Part VI: Galaxies and Beyond

Chapter 19. Our Galaxy

Chapter 19 introduces students to galaxies by detailing how our Milky Way works. The agenda of this chapter is twofold: to inform students about our home galaxy and to set the stage for the coverage of galaxy evolution in later chapters. In our view, galaxies are no less important than stars in preparing the conditions for life, because a large star system is needed to retain and recycle the elements created in the cores of stars. We find that students respond positively to this idea because it connects the behavior of galaxies, and the Milky Way in particular, to their own lives.

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 revised and clarified the discussion of spiral arms. New Figure 19.22 is a summary figure outlining how spiral arms stimulate star formation.
- New Figure 19.23 is a blowout sequence taking the reader from a wide-field view of the Milky Way's center right down to the neighborhood of the central black hole.
- We have expanded and updated our discussion of the black hole at the Milky Way's center to include the latest data on star orbits around Sgr A* (see new Figure 19.24) and X-ray flares from the galactic center (see new Figure 19.25).

Teaching Notes (By Section)

Section 19.1 The Milky Way Revealed

This section introduces the Milky Way by summarizing its structure and its contents. For students who have covered Part I of the text, this will be largely a review lesson.

- The historical material on humanity's discovery of the Milky Way's true size and scope appears in a Thinking About box titled "Discovering the Milky Way." Instructors who are pressed for time can skip this material, which is not essential to understanding the Milky Way itself, even though it's an interesting tale about how science progresses.

Section 19.2 The Star–Gas–Star Cycle

This section describes the workings of our galaxy's interstellar medium. We have found that tracing the star–gas–star cycle from stellar mass ejection, through the subsequent cooling of the gas and its collapse into clouds, to the process of star formation is an excellent way to tie together the various states of the interstellar medium and to show the dynamism of our galaxy. Students who understand how our galaxy cycles gas into stars are well prepared to understand how galaxies evolve from pristine gas clouds to vast collections of stars enriched with heavy elements.

- We have chosen to avoid the astronomical term *metals* in this book, preferring the term *heavy elements* instead. The term *metals* can confuse students who already know what real metals are, but we do provide the astronomical definition in a footnote.
- The text states that hot-gas bubbles fill roughly 20–50% of the Milky Way's disk, but the topology of the hot gas distribution is still debated among experts. Certainly some of the hot gas is in well-defined bubbles, but in other parts of the galaxy hot bubbles may be so interconnected that it makes more sense to speak of cooler clouds embedded in a hot substrate.
- Figure 19.13, which is drawn from a poster produced by NASA, is one of the best tools we have run across for demonstrating the power of multiwavelength astronomy. Consider spending some time going over this set of pictures in class. They summarize the various states of the interstellar medium while showing students how much richer our view of the cosmos becomes when we broaden our view to other parts of the electromagnetic spectrum.

Section 19.3 Galactic Environments

This section is essentially a lesson on stellar populations that connects the types of stars found in various parts of the galaxy with the distribution of the interstellar medium.

- We avoid using the terminology of stellar populations in this book because many students find it virtually impossible to remember which stars are population I and which are population II. We believe their effort is better spent learning *why* some regions of the galaxy contain only old stars while other regions continually form new stars.

Section 19.4 The Milky Way in Motion

This section addresses why the Milky Way looks as it does by explaining the motions of its stars and the origin of its spiral arms.

- We include the orbital velocity law within the text flow here because it is so fundamental to astronomy. Even if your course is nonmathematical, you can still explain to students that this expression relates the velocity at a given radius to the mass within that radius—measure the velocity and you have determined the mass.
- While we mention dark matter here, we postpone a detailed discussion of it to Chapter 22.
- We had hoped to include some sort of graphic in the book illustrating the Milky Way's spiral arms. Somewhat to our surprise, we found that they are so ill defined that there is no general agreement on how they would look from outside. We thus chose to show photos of other spiral galaxies instead.

