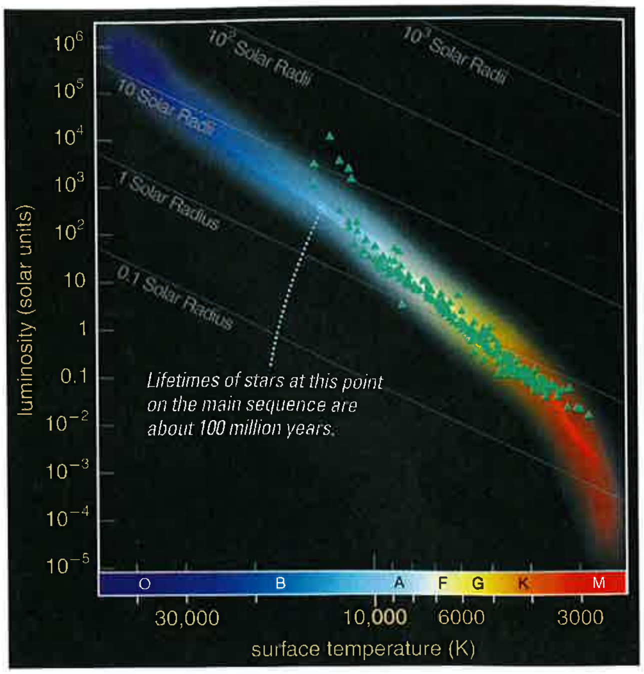


FIGURE 15.18 An H-R diagram for the stars of the Pleiades. Triangles represent individual stars. The Pleiades cluster is missing its upper main-sequence stars, indicating that these stars have already ended their hydrogen-burning lives. The main-sequence turnoff point at about spectral type B6 tells us that the Pleiades are approximately 100 million years old.

Comparing the H-R diagrams of other open clusters makes this effect more apparent (Figure 15.19). In each case, *the age of the cluster is equal to the lifetimes of stars at its main-sequence turnoff point.* Stars in a particular cluster that once resided above the turnoff point on the main sequence have

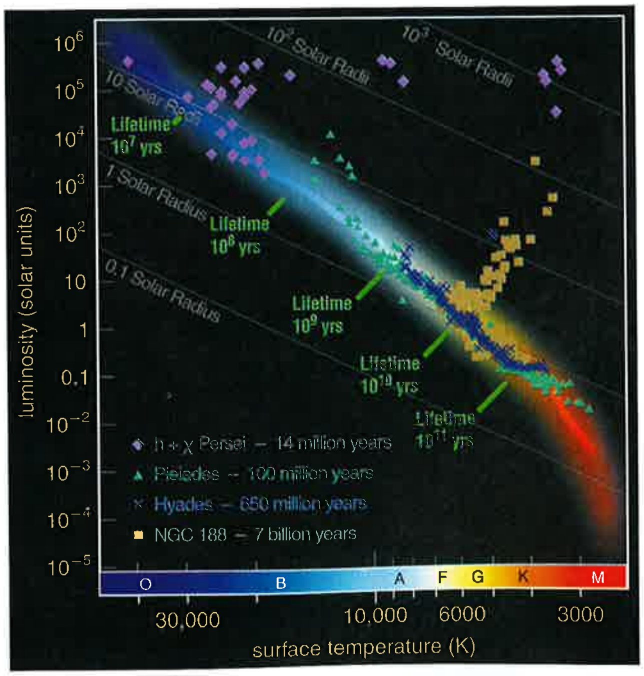


FIGURE 15.19 This H-R diagram shows stars from four clusters. Their differing main-sequence turnoff points indicate very different ages.

