Part V: Stellar Alchemy

Chapter 15. Our Star

This chapter on the Sun describes how the Sun works, laying the groundwork for the study of stars in general by focusing on this all-important example.

As always, when you prepare to teach this chapter, be sure you are familiar with the relevant media resources (see the complete, section-by-section resource grid in Appendix 3 of this Instructor's Guide) and the on-line quizzes and other study resources available on the Astronomy Place website.

What's New in the Third Edition That Will Affect My Lecture Notes?

As everywhere in the book, we have edited to improve the text flow, improved art pieces, and added new illustrations. In addition, those who have taught from previous editions of *The Cosmic Perspective* should be aware of the following organizational or pedagogical changes to this chapter (i.e., changes that will influence the way you teach) in the third edition:

- We have expanded our discussion of the solar thermostat to place more emphasis on the need for power generated in the solar core to match the power diffusing through the Sun and escaping from its surface. Figure 15.8, new in this edition, summarizes the processes that regulate the Sun's core temperature.
- Figure 15.10 is a new figure that shows how models of the solar interior compare with the interior temperatures and densities inferred from sun quakes.
- The discussion of the solar neutrino problem has been updated to include new results from the Sudbury Neutrino Observatory and the Nobel Prizes awarded for solar neutrino research in 2002.
- We have eliminated the jargon *differential rotation* in favor of a more descriptive approach to solar rotation.

Teaching Notes (By Section)

Section 15.1 Why Does the Sun Shine?

To begin, we address one of the most basic of all astronomical questions: Why does the Sun shine? This question immediately engages students because it relates directly to their personal experience of the Sun and perhaps even to questions they began asking as children. They are often surprised to find out how recently we learned the answer, and the process of elimination that led to the right answer provides a good example of scientific reasoning.

- Relating the history of ideas about how the Sun shines provides an early opportunity to discuss gravitational contraction, a mechanism that will arise repeatedly throughout the rest of the book. Introducing this idea early allows students to digest it somewhat before they encounter it again in star formation and stellar evolution.
- This section also introduces the very important idea of the balance between pressure and gravity within a star. Among astronomers this kind of equilibrium is known as *hydrostatic equilibrium.* We have found that the word "hydrostatic" is so foreign to students that they often have trouble remembering what it describes. Thus, we have elected to use the term *gravitational equilibrium* in this book so that the link between the term and the concept is easier for students to remember. Note that this term allows the following very simple contrast: Gravitational contraction occurs when gravity overwhelms pressure, and gravitational

equilibrium occurs when gravity is in balance with pressure. (In using the term *gravitational equilibrium,* we are following the lead of Mitch Begelman and Martin Rees in their book *Gravity's Fatal Attraction,* Scientific American Library, 1996.)

Section 15.2 Plunging to the Center of the Sun: An Imaginary Journey

This section introduces students to the properties and structure of the Sun. In an effort to paint a more vivid and memorable picture of the Sun, we have presented the relevant facts in the context of an imaginary journey to the solar core. We also provide a summary table of solar properties so that students don't have to extract all these numbers from the narrative.

- Here we encounter a potential dilemma for instructors: whether to describe the Sun as yellow or white. Because students already *know* that the Sun is yellow, they can have trouble with the idea that the Sun would look nearly white if they were not seeing it through the Earth's atmosphere. However, when astronomers speak of "white stars," they are usually talking about stars considerably hotter than the Sun. For this reason, we depict the Sun as yellow in our figures. (One way to demonstrate that the Sun is whiter than it appears is to point out that clouds look white because they are scattering both the blue light from the sky, which is indirect solar radiation, and the direct yellow light from the Sun. Combining these two colors of light more closely approximates the original color of the Sun.)

Section 15.3 The Cosmic Crucible

This section focuses on the process of nuclear fusion in the Sun and describes how the balance between gravity and pressure acts as a thermostat in the solar core, maintaining a constant fusion rate.

- The topic of fusion in the solar core presents an opportunity to discuss the role of mathematical modeling in science and to explain how we can be so certain of what's going on when we can't see the core and can't send in a probe to observe what's going on there.
- In this section we also discuss solar neutrinos as a way to "observe" the solar core, and we present the solar neutrino problem as a nearly solved problem in our understanding of the Sun.
- Based on recent experimental results confirming the fact that neutrinos oscillate, we have stated that neutrinos *do* have mass (e.g., Fukuda et al. 1998, *Physical Review Letters,* 81, 1562), though the amount of mass remains unknown. Again, be sure to stay current in class with the latest results on neutrino mass.

Section 15.4 From Core to Corona

This section describes how energy propagates outward through the Sun, providing details on each layer of the Sun, core through corona, that the energy passes through on its way out.

- This section's discussion of magnetic fields and magnetic field lines is the most detailed treatment of this subject in the book. You may want to refer students back to it when they encounter magnetic fields in later chapters.

Section 15.5 Solar Weather and Climate

This section discusses solar activity, including sunspots, and the ways in which solar activity can affect the Earth.

- Solar activity is one of the most direct ways in which cosmic events affect human activity. Don't miss this opportunity to engage your more practically minded students with some examples of how solar weather affects the Earth.

Answers/Discussion Points for Think About It Questions

The Think About It questions are not numbered in the book, so we list them in the order in which they appear, keyed by section number.

Section 15.1

- At higher altitudes there is less overlying air pressing down. Because of the lower pressure, the atmosphere is less compressed.

Section 15.2

- We measure the mass of the Sun by measuring the periods and semimajor axes of planetary orbits and then plugging these measurements into Newton's version of Kepler's third law. Because the Sun is so much heavier than anything else in the solar system, the sum of the masses in the equation is essentially equal to the Sun's mass.

Section 15.3

- The number of neutrinos passing through our bodies is not significantly lower at night because the Earth is transparent to neutrinos.
- Proton–proton fusion produces the solar neutrinos, which escape freely. Thus, we detect solar neutrinos about 8 minutes after they are created. The fact that we detect solar neutrinos tells us that fusion is currently operating. Note that, in contrast, the photons we see from the Sun originate from energy released many thousands of years ago in the solar core.

Section 15.4

- Students should be able to come up with numerous examples of diffusion after a little thought. Two especially appealing examples are cream in coffee and the scent from a baking pie.

Solutions to End-of-Chapter Problems (Chapter 15)

1. Before Einstein, gravitational contraction appeared to be a perfectly plausible mechanism for solar energy generation. *This statement is not sensible. Gravitational contraction has been known to be an insufficient source of stellar power since the 1800s, when geologists realized that the age of rocks on the Earth numbered in the billions of years. Gravitational contraction of the Sun, if the only source of the Sun's energy, would have powered the Sun only for some 25 million years, a time much less than the geological age.*
2. A sudden temperature rise in the Sun's core is nothing to worry about, because conditions in the core will soon return to normal. *This statement is sensible. The Sun's core acts as a thermostat, and thus if the inner core temperature increases, the reaction rate increases too, but the extra energy expands the core and cools it, thus reducing the nuclear reaction rates.*
3. If fusion in the solar core ceased today, worldwide panic would break out tomorrow as the Sun began to grow dimmer. *This statement is not sensible. If fusion in the core ceased, the photons would continue to percolate out of the Sun at about the same rate for many thousands of years. No dimming would be possible to measure the day after such an event. It is a debatable point as to when such an event might be noticed—certainly neutrino fluxes would drop noticeably, and eventually the structure of the Sun would be affected.*
4. Astronomers have recently photographed magnetic fields churning deep beneath the solar photosphere. *This statement is not sensible. The photosphere is as far in toward the Sun as we can "see" in photographs. Conditions beneath the photosphere must be inferred from other types of observations and theoretical models.*