Section 19.5 The Mysterious Galactic Center

This section focuses on the galactic center. Recent observations of stellar proper motions in the vicinity of Sgr A* have greatly strengthened the case for a black hole of 3 to 4 million solar masses within it.

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 19.2

- Stars in open clusters are generally much younger than those in globular clusters, having formed after many heavy elements accumulated in the interstellar medium. Thus, open clusters have higher proportions of heavy elements than globular clusters.
- Many different patterns are evident in Figure 18.13. The most prominent is the band of molecular clouds across the midplane, which appears bright in molecular emission, atomic

hydrogen 21-cm emission, far-infrared dust emission and gamma-ray emission, but dark in optical and X-ray light because of its obscuring effects.

Section 19.3

- In the far future, after all the gas in the disk has been transformed into stars, the disk environment will look more like today's halo environment because it will no longer harbor young stars.
- The red color is from hydrogen emission, the blue is starlight scattered by dust, and the black arises because dust obscures light from background stars.

Section 19.4

- Stars are so far apart, relative to their sizes, that there is little chance that a halo star will collide with the Sun or the Earth.
- Cars passing through the traffic jam near an accident scene are similar to stars passing through a spiral arm because the jam, like the arm, is a pattern that does not move with the flow of stars or traffic. (However, the arm can move through the galaxy, unlike the accident scene, which stays still.)

Solutions to End-of-Chapter Problems (Chapter 19)

1. We did not understand the true size and shape of our galaxy until NASA satellites were launched into the galactic halo, enabling us to see what the Milky Way looks like from outside. *This statement is not sensible, because NASA has not yet been able to get satellites much beyond our own solar system, let alone into the Milky Way's halo.*
2. Planets like the Earth probably didn't form around the very first stars because there were so few heavy elements back then. *This statement is sensible, because the Earth formed through the accretion of smaller, rocky objects made from heavy elements.*
3. If I could see infrared light, the galactic center would look much more impressive. *This statement is sensible, because infrared light from the galactic center can penetrate the Milky Way's disk much more easily than visible light can.*
4. Many spectacular ionization nebulae can be seen throughout the Milky Way's halo. *This statement is not sensible. Virtually no star formation is happening in the galactic halo, so there are no hot, short-lived stars there to generate ionization nebulae.*
5. The carbon in my diamond ring was once part of an interstellar dust grain. *This statement is sensible. Much of the carbon in the interstellar medium is in the form of dust grains, so the carbon in the interstellar cloud out of which the Earth formed must also have been largely in the form of dust grains.*
6. The Sun's velocity around the Milky Way tells us that most of our galaxy's dark matter lies within the solar circle. *This statement is not sensible. The Milky Way's rotation curve remains flat well beyond the orbit of the Sun, indicating that the majority of the Milky Way's mass lies beyond the Sun's orbit.*
7. We know that a black hole lies at our galaxy's center because numerous stars near it have vanished over the past several years, telling us that they've been sucked in. *This statement is nonsense. The orbital velocities of stars at the galactic center are what indicate a black hole. None of these stars has vanished from sight.*
8. If we could watch a time-lapse movie of a spiral galaxy over millions of years, we'd see many stars being born and dying within the spiral arms. *This statement is sensible. Spiral arms are bright because they contain many short-lived blue stars that shine for only a few million years.*

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. A star made of only helium and hydrogen would have to be among the first generation of stars ever born, arising out of the primordial mix of elements that came from the Big Bang. The oldest stars we know about are over 12–15 billion years old—a star made of only helium and hydrogen would have to be at least this old. (No such star has ever been discovered.)

20. If one supernova can blow out all of the interstellar gas from a globular cluster, no gas remains from which subsequent generations of stars can form. Therefore, a globular cluster may consist primarily of the original gas cloud's first (and only) generation of stars. The fact that one supernova can do so much damage to a cluster's interstellar gas may explain why stars ceased forming in clusters long ago. It also explains why globular clusters are rather deficient in heavy elements. Heavy elements collect as gas is processed by multiple generations of stars. If only one generation has passed, very few heavy elements build up.