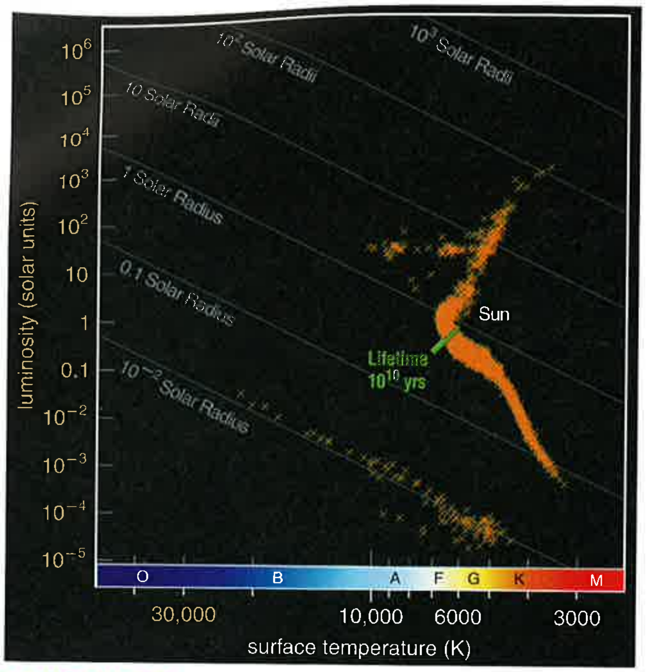


FIGURE 15.20 This H-R diagram shows stars from the globular cluster M4. The main-sequence turnoff point is in the vicinity of stars like our Sun, indicating an age for this cluster of around 10 billion years. A more technical analysis of this cluster places its age at around 13 billion years.

already exhausted their core supply of hydrogen, while stars below the turnoff point remain on the main sequence.

THINK ABOUT IT

Suppose a star cluster is precisely 10 billion years old. Where would you expect to find its main-sequence turnoff point? Would you expect this cluster to have any main-sequence stars of spectral type A? Would you expect it to have main-sequence stars of spectral type K? Explain. (*Hint:* What is the lifetime of our Sun?)

The technique of identifying main-sequence turnoff points is our most powerful tool for evaluating the ages of star clusters. We've learned that most open clusters are relatively young, with very few older than about 5 billion years. In contrast, the stars at the main-sequence turnoff points in globular clusters are usually less massive than our Sun (Figure 15.20). Because stars like our Sun have a lifetime of about 10 billion years and these stars have already died in globular clusters, we conclude that globular cluster stars are older than 10 billion years.

More precise studies of the turnoff points in globular clusters, coupled with theoretical calculations of stellar lifetimes, place the ages of these clusters at about 13 billion years, making them the oldest known objects in the galaxy. In fact, globular clusters place a constraint on the possible age of the universe: If stars in globular clusters are 13 billion years old, then the universe must be at least this old. Recent observations suggesting that the universe is about 14 billion years old therefore fit well with the ages of these stars and tell us that the first stars began to form by the time the universe was a billion years old.

THE BIG PICTURE

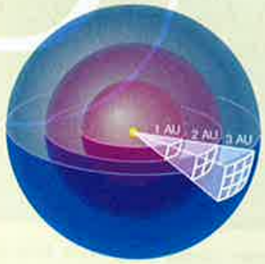
Putting Chapter 15 into Context

We have classified the diverse families of stars visible in the night sky. Much of what we know about stars, galaxies, and the universe itself is based on the fundamental properties of stars introduced in this chapter. Make sure you understand the following "big picture" ideas:

- All stars are made primarily of hydrogen and helium at the time they form. The differences between stars are primarily due to differences in mass and stage of life.
- Stars spend most of their lives as main-sequence stars that fuse hydrogen into helium in their cores. The most massive stars, which are also the hottest and most luminous, live only a few million years. The least massive stars, which are coolest and dimmest, will survive until the universe is many times its present age.
- The key to recognizing the patterns among stars was the H-R diagram, which shows stellar surface temperatures on the horizontal axis and luminosities on the vertical axis. The H-R diagram is one of the most important tools of modern astronomy.
- Much of what we know about the universe comes from studies of star clusters. We can measure a star cluster's age by plotting its stars on an H-R diagram and determining the hydrogen-burning lifetime of the brightest and most massive stars still on the main sequence.