5. Neutrinos probably can't harm me, but just to be safe I think I'll wear a lead vest. *This statement is not sensible. Neutrinos pass right through the Earth and would not be diminished at all by a lead vest.*

6. If you want to see lots of sunspots, just wait for solar maximum! *This statement is sensible. An enhancement in solar activity and sunspots defines what we mean by solar maximum.*

7. News of a major solar flare today caused concern among professionals in the fields of communications and electrical power generation. *This statement is sensible. Solar flares can cause havoc with satellites, communications, and power grids because of the energetic charged particles.*

8. By observing solar neutrinos, we can learn about nuclear fusion deep in the Sun's core. *This statement is sensible. Neutrinos are produced by fusion in the Sun's core and can travel directly from the Sun's core to neutrino detectors on Earth.*

9–18. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

19. We know the mass loss and the amount of mass converted into energy with each fusion reaction in the Sun, so we can compute the number of fusion reactions (proton–proton reactions) that occur each second:

$$\text{Number of fusion reactions / second} = \frac{\text{Mass loss / second}}{\text{Mass converted / reaction}} = \frac{\text{reactions}}{\text{second}}$$

$$= \frac{4.2\times10^{9}\ \text{kg / s}}{4.7\times10^{-29}\ \text{kg / reaction}} = 8.9\times10^{37}\ \text{reactions / s}$$

20. a. The total amount of mass in the Sun is 2.0×10^{30} kg, 75% of which is hydrogen and 13% of which becomes available for fusion. Thus, the total mass of hydrogen available for fusion over the Sun's lifetime is simply 13% of 75% of the total mass of the Sun or:

$$2.0\times10^{30}\ \text{kg}\times0.75\times0.13 = 1.95\times10^{29}\ \text{kg}$$

b. The Sun fuses 6×10^{11} kg per second and has 2×10^{29} kg available for fusion, so the Sun's lifetime is:

$$\text{lifetime} = \frac{\text{mass available}}{\text{rate mass burned}} = \frac{1.95\times10^{29}\ \text{kg}}{6\times10^{11}\ \text{kg / s}} = 3.25\times10^{17}\ \text{s}$$

or

$$3.25\times10^{17}\ \text{s}\times\frac{1\ \text{hr}}{3600\ \text{s}}\times\frac{1\ \text{day}}{24\ \text{hr}}\times\frac{1\ \text{yr}}{365\ \text{day}} = 10.3\ \text{billion years}$$

c. Subtracting the current age of the Sun from the lifetime found in part (b), we find:

10.3 billion yr – 4.6 billion yr = 5.7 billion yr

The Sun will run out of fuel in approximately 6 billion years.

21. a. The surface area of a sphere 1 AU ($=1.5 \times 10^{11}$ m) in radius is:

$$4\pi r^2 = 4\pi(1.5\times10^{11}\ \text{m})^2 = 2.83\times10^{23}\ \text{m}^2$$

b. The flux of solar radiation at the surface of this imaginary sphere is the luminosity of the Sun divided by the surface area of the sphere:

$$\frac{3.8\times10^{26}\text{ watts}}{2.83\times10^{23}\text{ m}^2}=1344\text{ watts per square meter}$$

c. The average power per square meter collected by a solar collector on the ground will always be less because of absorption by the atmosphere, the angle of incidence not being 90°, the weather (cloud cover), nighttime, and varying amounts of daylight.

d. To optimize the amount of power collected, a solar collector should be aimed up and south in the Northern Hemisphere, and up and north in the Southern Hemisphere (and up toward the celestial equator). To achieve even more optimization, one might rotate the face of the collectors east-to-west to follow the Sun's daily path across the sky, and north-to-south to match the Sun's changing path with the seasons.

22. a. The power requirement in watts (or joules/second) in the United States is:

$$\frac{2\times10^{20}\text{ joules / yr}}{3.1\times10^{7}\text{ s / yr}}=6.45\times10^{12}\text{ watts}$$

b. If we can achieve a power conversion efficiency for 200 watts per square meter, we require:

$$\frac{6.45\times10^{12}\text{ watts}}{200\text{ watts / m}^2}=3.22\times10^{10}\text{ m}^2\times\underbrace{\left(\frac{1\text{ km}}{1000\text{ m}}\right)^2}_{\text{convert to km}^2}=3.22\times10^{4}\text{ km}^2$$

of solar detector area to supply the entire United States.

c. The total surface area of the United States is 2×10^7 km^2, so this enterprise requires

$$\frac{3.22\times10^{4}\text{ km}^2}{2\times10^{7}\text{ km}^2}=0.0016,\text{ or }0.16\%$$

of the surface area of the United States. The solar collectors would probably be optimally placed in the sunnier, emptier parts of the country, where there aren't many cloudy days and the land is cheap and relatively unoccupied. The energy generated is renewable, so if the technology required to produce the solar cells, service the arrays, and distribute the power were also eco-friendly, this would be a reasonable way to supply power from an ecological standpoint. However, alternative power may be expensive to implement and might be opposed by some political constituencies. (For example, there will always be constituencies that would be less than thrilled to see this land paved over like a gigantic parking lot in Nevada.)

23. Wien's law states:

$$\lambda_{\text{max}}=\frac{2{,}900{,}000}{T(\text{Kelvin})}\text{ nm}$$

Plugging in the average temperature of the Sun's photosphere, 5800 K, gives:

$$\lambda_{\text{max}}=\frac{2{,}900{,}000}{5800}\text{ nm}=500\text{ nm}$$

Thus, the Sun's thermal spectrum peaks at a wavelength of 500 nm, which is in the green part of the visible spectrum. However, because the Sun also radiates other colors of the visible spectrum and the atmosphere scatters the bluer light, it appears white or yellow to our eyes.

Chapter 16. Properties of Stars

This chapter outlines how we measure and classify stars. It introduces many important ideas, such as the relationship between luminosity, brightness, and distance, that will be used later in the book, so you should allot enough time to cover them. If you are choosing to include Mathematical Insights in your course, this chapter will be one of the most mathematical and may require additional time. Whenever possible, we have used real stellar data from Hipparcos and other sources to construct the H–R diagrams in Chapters 16 and 17.

As always, when you prepare to teach this chapter, be sure you are familiar with the relevant media resources (see the complete, section-by-section resource grid in Appendix 3 of this Instructor's Guide) and the on-line quizzes and other study resources available on the Astronomy Place website.

What's New in the Third Edition That Will Affect My Lecture Notes?

As everywhere in the book, we have edited to improve the text flow, improved art pieces, and added new illustrations. In addition, those who have taught from previous editions of *The Cosmic Perspective* should be aware of the following organizational or pedagogical changes to this chapter (i.e., changes that will influence the way you teach) in the third edition:

- A new figure (Figure 16.1) illustrates the difference between luminosity and apparent brightness.
- We have removed the equation showing Newton's version of Kepler's third law from the text flow in order to make the text less threatening to students who fear math. Mathematical Insight 16.4 still shows how to use this law to measure masses for students who can handle the math.

Teaching Notes (By Section)

Section 16.1 Snapshot of the Heavens

Most students have no idea how slowly cosmic events unfold compared to a human lifetime and are often amazed to learn how slowly stars evolve. This section likens our observations of the stars to an instantaneous snapshot of their lives and explains that we must infer how stars age by looking at large numbers of stars of all different ages.