21. Because stars that are traveling along with us in the disk of the Milky Way move at a velocity relative to us of only about 20 km/s, we would reason that a star observed to be moving relative to us at a velocity of 200 km/s was *not* traveling with us in the disk but was part of some other component of the Milky Way, likely the halo. The orbits of halo stars are not concentrated in the flattened disk but are distributed more like a sphere. So a halo star flying through the disk would appear to us to have the rotational speed of the disk, 200 km/s.

22. First, we can derive a general-purpose formula for computing the mass interior to an orbit, using the units of light-years for the radius and km/sec for the velocity. Then we can just plug in the relevant radii and velocities for parts (a), (b), and (c).

$$M_r = \frac{rv^2}{G} = \frac{\left[r \times \left(\frac{9.46 \times 10^{15}\,\text{m}}{1\text{ ly}}\right)\right] \times \left[v^2 \times \left(\frac{1000\text{ m}}{1\text{ km}}\right)^2\right]}{\left(6.67 \times 10^{-11}\,\frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right) \times \left(2 \times 10^{30}\,\frac{\text{kg}}{M_{\text{Sun}}}\right)}$$

$$= 71\,M_{\text{Sun}} \times \underbrace{r}_{r\text{ in ly}} \times \underbrace{v^2}_{v\text{ in km/s}}$$

$$= 7.1 \times 10^9\ M_{\text{Sun}} \times \left(\frac{r}{10^4\text{ly}}\right) \times \left(\frac{v}{100\,\frac{\text{km}}{\text{s}}}\right)^2$$

a. For 10,000 ly, the plot reads approximately 230 km/s. Plugging into our formula, we get a mass interior to 10,000 ly of 1.4×10^{40} kg $\times$ $(2.3)^2$ = 7.4×10^{40} kg or 3.7×10^{10} M_{Sun}.

b. For 30,000 ly, the radius is 3 times greater and the velocity is nearly the same, so the mass is a factor of 3 more than in part (a): 2.2×10^{41} kg or $1.1 \times 10^{11} M_{\text{Sun}}$. (One might also read a somewhat lower velocity of 200 km/sec from the plot. The mass in this case is reduced by a factor of $(200/230)^2$ or 0.75.

c. For 50,000 ly, the radius is 5 times greater than in part (a), and again the velocity is nearly the same, so the mass is a factor of 5 more than in part (a): 3.7×10^{41} kg or $1.9 \times 10^{11} M_{\text{Sun}}$.

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

Chapter 20. Galaxies: From Here to the Horizon

This chapter describes the observed properties of galaxies and their implications. We first examine the morphology and color of galaxies and then explain how their distances are measured. Rather than postpone the implications of these distance measurements to a later chapter, we continue on and explain Hubble's law, how it tells us the age of the universe, and how the age of the universe limits how far we can see. By the end of the chapter, students have learned about the size, scope, age, and expansion history of the observable universe, preparing them for the discussion of galaxy evolution to follow in Chapter 21.

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?

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- We now discuss Hubble's system of galaxy classification as part of the main text flow, including a new figure showing a pictorial tuning-fork diagram.

Teaching Notes (By Section)

Section 20.1 Islands of Stars

This section introduces students to the subject of galaxies by way of the Hubble Deep Field.

- In our experience, the Hubble Deep Field is an excellent pedagogical tool for students of all ages. People love the image and often start classifying the galaxies in it into systems of their own. Consider having students do some sort of classification exercise with this image.

Section 20.2 Galaxy Types

This section describes the various types of galaxies that populate the universe.