SUMMARY OF KEY CONCEPTS

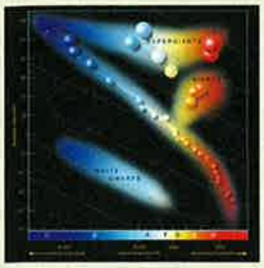
15.1 PROPERTIES OF STARS



- **How do we measure stellar luminosities?** The **apparent brightness** of a star in our sky depends on both its **luminosity**—the total amount of light it emits into space—and its distance from Earth, as expressed by the **inverse square law for light**. We can therefore calculate a star's luminosity from its apparent brightness and distance; we can measure the latter through stellar parallax.
- **How do we measure stellar temperatures?** We measure a star's surface temperature from its color or spectrum, and we classify spectra according to the sequence of **spectral types** OBAFGKM, which runs from hottest to coolest. Cool, red stars of spectral type M are much more common than hot, blue stars of spectral type O.
- **How do we measure stellar masses?** We can measure the masses of stars in **binary star systems** using Newton's version of Kepler's third law if we can measure the orbital period and separation of the two stars.

15.2 PATTERNS AMONG STARS

- **What is a Hertzsprung-Russell diagram?** An **H-R diagram** plots stars according to their surface temperatures (or spectral types) and luminosities. Stars spend most of their lives fusing hydrogen into helium in their cores, and stars in this stage of life are found in the H-R diagram in a narrow band known as the **main sequence. Giants** and **supergiants** are to the upper right of the main sequence and **white dwarfs** are to the lower left.



- **What is the significance of the main sequence?** Stars on the main sequence are all fusing hydrogen into helium in their cores, and a star's position along the main sequence depends on its mass. High-mass stars are at the upper left end of the main sequence, and the masses of stars become progressively smaller as we move toward the lower right end. Lifetimes vary in the opposite way, because higher-mass stars live shorter lives.

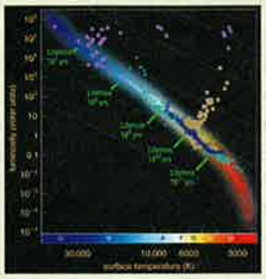
- **What are giants, supergiants, and white dwarfs?** Giants and supergiants are stars that have exhausted their core supplies of hydrogen for fusion and are undergoing other forms of fusion at a more rapid rate as they near the ends of their lives. White dwarfs are the exposed cores of stars that have already died, meaning they have no further means of generating energy through fusion.

- **Why do the properties of some stars vary?** Some stars fail to achieve a proper balance between the amount of fusion energy welling up from their cores and the amount of radiative energy emanating from their surfaces. The surfaces of these **variable stars** therefore pulsate in and out, periodically rising and falling in luminosity.

15.3 STAR CLUSTERS

- **What are the two types of star clusters? Open clusters** contain up to several thousand stars and are found in the disk of the galaxy. **Globular clusters** contain hundreds of thousands of stars, all closely packed together. They are found mainly in the halo of the galaxy.

- **How do we measure the age of a star cluster?** Because all of a cluster's stars were born at the same time, we can measure a cluster's age by finding the **main-sequence turnoff** point on an H-R diagram of its stars. The cluster's age is equal to the hydrogen-burning lifetime of the hottest, most luminous stars that remain on the main sequence. We've learned that open clusters are much younger than globular clusters, which can be as old as about 13 billion years.