Section 16.2 Stellar Luminosity

This section explains how we determine the luminosities of stars by measuring their brightness and distance.

- We avoid using the term *flux* in this book because it's an unfamiliar word that students do not find particularly descriptive. Instead we use the term *apparent brightness*, which refers explicitly to the concept of brightness.
- Likewise, we avoid the term *bolometric luminosity*, using *total luminosity* instead.
- This section also defines the important units of *solar luminosities* and *parsecs*.
- We introduce the magnitude system in this section, but we have chosen to downplay it. We find that magnitudes require great effort for students to master yet add little to students' understanding of other astronomical concepts. Very gradually, astronomers themselves are moving away from the magnitude system as astronomy grows to include more regions of the electromagnetic spectrum for which there are no standard filter sets. Magnitudes are included here largely because of their historical importance and because they are often indicated on star

charts and some astronomical tables. You can skip them if you choose, because we do not use magnitudes elsewhere in the book.

Section 16.3 Stellar Surface Temperatures

This section covers stellar surface temperatures and how they relate to spectral types of stars.

- This section presumes that students understand the material in Chapter 6 on color, temperature, and spectral lines. You may want to remind your students to consult Chapter 6 as they are reading this section.
- If you are inclined to highlight the contributions of women to astronomy, this is an excellent place to do so, because so many women contributed fundamentally to the science of stellar classification. The section provides some brief biographical notes on Williamina Fleming, Annie Jump Cannon, and Cecilia Payne-Gaposchkin that you might want to supplement.
- For simplicity, we limit the discussion of stellar classes to OBAFGKM, which covers the standard main sequence, omitting special cases like R, N, and S stars and Wolf–Rayet stars. Our intention is to make sure students clearly understand the main sequence, the bedrock of stellar studies, before branching off into more specialized topics.

Section 16.4 Stellar Masses

This section explains how we measure the masses of stars in binary systems.

- We refer to the fundamental law for measuring stellar masses as "Newton's version of Kepler's third law" in order to give proper credit to both individuals.
- This section mentions several different types of binary systems but does not provide an exhaustive nomenclature. We describe astrometric binaries without using the formal term, because the word *astrometric* is uninformative to students. Visual, spectroscopic, and eclipsing binaries are mentioned explicitly, because these terms are usefully descriptive.

Section 16.5 The Hertzsprung-Russell Diagram

The previous three sections have laid the groundwork for this section on the H–R diagram. While students can understand the observational H–R diagram before covering stellar masses, we find it prudent to discuss the H–R diagram after covering masses, because we can immediately point out that the main sequence is fundamentally a sequence of stellar masses. This approach helps counteract the tendency of students to think of the main sequence as a temporal evolution of stellar properties.

- In small class sections, it can be illustrative to have students plot stellar temperatures and luminosities on their own before you cover the H–R diagram, enabling them to discover the main sequence for themselves.
- Appendix F lists the 20 brightest stars as well as the stars within 12 light-years. One way to get students to think more deeply about the H–R diagram is to ask them why the spectral types of the stars in the two tables are so different.
- This section includes a discussion of main-sequence lifetimes showing how some simple order-of-magnitude estimates can reveal the vast differences between stellar lifetimes.
- Because this text focuses on the "big picture" of astronomy, we limit the coverage of variable stars to Cepheid variables, which will resurface in the chapters on galaxies.

Section 16.6 Star Clusters

The chapter concludes with this section on star clusters, emphasizing that they are excellent laboratories for comparing the properties of stars and establishing how stars evolve.

- This chapter emphasizes that a star's color depends primarily on its mass and age but does not mention that a star's heavy-element content also affects its color. Heavy elements tend to absorb blue light preferentially, hindering the flow of energy in the outer layers of a star and making it redder than it would be without these heavy elements. We find that downplaying this fact does not hinder students' comprehension of the "big picture," but it does complicate the issue of the main-sequence turnoff. Because globular clusters are poor in heavy elements, their main sequences are displaced to the left in the H–R diagram. Their turnoff points thus lie blueward of the Sun but at lower luminosities. We allude to this effect in our figure caption.

Answers/Discussion Points for Think About It Questions

The Think About It questions are not numbered in the book, so we list them in the order in which they appear, keyed by section number.

Section 16.3

- Inventing an original OBAFGKM mnemonic is a fun way for students to burn this sequence into their memory.

Section 16.4

- Stars orbiting perpendicular to our line of sight have zero radial velocity, and thus their spectral lines do not periodically shift.

Section 16.5

- The colors of the stars are similar to the star colors determined by blackbody radiation at the given surface temperature. The colors of stars are not necessarily related to their core temperatures. For example, a red supergiant and a red main-sequence star have very different core temperatures.
- Because O stars live only a few million years, life would have very little time to evolve on an orbiting planet.

Section 16.6

- The main-sequence turnoff point in a 10-billion-year-old star cluster should be around $1L_{Sun}$, because the Sun itself leaves the main sequence at an age of around 10 billion years. The turnoff should therefore be around spectral type G (in a cluster with solar proportions of heavy elements). All of the original M stars should still remain, but none of the original F stars. (Beyond the scope of the book: A few stars called *blue stragglers*, which are bluer than the stars at the turnoff point, can be found in old clusters. These stars probably resulted from relatively recent mergers of two smaller stars to form a single, more massive star.)

Solutions to End-of-Chapter Problems (Chapter 16)

1. Two stars that look very different must be made of different kinds of elements. *This statement is not sensible because most stars have very similar proportions of elements. Differences among the appearances of stars arise primarily because of differences in age and mass, not elemental contents.*
2. Sirius is the brightest star in the night sky, but if we moved it 10 times farther away it would look only one-tenth as bright. *This statement is not sensible. If we moved Sirius 10 times farther away, it would be 10^2 or 100 times fainter.*
3. 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. *This statement is sensible. The parallax for Alpha Centauri is larger than that for Sirius because Alpha Centauri is closer to us.*
4. Stars that look red-hot have hotter surfaces than stars that look blue. *This statement is not sensible. Blue stars are hotter than red stars.*

5. Some of the stars on the main sequence of the H–R diagram are not converting hydrogen into helium. *This statement is not sensible. All main-sequence stars are converting hydrogen to helium.*
6. The smallest, hottest stars are plotted in the lower left-hand portion of the H–R diagram. *This statement is sensible. Temperature on the H–R diagram increases from right to left, and stellar radius on the same diagram increases diagonally from lower left to upper right. So the smallest, hottest stars are in the lower left-hand corner of the H–R diagram.*
7. Stars that begin their lives with the most mass live longer than less massive stars because it takes them a lot longer to use up their hydrogen fuel. *This statement is not sensible. The most massive stars burn their fuel a lot faster than the conservative, low-mass stars. They burn fuel at a profligate rate that negates their size/mass advantage.*
8. Star clusters with lots of bright, blue stars are generally younger than clusters that don't have any such stars. *This statement is sensible. Clusters with no blue stars probably had some blue stars in the past, but as the clusters aged the blue stars rapidly died off.*
9. All giants, supergiants, and white dwarfs were once main-sequence stars. *This statement is sensible. Giants, supergiants, and white dwarfs are later stages in the evolution of stars that began life as main-sequence stars.*
10. Most of the stars in the sky are more massive than the Sun. *This statement is not sensible. Most of the stars are less massive than the Sun. Many more low-mass stars are formed than are high-mass stars. The high-mass stars burn out sooner, too, while the low mass stars persist for billions of years.*