- In this book we do not delve very deeply into galaxy classification because, unlike stellar classification, which prepares students to understand stellar evolution, galaxy classification does not prepare students to understand galaxy evolution.
- Lenticular (S0) galaxies defy easy pigeonholing into the categories "spiral" and "elliptical" because they share some characteristics with each type. We include them with spirals in order to keep the discussion compact, but they could just as easily be given separate billing.
- Elliptical galaxies have an undeserved reputation for having no interstellar medium. In fact, elliptical galaxies tend to be filled with hot gas that radiates profusely in the X-ray band but is invisible in the optical band.

Section 20.3 Measuring Cosmic Distances

In order to know more about galaxies than just shape and color, we need to know their distances. This section describes the chain of distance measurement techniques that gives us the distances of galaxies. To help students comprehend how we proceed to measure distances step-by-step to the edge of the observable universe, we consolidate all the relevant material in this section.

- We have had success likening the Hubble constant to the scale of a map. Redshift measurements accurately give us the relative distances of galaxies, enabling us to make a threedimensional map of the universe. But until we know the scale of the map, we don't know the absolute distances of all the galaxies. However, just a handful of accurate measurements of absolute distances tells us the scale of the map, which provides absolute distance measurements for all the rest of the galaxies.

- FYI: The Tully–Fisher relation is not unique. An analogous relation exists between the luminosity of an elliptical galaxy and the characteristic velocities of its stars.

Section 20.4 Measuring Cosmic Ages

Hubble's law has deep implications for the ages of galaxies. In this section we introduce the concept of lookback time and its relationship to a galaxy's redshift. The stage is then set for the discussion of galaxy evolution in Chapter 21.

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 20.2

- The purpose of this classification question is just to get the students to look at the Hubble Deep Field and think.

Section 20.3

- A galaxy moving at 10,000 km/s is at 143 Mpc if H_0 = 70 km/s/Mpc and is at 167 Mpc if H_0 = 60 km/s/Mpc.

Section 20.4

- A dot 9 cm from Dot B would move at 9 cm/3 s = 3 cm/s according to scientists on Dot B.
- The Local Group is not expanding, and light travel times within it are only a few million years. Thus, the distances of Local Group galaxies have not changed much since they emitted the light we see today. On the other hand, galaxies billions of light-years away have traveled huge distances since they emitted the light we see today, making it tricky to define their distances.

Solutions to End-of-Chapter Problems (Chapter 20)

1. If you want to find elliptical galaxies, you'll have better luck looking in clusters of galaxies than elsewhere in the universe. *This statement is sensible, because clusters of galaxies have a much higher percentage of elliptical galaxies than do other parts of the universe.*
2. Cepheid variables make good standard candles because they all have exactly the same luminosity. *This statement is not sensible. Cepheid variables differ in luminosity, but we can determine the luminosity of a Cepheid from the period–luminosity relation.*
3. If the standard candles you are using are less luminous than you think they are, then the distances you determine from them will be too small. *This statement is not sensible. If your standard candles are less luminous than you think they are, then they are closer than you think they are. Thus, the distances you determine from them will be too large.*
4. Galaxy A is moving twice as fast as Galaxy B. That probably means it's twice as far away. *This statement is sensible, because the relationship between speed and distance obeys Hubble's law.*
5. The lookback time to the Andromeda Galaxy is about 2.5 million years. *This statement is sensible, because the Andromeda Galaxy is about 2.5 million light-years away.*
6. I'd love to live in one of the galaxies at the very edge of the universe, because I want to see the black void into which the universe is expanding. *This statement is not sensible. According to our current understanding, the universe has no center and no edge. It looks more or less the same no matter where you are located.*

7. We can't see galaxies beyond the cosmological horizon because they are moving away from us faster than the speed of light. *This statement is not sensible. The reason we cannot see galaxies beyond the cosmological horizon is because the age of the universe limits how far we can look back into the past. We can't look back to a time before the universe began.*
8. We see distant galaxies as they were when the universe was younger, and any people living in those galaxies today would see the Milky Way as it was when the universe was younger. *This statement is sensible. Everything we or anyone else sees in the universe happened sometime in the past because light requires a finite time to travel between any two points in the universe.*

9–15. 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.