EXERCISES AND PROBLEMS

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REVIEW QUESTIONS

Short-Answer Questions Based on the Reading

1. Briefly explain how we can learn about the lives of stars, even though their lives are far longer than human lives.
2. In what ways are all stars similar? In what ways do they differ?
3. How is a star's *apparent brightness* related to its *luminosity?* Explain by describing the *inverse square law for light.*
4. Briefly explain how we use *stellar parallax* to determine a star's distance. Once we know a star's distance, how can we determine its luminosity?
5. What do we mean by a star's *apparent* and *absolute magnitudes?* How are they related to apparent brightness and luminosity?
6. What do we mean by a star's *spectral type?* How is a star's spectral type related to its surface temperature and color? Which stars are hottest and coolest in the spectral sequence OBAFGKM?
7. How was the spectral sequence discovered? Describe the roles of a few of the most prominent scientists in the early history of stellar astronomy.
8. What are the three basic types of *binary star systems?* Why are *eclipsing binaries* so important to measuring masses of stars?
9. Draw a sketch of a basic *Hertzsprung-Russell (H-R) diagram.* Label the *main sequence, giants, supergiants,* and *white dwarfs.* Where on this diagram do we find stars that are cool and dim? Cool and luminous? Hot and dim? Hot and luminous?
10. What do we mean by a star's *luminosity class?* What does the luminosity class tell us about the star? Briefly explain how we classify stars by spectral type and luminosity class.
11. What is the defining characteristic of a main-sequence star? Briefly explain why massive main-sequence stars are more luminous and have hotter surfaces than less massive main-sequence stars.
12. Which stars have longer lifetimes: massive stars or less massive stars? Explain why.
13. Why is a star's birth mass its most fundamental property?
14. How do giants and supergiants differ from main-sequence stars? What are white dwarfs?
15. How does the luminosity of a *pulsating variable star* change with time?
16. Describe in general terms how *open clusters* and *globular clusters* differ in their numbers of stars, ages, and locations in the galaxy.
17. Explain why H-R diagrams look different for star clusters of different ages. How does the location of the *main-sequence turnoff* point tell us the age of the star cluster?

TEST YOUR UNDERSTANDING

Does It Make Sense?

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

18. Two stars that look very different must be made of different kinds of elements.
19. Two stars that have the same apparent brightness in the sky must also have the same luminosity.
20. Sirius looks brighter than Alpha Centauri, but we know that Alpha Centauri is closer because its apparent position in the sky shifts by a larger amount as Earth orbits the Sun.
21. Stars that look red have hotter surfaces than stars that look blue.
22. Some of the stars on the main sequence of the H-R diagram are not converting hydrogen into helium.
23. The smallest, hottest stars are plotted in the lower left-hand portion of the H-R diagram.
24. Stars that begin their lives with the most mass live longer than less massive stars because they have so much more hydrogen fuel.
25. Star clusters with lots of bright, blue stars of spectral type O and B are generally younger than clusters that don't have any such stars.
26. All giants, supergiants, and white dwarfs were once main-sequence stars.
27. Most of the stars in the sky are more massive than the Sun.

Quick Quiz

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

28. If the star Alpha Centauri were moved to a distance 10 times as far from Earth as it is now, its parallax angle would (a) get larger. (b) get smaller. (c) stay the same.
29. What do we need to measure in order to determine a star's luminosity? (a) apparent brightness and mass (b) apparent brightness and temperature (c) apparent brightness and distance
30. What two pieces of information would you need in order to measure the masses of stars in an eclipsing binary system? (a) the time between eclipses and the average distance between the stars (b) the period of the binary system and its distance from the Sun (c) the velocities of the stars and the Doppler shifts of their absorption lines
31. Which of these stars has the coolest surface temperature? (a) an A star (b) an F star (c) a K star
32. Which of these stars is the most massive? (a) a main-sequence A star (b) a main-sequence G star (c) a main-sequence M star
33. Which of these stars has the longest lifetime? (a) a main-sequence A star (b) a main-sequence G star (c) a main-sequence M star
34. Which of these stars has the largest radius? (a) a supergiant A star (b) a giant K star (c) a supergiant M star
35. Which of these stars has the greatest surface temperature? (a) a $30M_{\text{Sun}}$ main-sequence star (b) a supergiant A star (c) a Cepheid variable star
36. Which of these star clusters is youngest? (a) a cluster whose brightest main-sequence stars are white (b) a cluster whose brightest stars are red (c) a cluster containing stars of all colors
37. Which of these star clusters is oldest? (a) a cluster whose brightest main-sequence stars are white (b) a cluster whose brightest main-sequence stars are yellow (c) a cluster containing stars of all colors