11–20. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

21.
  a. Sirius appears brightest in our sky because it has the smallest (most negative) apparent magnitude.
  b. Regulus appears faintest of the stars on the list because it has the largest apparent magnitude.
  c. Antares has the greatest luminosity of the stars on the list because it has the smallest (most negative) absolute magnitude.
  d. Alpha Centauri A has the smallest luminosity of the stars on the list because it has the largest absolute magnitude.
  e. Sirius has the highest surface temperature of the stars on the list because its spectral type, B1, is hotter than any other spectral type on the list.
  f. Antares has the lowest surface temperature of the stars on the list because its spectral type, M1, is cooler than any other spectral type on the list.
  g. Alpha Centauri A is most similar to the Sun because it has the same spectral type and luminosity class, G2 V.
  h. Antares is a red supergiant; its spectral type M means it is red, and its luminosity class I indicates a supergiant.
  i. Antares has the largest radius because it is the only supergiant on the list.
  j. Aldebaran, Antares, and Canopus have luminosity classes other than V, which means that they have left the main sequence and are no longer burning hydrogen in their cores.
  k. Spica is the most massive of the main-sequence stars listed because it has the hottest spectral type of the main-sequence stars; thus, it appears higher on the main sequence on an H–R diagram, where masses are larger.

l. Alpha Centauri A, with spectral type G2, is the coolest and therefore the longest-lived main-sequence star in the table.

22. The list of the brightest stars will include the very luminous hot stars from distances greater than 12 light-years, while the list of the fainter yet closer low-mass stars will not. The list of stars within 12 light-years is "volume-limited," which means that nearly all of the stars within that distance are listed regardless of luminosity. Such a list is more representative of the total population of stars and is more likely to be dominated by low-mass stars. The list of brightest stars contains only those stars that are above a certain apparent brightness threshold. Therefore, the faintest nearby stars are left out, but the brightest and rarer hot stars are included in higher proportion than they are in a volume-limited list.

23. We don't need the value of the AU to do this problem, since the apparent brightness (flux) of the Sun scales with the distance.

Distance from Sun (d_{new})	$\frac{d_{new}}{1\text{ AU}}$	$\frac{1}{(d_{new}/1\text{ AU})^2}$	New Apparent Brightness (watts/m^2)
a. 1/2 AU	1/2	4	$4 \times 1{,}300 = 5{,}200$
b. 2 AU	2	1/4	$0.25 \times 1{,}300 = 325$
c. 5 AU	5	1/25	$0.04 \times 1{,}300 = 52$

24. a. We rearrange the luminosity–distance formula to solve for the luminosity:

$$\text{apparent brightness} = \frac{L}{4\pi \times d^2} \quad \Rightarrow \quad L = (\text{apparent brightness}) \times 4\pi \times d^2$$

Now we need to convert the values for distance and apparent brightness into standard units. A light-year is about 9.5 trillion km, or 9.5×10^{15} m, so Alpha Centauri's distance of 4.4 light-years = 4.2×10^{16} m. Combining this with its apparent brightness in our night sky of 2.7×10^{-8} watt/m^2, we find:

$$L = \left(2.7 \times 10^{-8}\ \frac{\text{watt}}{\text{m}^2}\right) \times 4\pi \times \left(4.2 \times 10^{16}\ \text{m}\right)^2 = 6.0 \times 10^{26}\ \text{watts}$$

Note that the luminosity of Alpha Centauri A, about 6.0×10^{26} watts, is similar to that of our Sun.

b. In this problem we must solve for the distance of a light bulb with a luminosity of 100 watts and an apparent brightness of 2.7×10^{-8} watt. First, we solve the formula for the distance.

Starting formula:

$$\text{apparent brightness} = \frac{\text{luminosity}}{4\pi \times (\text{distance})^2}$$

Multiply both sides by distance^2 and divide by (apparent brightness):

$$(\text{distance})^2 = \frac{\text{luminosity}}{4\pi \times (\text{apparent brightness})}$$

Square root of both sides:

$$\text{distance} = \sqrt{\frac{\text{luminosity}}{4\pi \times (\text{apparent brightness})}}$$

Now we plug in the numbers to find the distance of the light bulb:

$$\text{distance} = \sqrt{\frac{100 \text{ watts}}{4\pi \times 2.7 \times 10^{-8} \text{ watts / m}^2}} = \sqrt{2.9 \times 10^8 \text{ m}^2} = 1.7 \times 10^4 \text{ m}$$

The light bulb must be located at a distance of 17,000 meters, or 17 kilometers, to have the same apparent brightness as Alpha Centauri A.

25. a. A star with the same luminosity as our Sun but at a distance of 10 light-years would have an apparent brightness of:

$$\frac{L}{4\pi r^2} = \frac{3.8 \times 10^{26} \text{ watts}}{4\pi \left[10 \text{ ly} \times \left(9.5 \times 10^{15} \frac{\text{m}}{\text{ly}}\right)\right]^2} = 3.35 \times 10^{-9} \frac{\text{watts}}{\text{m}^2}$$

b. A star with the same apparent brightness as Alpha Centauri (see problem 14), but located at a distance of 200 light-years, has an intrinsic luminosity of:

$$L = 4\pi \times \left(200 \text{ ly} \times 9.5 \times 10^{15} \frac{\text{m}}{\text{ly}}\right)^2 \times \left(2.7 \times 10^{-8} \frac{\text{watt}}{\text{m}^2}\right) = 1.2 \times 10^{30} \text{ watts}$$

or 3,200 solar luminosities.

c. If a star has a luminosity of 8×10^{26} watts and an apparent brightness of 3.5×10^{-12} watt/m^2, its distance is (using F for apparent brightness):

$$d = \sqrt{\frac{L}{4\pi F}} = \sqrt{\frac{8 \times 10^{26} \text{ watts}}{4\pi \left(3.5 \times 10^{-12} \frac{\text{watt}}{\text{m}^2}\right)}} = 4.3 \times 10^{18} \text{ m} = 4.3 \times 10^{15} \text{ km} = 450 \text{ light years}$$

d. If a star has a luminosity of 5×10^{29} watts and an apparent brightness of 9×10^{-15} watt/m^2, its distance is (using F for apparent brightness):

$$d = \sqrt{\frac{L}{4\pi F}} = \sqrt{\frac{5 \times 10^{29} \text{ watts}}{4\pi \left(9 \times 10^{-15} \frac{\text{watt}}{\text{m}^2}\right)}} = 2.1 \times 10^{21} \text{ m} = 2.1 \times 10^{18} \text{ km} = 220{,}000 \text{ light years}$$

Note that this star lies outside the Milky Way Galaxy.

26. a. Alpha Centauri: parallax angle of 0.742″. Using the parallax formula, we find that the distance to Alpha Centauri is:

$$d = \frac{1}{0.742''} = 1.35 \text{ pc} = 4.39 \text{ light years}$$

Because 1 parsec is 3.26 light-years, this is the same as 4.39 light-years.

b. Procyon: parallax angle of 0.286″. Using the parallax formula, we find that the distance to Procyon is:

$$d = \frac{1}{0.286''} = 3.5 \text{ pc} = 11.4 \text{ light years}$$

Because 1 parsec is 3.26 light-years, this is the same as 11.4 light-years.

27. a. A star with apparent magnitude 2 is 100 times brighter than a star with apparent magnitude 7. (5 magnitudes indicates a factor-of-100 difference; larger apparent magnitude stars are always fainter.)

b. A star with absolute magnitude –6 is intrinsically more luminous than a star of magnitude +4. The difference is 10 magnitudes, so the difference in luminosity is a factor of 100 for the first 5 magnitudes and a factor of 100 for the second 5 magnitudes, making an overall difference of a factor of $100^2 = 10{,}000$.