16. Parallax is similar to what your brain does to estimate distance. Your brain is sent two ever so slightly different pictures from each eye, and the brain assembles this information into a 3-D representation of what you see. Parallax measurements exploit the ever so slightly different positions a nearby star appears against the more distant background stars as the Earth sees it from opposite sides of the Sun. One might be able to estimate the distance to an oncoming car at night by noting (1) how bright the lights appear to be and (2) how far apart the headlights seem to be. Both these ideas are similar to standard candle techniques, because they work only if you already have a good sense of how bright car lights actually are and how far apart they really are.
17. From Figure 20.12, one can read off the intrinsic luminosity of a Cepheid, given a certain period. An approximate reading shows that a Cepheid with a period of 8 days has a luminosity of 2,000 solar luminosities and that a Cepheid with a period of 35 days has a luminosity of a little over 10,000 solar luminosities.
18. Again, the exercise of counting galaxies in this picture will vary with individual students. It will be interesting to the instructor to determine *how* the students counted the galaxies. Did they estimate from counting a few galaxies and estimating a mean density? Did they try to count them all?
19. We can solve the luminosity–distance formula for the distance *d*:

$$d = \sqrt{\frac{\text{luminosity}}{4\pi \times \text{apparent brightness}}}$$

Substituting the given values, we find:

- Cepheid 1: $d = 5.8 \times 10^{23} = 6.1 \times 10^{7}$ light-years
- Cepheid 2: $d = 5.0 \times 10^{23} = 5.3 \times 10^{7}$ light-years
- Cepheid 3: $d = 4.8 \times 10^{23} = 5.1 \times 10^{7}$ light-years

The results do not perfectly agree because of observational uncertainties. Taking the average, the distance is 5.6×10^{7} light-years with a spread of ± 4.5 million light-years, or a spread of a little less than 10% of the total distance to the galaxy M100.

20. From the data we have provided for each galaxy, we can make a table of derived values. The lab (rest) wavelength is 656.3 nm for the hydrogen emission line of interest here. Note that the redshift z we compute is equivalent to the derived recession velocity divided by the speed of light. The speed of light is 300,000 km/sec. The Hubble constant we assume here is 72 km/sec/Mpc, so the distance we quote is in Mpc.

	Wavelength (nm)	a. $z = \frac{\lambda_{obs} - \lambda_{lab}}{\lambda_{lab}}$	b. $v = cz$	c. $d = \frac{v}{H_0}$
Galaxy 1	659.6	0.0050	1,500 km/s	20.8 Mpc
Galaxy 2	664.7	0.0128	3,840 km/s	53.3 Mpc
Galaxy 3	679.2	0.0349	10,500 km/s	146 Mpc

Chapter 21. Galaxy Evolution

This chapter surveys what we currently know about how galaxies evolve. It brings together material on distant galaxies, starburst galaxies, and active galaxies and explains how each of these manifestations might represent a different chapter in the life of a "normal" galaxy.

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.

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- Our discussion of what makes some galaxies spiral and others elliptical contains some new artwork. New Figure 21.5 shows how an early stage in the Milky Way's development might have looked. Figures 21.6a and 21.6b illustrate the roles of angular momentum and primordial density in determining the differences between spiral and elliptical galaxies.
- In order to connect the topic of active galactic nuclei more closely to galaxy evolution, we mention the new evidence relating the mass of a central black hole to the mass of its spheroidal component.

Teaching Notes (By Section)

Section 21.1 Looking Back Through Time

This section introduces the idea of galaxy evolution by presenting "family albums" of various types of galaxies at different lookback times. We emphasize that astronomers do not yet know many of the details of galaxy evolution, so the story presented in this chapter is incomplete.