PROCESS OF SCIENCE

Examining How Science Works

38. *Classification.* As discussed in the text, Annie Jump Cannon and her colleagues developed our modern system of stellar classification. Why do you think rapid advances in our understanding of stars followed so quickly on the heels of their efforts? What other areas in science have had huge advances in understanding following directly from improved systems of classification?
39. *Life Spans of Stars.* Scientists estimate the life spans of stars by dividing the total amount of energy available for fusion by the rate at which they radiate energy into space. Those calculations predict that the life spans of high-mass stars are shorter than those of low-mass stars. Describe a type of observation that can test this prediction and verify that it is correct.

INVESTIGATE FURTHER

In-Depth Questions to Increase Your Understanding

Short-Answer/Essay Questions

40. *Stellar Data.* The table below gives basic data for several bright stars; M_V is absolute magnitude and m_V is apparent magnitude. Use these data to answer the following questions. Include a brief explanation with each answer. [*Hint:* Remember that the magnitude scale runs backward, so brighter stars have smaller (or more negative) magnitudes.]

Star	M_V	m_V	Spectral Type	Luminosity Class
Aldebaran	−0.2	+0.9	K5	III
Alpha Centauri A	+4.4	0.0	G2	V
Antares	−4.5	+0.9	M1	I
Canopus	−3.1	−0.7	F0	II
Fomalhaut	+2.0	+1.2	A3	V
Regulus	−0.6	+1.4	B7	V
Sirius	+1.4	−1.4	A1	V
Spica	−3.6	+0.9	B1	V

a. Which star appears brightest in our sky? b. Which star appears faintest in our sky? c. Which star has the greatest luminosity? d. Which star has the least luminosity? e. Which star has the highest surface temperature? f. Which star has the lowest surface temperature? g. Which star is most similar to the Sun? h. Which star is a red supergiant? i. Which star has the largest radius? j. Which stars have finished burning hydrogen in their cores? k. Among the main-sequence stars listed, which one is the most massive? l. Among the main-sequence stars listed, which one has the longest lifetime?

41. *Data Tables.* Study the spectral types listed in Appendix F for the 20 brightest stars and for the stars within 12 light-years of Earth. Why do you think the two lists are so different? Explain.
42. *Interpreting the H-R Diagram.* Using the information in Figure 15.10, describe how Proxima Centauri differs from Sirius.
43. *Parallax from Jupiter.* Suppose you could travel to Jupiter and observe changes in positions of nearby stars during one orbit of Jupiter around the Sun. Describe how those changes would be

different from what we measure from Earth. How would your ability to measure the distances to stars be different from the vantage point of Jupiter?

44. *An Expanding Star.* Describe what would happen to the surface temperature of a star if its radius doubled in size with no change in luminosity.
45. *Colors of Eclipsing Binaries.* Figure 15.7 shows an eclipsing binary system consisting of a small blue star and a larger red star. Explain why the decrease in apparent brightness of the combined system is greater when the blue star is eclipsed than when the red star is eclipsed.
46. *Visual and Spectroscopic Binaries.* Suppose you are observing two binary star systems at the same distance from Earth. Both are spectroscopic binaries consisting of similar types of stars, but only one of these binary systems is a visual binary. Which of these star systems would you expect to have the greater Doppler shifts in its spectra? Explain your reasoning.
47. *Life of a Star Cluster.* Imagine you could watch a star cluster from the time of its birth to an age of 13 billion years. Describe in one or two paragraphs what you would see happening during that time.