28. Each of the stars in the binary completes an orbit once every 6 months (or 0.5 year), at a velocity of 80,000 m/s. The circumference of that orbit is thus the time it takes to complete an orbit multiplied by the speed at which the stars move through the orbit, or:

$$\text{orbital distance} = \text{velocity} \times \text{time} = 80{,}000\,\frac{\text{m}}{\text{s}} \times 0.5\ \text{yr} \times 3.1 \times 10^7\ \frac{\text{s}}{\text{yr}} = 1.26 \times 10^{12}\,\text{m}$$

The average distance a of that orbit is thus:

$$r = \frac{\text{circumference}}{2\pi} = \frac{1.26 \times 10^{12}\,\text{m}}{2\pi} = 2.01 \times 10^{11}\,\text{m} = 1.3\ \text{AU}$$

We can now plug the period ($p = 0.5$ year) and average distance ($a = 1.3$ AU) into the formula for Kepler's third law, normalized to solar values, to get the M_1+M_2 value in solar masses:

$$M_1 + M_2 = \frac{a^3}{p^2} = \frac{(1.3)^3}{(0.5)^2} = 8.8\ \text{solar masses}$$

Because the stars have equivalent orbits, they must have equal masses, so each one has a mass of $4.4M_{\text{Sun}}$.

29. Sirius has a luminosity of $26L_{\text{Sun}}$ and a surface temperature of 9,400 K, so its radius is:

$$r = \sqrt{\frac{L}{4\pi\sigma T^4}} = \sqrt{\frac{26 \times 3.8 \times 10^{26}\ \text{watts}}{4\pi \times \left(5.7 \times 10^{-8}\ \frac{\text{watt}}{\text{m}^2\text{K}^4}\right) \times \left(9400\ \text{K}\right)^4}} = 1.3 \times 10^9\,\text{m}$$

or about twice the radius of the Sun.

Chapter 17. Star Stuff

This chapter covers the subject of stellar evolution, highlighting the role that stars play in creating the elements necessary for life. We have chosen to cover the whole story of stellar evolution in a single chapter so that students can more easily follow the entire thread of a star's life from birth to death. Because of this choice, the chapter may require more time than average to cover.

As always, when you prepare to teach this chapter, be sure you are familiar with the relevant media resources (see the complete, section-by-section resource grid in Appendix 3 of this Instructor's Guide) and the on-line quizzes and other study resources available on the Astronomy Place website.

What's New in the Third Edition That Will Affect My Lecture Notes?

As everywhere in the book, we have edited to improve the text flow, improved art pieces, and added new illustrations. In addition, those who have taught from previous editions of *The Cosmic Perspective* should be aware of the following organizational or pedagogical changes to this chapter (i.e., changes that will influence the way you teach) in the third edition:

- The discussion on star birth has been expanded to include more discussion of molecular clouds, their fragmentation, and the development of molecular cloud cores. New Figure 17.2 illustrates the fragmentation process.
- We have revised Figure 17.6 and the accompanying discussion to be clearer about the difference between Stage 2, in which convection dominates interior energy transport, and Stage 3, in which radiation dominates energy transport.
- New Figure 17.15 summarizes the evolution of the Sun by illustrating how the Sun's luminosity and radius change with time.
- In an effort to reduce jargon, we have eliminated the terms *protoplanetary disk* and *red-giant winds.*

Teaching Notes (By Section)

Section 17.1 Lives in the Balance

This section introduces the subject of stellar evolution by returning to the idea of gravitational equilibrium and explaining that the tug of war between gravity and thermal pressure is what governs a star's life. If students understand that all the changes a star goes through are driven by the need to balance pressure and gravity, they will have a much easier time understanding how stars evolve.

- In this section, we divide stars into three categories of initial mass: low-mass stars ($< 2M_{\text{Sun}}$), intermediate-mass stars ($2M_{\text{Sun}}$–$8M_{\text{Sun}}$), and high-mass stars ($> 8M_{\text{Sun}}$). Later in the chapter we discuss the lives of low-mass stars and high-mass stars explicitly in order to point out the sharp contrasts between them. Because intermediate-mass stars behave sometimes like high-mass stars and sometimes like low-mass stars, we do not discuss them separately but instead include them in our discussion of high-mass stars, pointing out their similarities and differences where appropriate.

Section 17.2 Star Birth

This section explains how stars form. Some of this material overlaps the discussions of solar system formation in Chapter 8 and the star–gas–star cycle in Chapter 19.

- While we point out that protostars often display jets, we do not explain how they arise. Most workers in this field believe that protostellar jets are hydromagnetic, arising from the twisting of the magnetic field lines that thread the disk. Blobs of matter lifting off the protostellar disk's surface are flung outward and then upward along the spin axis by centrifugal effects as they move along the twisted magnetic field lines. One can demonstrate this effect in class using a piece of hanger wire twisted into a conical spiral and attached to a power drill. An object that can travel freely along the wire will travel up and away from the drill bit when the drill is turned on.
- We use the term *life track* instead of *evolutionary track* to describe a star's path through the H–R diagram. We find that this term is clearer to students.
- Students who have not read Chapter S4 will first encounter degeneracy pressure in this section on star birth, where we explain how degeneracy pressure produces the low-mass cutoff in the main sequence.

Section 17.3 Life as a Low-Mass Star

This section describes how a low-mass star progresses from birth to death, covering the transition to the red giant stage, hydrogen shell burning, helium burning, the horizontal branch of the H–R diagram, and planetary nebulae.

- High-mass stars are often given all the credit for producing the elements necessary for life, but most of the carbon in the universe does not come from the stars that explode. Late in their lives the more massive low-mass stars (those beginning at around $2M_{\text{Sun}}$) and intermediate-mass stars expel dredged-up carbon from the carbon-burning core via winds and planetary nebulae. These stars are the source of most carbon in the universe.
- The atmospheres of some red-giant stars are more oxygen-rich than carbon-rich, and these stars tend to produce silicate dust grains rather than carbon grains. We avoid mentioning them here in order to keep the discussion simple and focused on carbon production, but the mass of interstellar dust in the form of silicates is roughly equal to the mass in the form of carbon particles.
- We have found that one of the best ways to engage students is to relate astronomical phenomena to life on Earth. To that end, this section concludes with speculation about the fate of the Earth once the Sun exhausts its core hydrogen. Vividly telling this story in class is a good way to help students remember the evolutionary stages of low-mass stars.

Section 17.4 Life as a High-Mass Star

This section traces the life of a high-mass star, while pointing out how intermediate-mass stars are similar and different. It includes discussions of the CNO cycle, advanced nuclear burning, the difficulty of extracting energy from iron, and supernovae.

- The text explains that higher-mass stars fuse hydrogen via the CNO cycle because their higher core temperatures enable hydrogen to fuse to heavier nuclei, but it does not explain why higher-mass stars prefer the CNO cycle to the proton–proton chain. The reason has to do with the need for protons to decay to neutrons via weak interactions. In the proton–proton chain, fusion of two protons into deuterium requires this decay to happen on a very short time scale, making successful fusion highly improbable in any one proton–proton collision. The CNO cycle circumvents this bottleneck because it creates unstable isotopes that can take their time decaying. Thus, it is strongly preferred when core temperatures are high enough.
- Intermediate-mass stars burn via the CNO cycle during their main-sequence lives but never burn all the way to iron and therefore do not explode as supernovae. The initial mass cutoff separating these stars from high-mass stars that do explode is still somewhat uncertain. Analyses of the main-sequence turnoff points in star clusters that contain white dwarfs indicate that the cutoff must be at least as high as $8M_{\text{Sun}}$.
- Supernova remnants are discussed near the end of this section, but they are covered in more detail in Chapter 19.
- Figure 16.23 provides a pictorial summary of stellar evolution that can serve as a study aid for visually oriented students.