- Students are generally captivated by the idea that we can look back in time by looking deeply into space. When explaining this concept, we find it helpful to speak about observing "old light from young galaxies." This approach counteracts the tendency for students to think of these galaxies as "very old" because we are seeing them as they were "billions of years ago." They are not ancestors of the Milky Way but rather its cousins, and by looking at their "baby pictures" we are seeing what our middle-aged Milky Way was like during its childhood.
- We have found that the term *active galaxy* can confuse students because they mistake it for a galaxy type different from the ellipticals and spirals they already know about. Because active galaxies, aside from their luminous nuclei, are just like other elliptical and spiral galaxies, we

speak only about *active galactic nuclei* in order to keep students focused on the part of an active galaxy that makes it active.

Section 21.2 Galaxy Formation

This section discusses what is currently known about the process of galaxy formation, highlighting the inferences we draw from theoretical modeling, the characteristics of galaxy disks and spheroids, and detailed observations of our own Milky Way.

Section 21.3 Why Do Galaxies Differ?

This section presents various ideas about how galaxies evolved into their present form. We motivate the material by posing the question "Why do spiral galaxies have gas-rich disks while elliptical galaxies do not?" In addressing this question, we explain how both the characteristics of the original protogalactic cloud and environmental effects such as collisions with other galaxies can influence the evolution of a galaxy.

Section 21.4 Starburst Galaxies

This section focuses on starburst galaxies. Stars are currently forming in these galaxies at an unsustainably high rate, so we know that the starburst phenomenon is a transient episode in galaxy evolution. The effects of a starburst on the subsequent evolution of a galaxy can be profound because the many supernovae buffeting the interstellar medium can drive a galactic wind that carries gas away from the galaxy.

Section 21.5 Quasars and Other Active Galactic Nuclei

This section covers active galactic nuclei and the evidence for supermassive black holes at their cores. Many introductory texts treat active galactic nuclei as a sort of astronomical sideshow. However, current astronomical research is showing that the nuclei of virtually all galaxies might pass through an active stage at least once. Because nuclear activity would then be a common stage in the evolution of galaxies, we believe that quasars and other such beasts fall naturally into a discussion of galaxy evolution. Furthermore, the great prevalence of quasars in the early universe is telling us something very important about galaxy evolution, even if we don't yet know what it's saying.

- In order to keep students focused on the physics of active galactic nuclei, we have kept the classification and nomenclature of active galaxies to a minimum. We call all the most luminous active galactic nuclei *quasars*, even though some astronomers separate these into *QSOs*, which are radio quiet, and quasars, which are radio loud. We also avoid the terms *Seyfert galaxy*, which describes lower-luminosity active galactic nuclei, and *BL Lac object*, which describes active galactic nuclei with very weak emission lines. In all these objects, the underlying engines are likely to be quite similar, and a proliferation of terminology tends to distract students from that fact.
- We elected not to allocate much space to discussing whether quasars really are at cosmological distances because this issue has been settled to the satisfaction of all but a vocal few in the astronomical community. In our opinion, discussing whether black holes really lie at the cores of quasars is a much better use of the limited time available in an astronomy course.

Section 21.6 Shedding Light on Protogalactic Clouds

This section completes our discussion of galaxy evolution by describing how we can probe what's going on in protogalactic clouds by analyzing the absorption lines in the spectra of quasars.

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 21.1

- Compared to the 14-billion-year lifetime of the universe, 20 million years is very short. Galaxies that close haven't had much time to change since their light left, so we are seeing them essentially as they are today.

Section 21.2

- The universe was much denser in the past, so its galaxies were much closer together, making collisions much more frequent.

Section 21.4

- Because star bursts in dwarf galaxies can eject heavy elements, they have fewer of these elements to incorporate into new stars.