Quantitative Problems

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

48. *The Inverse Square Law for Light.* Earth is about 150 million kilometers from the Sun, and the apparent brightness of the Sun in our sky is about 1300 watts/m^2. Using these two facts and the inverse square law for light, determine the apparent brightness that we would measure for the Sun *if* we were located at the following positions.
    a. Half Earth's distance from the Sun b. Twice Earth's distance from the Sun c. Five times Earth's distance from the Sun
49. *The Luminosity of Alpha Centauri A.* Alpha Centauri A lies at a distance of 4.4 light-years and has an apparent brightness in our night sky of 2.7×10^{-8} watt/m^2. Recall that 1 light-year = 9.5×10^{12} km = 9.5×10^{15} m.
    a. Use the inverse square law for light to calculate the luminosity of Alpha Centauri A. b. Suppose you have a light bulb that emits 100 watts of visible light. (*Note:* This is *not* the case for a standard 100-watt light bulb, in which most of the 100 watts goes to heat and only about 10–15 watts is emitted as visible light.) How far away would you have to put the light bulb for it to have the same apparent brightness as Alpha Centauri A in our sky? (*Hint:* Use 100 watts as L in the inverse square law for light, and use the apparent brightness given above for Alpha Centauri A. Then solve for the distance.)
50. *More Practice with the Inverse Square Law for Light.* Use the inverse square law for light to answer each of the following questions.
    a. Suppose a star has the same luminosity as our Sun (3.8×10^{26} watts) but is located at a distance of 10 light-years. What is its apparent brightness? b. Suppose a star has the same apparent brightness as Alpha Centauri A (2.7×10^{-8} watt/m^2) but is located at a distance of 200 light-years. What is its luminosity? c. Suppose a star has a luminosity of 8×10^{26} watts and an apparent brightness of 3.5×10^{-12} watt/m^2. How far away is it? Give your answer in both kilometers and light-years. d. Suppose a star has a luminosity of 5×10^{29} watts and an apparent brightness of 9×10^{15} watts/m^2. How far away is it? Give your answer in both kilometers and light-years.
51. *Parallax and Distance.* Use the parallax formula to calculate the distance to each of the following stars. Give your answers in both parsecs and light-years.
    a. Alpha Centauri: parallax angle of 0.7420" b. Procyon: parallax angle of 0.2860"
52. *The Magnitude System.* Use the definitions of the magnitude system to answer each of the following questions.
    a. Which is brighter in our sky, a star with apparent magnitude 2 or a star with apparent magnitude 7? By how much? b. Which has a greater luminosity, a star with absolute magnitude −4 or a star with absolute magnitude +6? By how much?
53. *Measuring Stellar Mass.* The spectral lines of two stars in a particular eclipsing binary system shift back and forth with a period of 6 months. The lines of both stars shift by equal amounts, and the amount of the Doppler shift indicates that each star has an orbital speed of 80,000 m/s. What are the masses of the two stars? Assume that each of the two stars traces a circular orbit around their center of mass. (*Hint:* See Mathematical Insight 15.4.)
54. *Calculating Stellar Radii.* Sirius A has a luminosity of $26L_{\text{Sun}}$ and a surface temperature of about 9400 K. What is its radius? (*Hint:* See Mathematical Insight 15.5.)
55. *Lifetime as a Red Giant.* The H-R diagram in Figure 15.20 shows a star cluster with a large number of red giants in it.
    a. What is the approximate mass of the most massive stars left on the main sequence of this star cluster? b. What is the luminosity of the most luminous stars in the cluster? c. Compute the ratio of the luminosity from part (b) to the mass from part (a). How does that ratio compare with the Sun's ratio of luminosity to mass? d. Estimate the maximum amount of time these very luminous stars can last as red giants from your answer to part (c).