Section 17.5 The Lives of Close Binary Stars

This last section briefly outlines how mass transfer in close binary systems can alter the standard pathways of stellar evolution.

- This section helps prepare students for the following chapter, in which mass transfer onto white dwarfs, neutron stars, and black holes receives considerable attention.
- In the interests of focusing on the "big picture," we avoid going into the nomenclature of close binaries (e.g., contact binaries, common-envelope systems). Our primary goal is to provide an example of what can happen when stars transfer mass, not to enumerate all the possibilities.

Answers/Discussion Points for Think About It Questions

The Think About It questions are not numbered in the book, so we list them in the order in which they appear, keyed by section number.

Section 17.2

- Some protostellar disks certainly go on to form planets, but unless all stars have planets, some protostellar disks do not form planets. We invite students to speculate about why some stars might not have planets. (Most astronomers believe that star systems in which two stars orbit closely together are unlikely to have planets, because gravitational interactions tend to eject all but the two heaviest bodies in such a system.)
- Figures 16.5 and 16.6 are pre-main-sequence tracks because they show stellar evolution only up to the point of self-sustaining core fusion. In Figure 16.6 the pre-main-sequence track for a $25M_{\text{Sun}}$ star would proceed almost vertically across the top of the H–R diagram, while that of a $0.1M_{\text{Sun}}$ star would drop sharply down to the bottom of the main sequence.

Section 17.3

- A star grows larger and brighter after core hydrogen is exhausted because hydrogen then begins to burn in a shell around the core. Shell burning can proceed at a much higher temperature than core burning, resulting in a much larger luminosity that causes the star to expand. The red-giant stage halts either when helium starts to burn in the core or when the overlying hydrogen envelope is gone. If the temperature required for core helium to ignite were larger, helium core fusion would ignite later, after the red-giant star had grown even larger and more luminous.
- If the universe contained only low-mass stars, elements heavier than carbon would be very rare, because the core temperatures of most low-mass stars are insufficient for fusing other nuclei to carbon. (However, stars on the upper end of the low-mass range can fuse helium to carbon, making some oxygen.)

Section 17.4

- If hydrogen had the lowest mass per nuclear particle, nuclear fusion would be impossible, so stars would not give off any energy other than that released by gravitational contraction. All stars would be like brown dwarfs—bad news for life!
- This is a good topic for class discussion about how important the night sky was to various cultures.

Solutions to End-of-Chapter Problems (Chapter 17)

1. The iron in my blood came from a star that blew up over 4 billion years ago. *This statement is sensible. The iron in the solar system was created before our Sun was formed about 4.6 billion years ago. Because iron is created in high-mass stars and delivered into interstellar space by supernova explosions, the supernova (or supernovae) responsible for creating the solar system's iron must have occurred before the Sun formed.*
2. A protostellar cloud spins faster as it contracts, even though its angular momentum stays the same. *This statement is sensible. Any cloud that contracts will spin faster as long as its angular momentum remains the same.*
3. When helium fusion begins in the core of a low-mass star, the extra energy generated causes the star's luminosity to rise. *This statement is not sensible. When helium fusion begins, the star's core expands, lowering the luminosity generated by hydrogen shell burning.*

4. Humanity will eventually have to find another planet to live on, because one day the Sun will blow up as a supernova. *This statement is not sensible. The Sun will eject a planetary nebula and fade away as a white dwarf. It is not massive enough to explode as a supernova. However, if humanity survives that long, we will probably have to find another place to live.*
5. I sure am glad hydrogen has a higher mass per nuclear particle than many other elements. If it had the lowest mass per nuclear particle, none of us would be here. *This statement is sensible. Iron has the lowest mass per nuclear particle, making it the end of the road for stellar energy production through fusion. If hydrogen had the lowest mass, it would be the end of the road, and none of the other elements would form via fusion in stars. Stars would be powered only by gravitational contraction, an energy source that does not last very long compared to the time needed for humans to evolve.*
6. I just discovered a $3.5M_{\text{Sun}}$ main-sequence star orbiting a $2.5M_{\text{Sun}}$ red giant. I'll bet that red giant was more massive than $3M_{\text{Sun}}$ when it was a main-sequence star. *This statement is sensible. The $2.5M_{\text{Sun}}$ red giant had to be more massive than its companion at some point in the past in order for it to be more advanced in its evolutionary state than its companion.*
7. If the Sun had been born as a high-mass star some 4.6 billion years ago, rather than as a low-mass star, the planet Jupiter would probably have Earth-like conditions today, while Earth would be hot like Venus. *This statement is not sensible. If the Sun had been born as a high-mass star 4.6 billion years ago, it would have exploded as a supernova a long time ago.*
8. If you could look inside the Sun today, you'd find that its core contains a much higher proportion of helium and a lower proportion of hydrogen than it did when the Sun was born. *This statement is sensible. Because the Sun is about halfway through its hydrogen-burning life, it has turned about half the core hydrogen into helium.*

The answers to problems 9–14 revolve around several features of stars: their lifetime compared to the time presumably required to spawn an advanced civilization, their effect on complex life forms that rely on a protective environment such as an atmosphere or an ocean and a reliable replication to survive. All of these assumptions are, of course, debatable. Informed answers to these problems will address what stage of life each star is in, what stages of life it has passed through, what may have happened to a planet in that time, and how long it has lived so far. Here are sample answers to each question:

9. A 10-solar-mass star has a very short lifetime. It also produces copious amounts of ultraviolet radiation that may discourage living organisms.
10. A flare star has violent flare activity that might disrupt the upper atmosphere of a planet and send energetic particles and X rays flying through living organisms—not very pleasant.
11. A carbon star is a very old low-mass star after it has passed through the red giant phase. The Earth may not survive the red giant phase of the Sun, but perhaps planets farther out will. The cool red radiation may make processes such as photosynthesis difficult. Maybe an advanced civilization could have developed around this star, but it would have had to make special arrangements to survive the red giant phase of its mother star.
12. A 1.5-solar-mass red giant is a temporary stage of life for a low-mass star. If an advanced civilization had already developed around this star, which is possible, then it may have had the resources to respond to its expanding, reddened sun, as in problem 11.
13. A 1.0-solar-mass horizontal branch star is a late-stage low-mass-star, burning helium. Again, the answer to problem 11 applies. Life had time to develop, but it would have had to be very clever and have sufficient natural resources and probably a lot of cooperation to persist.
14. A red supergiant is a late-stage high-mass star in the advanced state of nuclear burning, that is, burning elements heavier than helium in its core. Its envelope is gigantic. Its age at this

point is rather young because massive stars live short lives. With our stated assumptions, an advanced civilization probably does not have enough time to develop.

15–25. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

26. Helium fuses into carbon by combining three helium nuclei (atomic number 2) into one carbon nucleus (atomic number 6) and therefore bypassing the elements lithium, beryllium, and boron with atomic numbers 3 through 5. Therefore, fusion processes in the cores of stars do not form these three elements. (Beyond the scope of this book: Trace amounts of lithium and perhaps beryllium and boron formed in the Big Bang. Most of the beryllium and boron may have formed via cosmic ray collisions with heavier elements. The exact origin of these elements is still a topic of astronomical research. These three elements are also rather fragile and tend to be destroyed in the cores of stars rather than being created there.)

27. If the Sun as a red giant spans 30° across the sky, it will be substantially larger than its current span of 0.5°. Thirty degrees is one-sixth of total arc across the visible sky (one-sixth of 180°). Sunset and sunrise would begin earlier and end later on any given day, and therefore, sunset and sunrise would take longer. That is, twilight would last longer. If the beginning and end of sunset were defined by the time the visible disk of the Sun touched the horizon and the time the visible disk of the Sun disappeared below the horizon, sunset would take approximately 2 hours (one-sixth of 12 hours). The daylight sky would be a different color than it is today, since the sky color arises because blue light scatters more than red light, and the sky turns out to be blue because there are blue photons in the Sun's spectrum. However, if there were very little blue light in the Sun's spectrum, the sky would not be blue, but would be a redder color. It might be green or yellow or even red, depending on the temperature of the red giant. Whatever the sky's color, it would be somewhat bluer than the star itself because of the effect of scattering.

28. This question involves independent research. Answers will vary.

Chapter 18. The Bizarre Stellar Graveyard

This chapter covers the end points of stellar evolution: white dwarfs, neutron stars, and black holes. Students often enter an astronomy course interested in and enthusiastic about these objects. If you have the time, we recommend supplementing this chapter with material from Chapters S2 and S3 on relativity and/or Chapter S4 on quantum mechanics. Capable students find these subjects fascinating, and their comprehension of stellar corpses will be much deeper with this additional background.

As always, when you prepare to teach this chapter, be sure you are familiar with the relevant media resources (see the complete, section-by-section resource grid in Appendix 3 of this Instructor's Guide) and the on-line quizzes and other study resources available on the Astronomy Place website.

What's New in the Third Edition That Will Affect My Lecture Notes?

As everywhere in the book, we have edited to improve the text flow, improved art pieces, and added new illustrations. In addition, those who have taught from previous editions of *The Cosmic Perspective* should be aware of the following organizational or pedagogical changes to this chapter (i.e., changes that will influence the way you teach) in the third edition:

- The discussion of the sources of gamma-ray bursts has been updated to emphasize the growing evidence that supernovae are responsible for at least some of these bursts.

Teaching Notes (By Section)

Section 18.1 A Star's Final Battle

Once again, we frame the discussion to follow by discussing the crucial balance between pressure and gravity, but in this section the governing pressure is degeneracy pressure, which students will have encountered in Chapter 17.

Section 18.2 White Dwarfs

This section discusses white dwarfs and the consequences of mass transfer in a close binary that contains a white dwarf. Here is where we cover white dwarf supernovae (a.k.a. Type Ia) and the differences between supernova light curves.

- In order to keep the terminology as descriptive as possible, we call $1.4M_{\text{Sun}}$ the *white dwarf limit* rather than the *Chandrasekhar limit*. The Thinking About box later in the chapter tells how Chandrasekhar discovered this limit.
- In the same vein, we use the term *white dwarf supernova* when referring to the supernovae that come from exploding white dwarfs, and *massive star supernova* when referring to the supernovae that come from exploding massive stars. Even professional astronomers sometimes have trouble keeping the Type Ia, Type Ib, Type II nomenclature straight! A footnote explains these terms, should you want to use them in class.
- A simple in-class way to reinforce the idea that friction is what heats accretion disks is to have the students rub their hands together until they heat up.
- Regarding white dwarf supernovae as distance indicators: Fusion in the incredibly hot, dense environment inside an exploding white dwarf creates radioactive nickel-56. After the explosion, the luminosity of the supernova's expanding cloud of gas comes from radiation emitted as this nickel-56 decays into iron. First, the nickel-56 (28 protons, 28 neutrons) decays into cobalt-56 (27 protons, 29 neutrons) with a half-life of 6.1 days. The cobalt-56 then decays into iron-56 (26 protons, 30 neutrons) with a half-life of 77 days. Because every white-dwarf explosion produces the same amount of nickel-56—about 1 solar mass of it—the light curves of all white dwarf supernovae are nearly identical.
- This section glosses over the fact that astronomers disagree about the progenitors of white dwarf supernovae. Most astronomers now believe that gradual accretion drives a single white dwarf past the $1.4M_{\text{Sun}}$ limit; however, a few believe that these explosions could arise from the mergers of two white dwarfs in the same binary system. (A review of the topic can be found in Livio, 2000, astro-ph/0005344.)

Section 18.3 Neutron Stars

This section covers neutron stars and their manifestations as pulsars, X-ray binaries, and X-ray bursters.

- We briefly cover the idea of gravitational redshift here, but Chapter S3 covers it in much greater detail.
- Pulsar B1257+12 was originally thought to have three planets, but the 25-day modulation of its pulses now appears to stem from a periodicity in the characteristics of the solar wind through which the pulsar is viewed (see Scherer et al., 1997, *Science* 278, 1919). Evidence for the two other planets is more solid.

Section 18.4 Black Holes: Gravity's Ultimate Victory

This section introduces students to the weird world of black holes, the highlight of an astronomy course for many students.

- Because we discuss general relativity and the idea of curved spacetime in depth in Chapter S3, the coverage of these topics in this section is relatively superficial. However, in our experience, students' enthusiasm for black holes often motivates them to want to learn more about relativity.

- The masses we quote for the Cygnus X-1 system are somewhat smaller than those you might find elsewhere. We have taken them from the work of Herrero et al. (1995, *A&A* 297, 556), who measured the mass of the O star in this system by analyzing its spectrum to determine its surface gravity.

Section 18.5 The Mystery of Gamma-Ray Bursts

This section introduces the mystery of gamma-ray bursts, whose cause is not yet known but which we know occur in distant galaxies (not in the Oort cloud or the Milky Way).

- Our knowledge about gamma-ray bursts has continued to advance very rapidly since the first discoveries of their optical counterparts in 1997. While we now know that these bursts come from explosions in distant galaxies and are likely to be somehow associated with the process of star formation, this field is an extremely active one, and therefore it is worth looking for the most-up-to date material available when you present this subject.

Answers/Discussion Points for Think About It Questions

The Think About It questions are not numbered in the book, so we list them in the order in which they appear, keyed by section number.

Section 18.2

- The infalling mass around a white dwarf forms an accretion disk because it has a significant amount of angular momentum—as it falls in, it begins to orbit. An accretion disk is similar to a protoplanetary disk because it is made of gas orbiting a star. An accretion disk is different from a protoplanetary disk because it is steadily fed by a stream of new matter. It is constantly replenished with new gas, and because it remains hot it does not form planets.
- Exploding white dwarfs burn carbon because that is what they are made of—they contain very little hydrogen or helium.

Section 18.3

- If a neutron star is a pulsar but its rotating beams of radiation never touch the Earth, then we will not see it as a pulsar. However, if these rotating beams periodically point at some other civilization, then that civilization will see the neutron star as a pulsar.

Section 18.4

- X-ray bursts are bursts of fusion on the surface of an accreting neutron star. A black hole does not have a surface, only an event horizon that accreting material passes right through. Thus, black holes can never be X-ray bursters.