Discussion Question

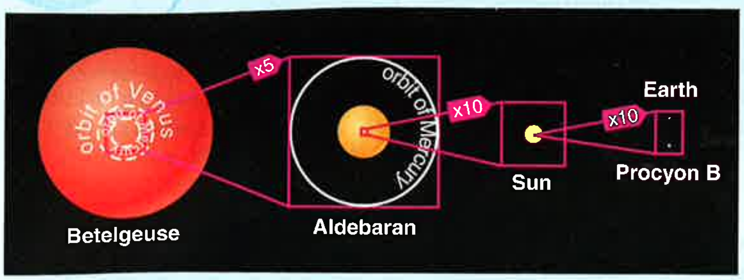
56. *Snapshot of the Heavens.* The beginning of the chapter likened the problem of studying the lives of stars to learning about human beings through a 1-minute glance at human life. What could you learn about human life by looking a single snapshot of a large, extended family, including babies, parents, and grandparents? How is the study of such a snapshot similar to what scientists do when they study the lives of stars? How is it different?

Web Projects

57. *Women in Astronomy.* Until fairly recently, men greatly outnumbered women in professional astronomy. Nevertheless, many women made crucial discoveries in astronomy throughout history—including discovering the spectral sequence for stars. Do some research on the life and discoveries of a female astronomer from any time period and write a two- to three-page scientific biography.
58. *The* Hipparcos *Mission.* The European Space Agency's *Hipparcos* mission, which operated from 1989 to 1993, made precise parallax measurements of more than 40,000 stars. Learn about how *Hipparcos* allowed astronomers to measure smaller parallax angles than they could from the ground and how *Hipparcos* discoveries have affected our knowledge of the universe. Write a one- to two-page report on your findings.
59. *The* GAIA *Mission.* The European Space Agency's *GAIA* mission, slated for launch in 2011, should make even better parallax measurements than *Hipparcos*. Research the *GAIA* mission and what scientists hope to learn from it. Write a one- to two-page report on your findings.

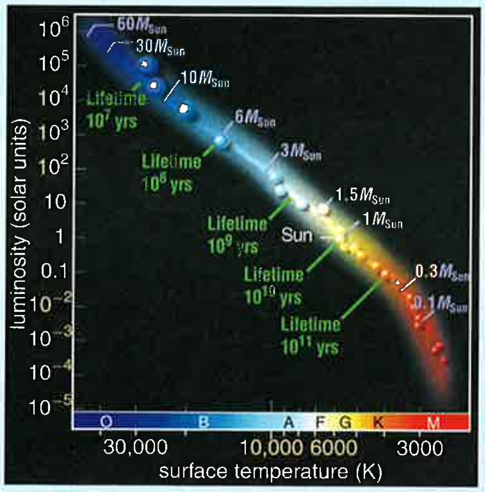
VISUAL SKILLS CHECK

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 15 Visual Quiz at www.masteringastronomy.com.



The figure above, similar to Figure 15.13, uses zoom-ins to compare the sizes of giant and supergiant stars to the sizes of Earth and the Sun.

1. Suppose we wanted to represent all of these objects using the 1-to-10-billion scale from Chapter 1, on which the Sun is about the size of a grapefruit. Approximately how large in diameter would the star Aldebaran be on this scale?
   a. 40 centimeters (the size of a typical beach ball)
   b. 4 meters (roughly the size of a dorm room)
   c. 15 meters (roughly the size of a typical house)
   d. 70 meters (slightly smaller than a football field)
2. Approximately how large in diameter would the star Betelgeuse be on this same scale?
   a. 40 centimeters (the size of a typical beach ball)
   b. 4 meters (roughly the size of a dorm room)
   c. 70 meters (slightly smaller than a football field)
   d. 3 kilometers (the size of a small town)
3. Approximately how large in diameter would the star Procyon B be on this same scale?
   a. 10 centimeters (the size of a large grapefruit)
   b. 1 centimeter (the size of a grape)
   c. 1 millimeter (the size of a grape seed)
   d. 0.1 millimeter (roughly the width of a human hair)



The H-R diagram above is identical to Figure 15.11. Answer the following questions based on the information given in the figure.

4. What are the approximate luminosity and lifetime of a star whose mass is 10 times that of the Sun?
5. What are the approximate luminosity and lifetime of a star whose mass is 3 times that of the Sun?
6. What are the approximate luminosity and lifetime of a star whose mass is twice that of the Sun?