Solutions to End-of-Chapter Problems (Chapter 18)

1. Most white dwarfs have masses close to that of our Sun, but a few white dwarf stars are up to three times more massive than the Sun. *This statement is not sensible. A $3M_{\text{Sun}}$ star would exceed the white dwarf mass limit of 1.4 solar masses.*
2. The radii of white dwarf stars in close binary systems gradually increase as they accrete matter. *This statement is not sensible. The higher gravity of the more massive white dwarf compresses the white dwarf material to a higher density and a smaller, not larger, radius.*
3. White dwarf supernovae are useful distance indicators. *This is a sensible statement. White dwarf supernovae turn out to be bright, and all have about the same light output. Therefore, they are excellent standard candles.*

4. Before pulsars were discovered, no one knew for sure whether neutron stars existed. *This is a sensible statement. The rapid pulses from pulsars could be generated only by a compact object like a neutron star. Thus, they were the first strong piece of evidence for the existence of neutron stars.*
5. If you want to find a pulsar, you might want to look near the remnant of a supernova described by ancient Chinese astronomers. *This statement is sensible. Other pulsars have been discovered in historical supernova remnants such as the Crab Nebula. Pulsars are the product of supernova explosions; therefore, it makes sense to look for them in supernova remnants or in locations where supernovae were noted historically.*
6. If a black hole 10 times more massive than our Sun were lurking just beyond Pluto's orbit, we'd have no way of knowing it was there. *This statement is not sensible. A black hole of 10 solar masses would exert a profound gravitational influence on the orbits of the planets, even if the black hole lurked beyond the orbit of Pluto.*
7. If the Sun suddenly became a $1M_{\text{Sun}}$ black hole, the orbits of the nine planets would not change at all. *This statement is sensible. The orbits of the planet depend only on the mass of the object they are orbiting, regardless of whether it is a black hole, a neutron star, a main-sequence star, or anything else.*
8. We can detect black holes with X-ray telescopes because matter falling into a black hole emits X rays after it smashes into the event horizon. *This statement is not sensible. The black hole has no surface for material to smash into. X-ray telescopes can detect black holes because the gas falling into a black hole can be very hot despite the black hole's lack of a surface.*

9, 10. These are extended essays; answers will vary. (*Note:* Many students really enjoy these problems, but you will need adequate resources to grade these essays if you assign them.)

11–18. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

19. a. The mean density is simply the total mass divided by the volume of the neutron star:

$$\begin{aligned}\text{mean density} &= \frac{1.5\ M_{\text{Sun}}}{\frac{4}{3}\pi R_{\text{Earth}}^3} \\ &= \frac{1.5\times\left(2\times10^{30}\,\text{kg}\right)}{\frac{4}{3}\pi\left(10\ \text{km}\times100,000\ \frac{\text{cm}}{\text{km}}\right)^3} \\ &= 7\times10^{11}\ \frac{\text{kg}}{\text{cm}^3}\end{aligned}$$

b. The mass of 1 cm^3 of neutron star material is more than 10 times that of Mount Everest!

20. a. To calculate the sum of the masses, we simply solve Kepler's law algebraically and convert the period to seconds (4 days = 345,600 seconds) and the separation to meters (2×10^7 km = 2×10^{10} meters):

$$(m_1+m_2)=\frac{4\pi^2}{G}\frac{a^3}{p^2}=\frac{4\pi^2}{\left(6.67\times10^{-11}\ \frac{\text{m}^3}{\text{kg}\times\text{s}^2}\right)}\frac{\left(2\times10^{10}\,\text{m}\right)^3}{(345,600\text{s})^2}=4\times10^{31}\,\text{kg}$$

The sum of the masses of the two stars is 4×10^{31} kg. Dividing the mass sum of 4×10^{31} kg by the solar mass of 2×10^{30} kg, we find that the mass sum is equivalent to $20M_{\text{Sun}}$.

b. Because the combined mass of the two stars is about $20M_{\text{Sun}}$ and the B2 star has a mass of $10M_{\text{Sun}}$, the unseen companion also has a mass of about $10M_{\text{Sun}}$—far too large for a neutron star. It must be a black hole.

21. a. For the $10^8 M_{\text{Sun}}$ black hole, the Schwarzschild radius is:

$$R_S = 3 \times \frac{10^8 M_{\text{Sun}}}{M_{\text{Sun}}} \text{km} = 3 \times 10^8 \text{ km}$$

The Schwarzschild radius of a $10^8 M_{\text{Sun}}$ black hole is about 300 million km, or about 2 AU (twice the distance from the Earth to the Sun). Because of the relatively large size of such a black hole, tidal forces across a small object—such as a person or a spaceship—will be less significant than those caused by a smaller black hole. It *might* be possible to survive a trip across the event horizon of a massive black hole, but what would you find when you got there?

b. The Schwarzschild radius of a $5M_{\text{Sun}}$ black hole is:

$$R_S = 3 \times \frac{5 M_{\text{Sun}}}{M_{\text{Sun}}} \text{km} = 15 \text{ km}$$

The Schwarzschild radius of a $5M_{\text{Sun}}$ black hole is about 15 km.

c. The first formula in Mathematical Insight 18.1 is more useful in this case. The mass of the Moon is about 7.4×10^{22} kg, so its Schwarzschild radius is:

$$R_S = \frac{2GM}{c^2} = \frac{2 \times \left(6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right)\left(7.4 \times 10^{22} \text{ kg}\right)}{\left(3 \times 10^8 \frac{\text{m}}{\text{s}}\right)^2} \approx 1.1 \times 10^{-4} \text{m} = 0.11 \text{ mm}$$

The Schwarzschild radius of the Moon is barely a tenth of a millimeter. The Moon would have to be crushed to smaller than a pinhead to become a black hole.

d. Your Schwarzschild radius will depend slightly on your mass. Let's take 50 kg as a typical mass for a person. Then your Schwarzschild radius would be about:

$$R_S = \frac{2GM}{c^2} = \frac{2 \times \left(6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right)(50 \text{ kg})}{\left(3 \times 10^8 \frac{\text{m}}{\text{s}}\right)^2} \approx 7 \times 10^{-26} \text{m}$$

Your Schwarzschild radius is about 7×10^{-26} meter. Recall that the typical size of an atom is about 10^{-10} meter and the typical size of an atomic *nucleus* is about 10^{-15} meter. You would have to be crushed to some *10 billion times smaller* than an atomic nucleus to become a black hole.

22. If a neutron star suddenly appeared in your hometown, its mass (and therefore its gravity) would be far larger than that of the Earth. The entire Earth would wrap itself around the neutron star in a thin layer. The hint describes the method for determining the thickness of the layer formed by the Earth: The total mass of the Earth ($M_{\text{Earth}} \approx 6 \times 10^{24}$ kg) would be compressed to neutron-star density and thus have a volume of:

$$
\begin{aligned}
V_{\text{shell}} &= \frac{M_{\text{Earth}}}{\text{density}} \\
&= \frac{6 \times 10^{24}\,\text{kg}}{7 \times 10^{11}\,\frac{\text{kg}}{\text{cm}^3}} \\
&= 9 \times 10^{12}\ \text{cm}^3
\end{aligned}
$$

You can then calculate the thickness of the shell on the neutron star from the formula given, where r is the 10-km radius of the neutron star:

$$V_{\text{shell}} \approx 4\pi r_{\text{shell}}^2 \times \text{thickness} \;\Rightarrow\; \text{thickness} = \frac{V_{\text{shell}}}{4\pi r_{\text{shell}}^2}$$

Plugging in the volume found above and 10 km (= 10^6 cm) for the shell radius, we find that the thickness of the layer formed by the Earth would be about 0.7 cm, or 7 mm.