Solutions to End-of-Chapter Problems (Chapter 21)

1. Galaxies that are more than 10 billion years old are too far away to see even with our most powerful telescopes. *This statement is not sensible. Hubble and other telescopes have detected many galaxies more than 10 billion light-years away, and some of those pictures appear in the textbook.*
2. Heavy elements ought to be much more common near the Milky Way's center than at its outskirts. *This statement is sensible. Stars create heavy elements, and there has been much more star formation near the galaxy's center than at its outskirts. Observations of stars in the Milky Way's halo show that they contain a much smaller percentage of heavy elements than stars near the galactic center.*
3. If the Andromeda Galaxy someday collides and merges with the Milky Way, the resulting galaxy would probably be elliptical. *This statement is sensible, because computer simulations of collisions between two large spiral galaxies show that these collisions create elliptical galaxies.*
4. Starburst galaxies have been forming stars at the same furious pace ever since the universe was about a billion years old. *This statement is not sensible. The bursts of star formation in starburst galaxies must be temporary because they can turn all of a galaxy's gas into stars in a time much shorter than the age of the universe.*
5. We know that some galaxies contain supermassive black holes because their centers are completely dark. *This statement is not sensible. On the contrary, many galaxies with supermassive black holes have centers that are quite bright. The evidence for supermassive black holes rests on the orbital speed of objects that orbit close to the centers of galaxies.*
6. The black hole at the center of our galaxy may once have powered an active galactic nucleus. *This statement is sensible. The active nuclei in other galaxies appear to be powered by accretion of matter onto supermassive black holes, so it is quite possible that our own galaxy underwent a similar episode of nuclear activity.*
7. Analyses of quasar light can tell us about intergalactic clouds that might otherwise remain invisible. *This statement is sensible. Quasar light typically passes through many interstellar clouds on its journey to Earth, and each of these clouds absorbs a little bit of light. Analysis of the resulting absorption lines in the quasar's spectrum can tell us about the characteristics of these clouds.*

9–16. 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.

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

19. a. One author's mass in kilograms is 120 pounds ÷ 2.2 pounds/kg = 54.5 kg.

b. The radiative energy released by mass falling into a black hole is about 10% of the rest mass energy. Thus, the energy released is:

$$0.10 \times mc^2 = 0.10 \times 54.5 \text{ kg} \times \left(3 \times 10^8 \frac{\text{m}}{\text{s}}\right)^2 = 4.9 \times 10^{17} \frac{\text{kg} \times \text{m}^2}{\text{s}^2} = 4.9 \times 10^{17} \text{ joules}$$

c. A 100-watt light bulb uses 100 joules per second, so we divide the energy released by the rate of energy release to see how long a bulb would have to burn to release the same amount of energy:

$$\frac{4.9 \times 10^{17} \text{ J}}{100 \text{ J / s}} = 4.9 \times 10^{15} \text{ s} = 1.6 \times 10^8 \text{ yr}$$

A bulb would have to burn for 160 million years to release the same amount of energy.

20. Using the orbital velocity law, we calculate the mass of this black hole to be:

$$M = \frac{\left(4.8 \times 10^{15} \text{m}\right) \times \left(1.0 \times 10^6 \frac{\text{m}}{\text{s}}\right)^2}{\left(6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right)} = 7.2 \times 10^{37} \text{ kg}$$

Converting to solar masses gives:

$$M = \left(7.2 \times 10^{37} \text{ kg}\right) \times \frac{1 M_{\text{Sun}}}{2.0 \times 10^{30} \text{ kg}} = 3.6 \times 10^7 M_{\text{Sun}}$$

Chapter 22. Dark Matter and the Fate of the Universe

This chapter focuses on dark matter, its significance in the universe, and its influence on the universe's fate. Dark matter arises in many different astronomical contexts, and the dark matter that dominates galaxies may not even be the same stuff as the dark matter that governs the fate of the universe. Nevertheless, the underlying idea is the same: Dark matter is stuff whose gravitational influence is detectable but that we have not yet seen because it is much dimmer than normal stars. We devote this entire chapter to issues involving dark matter for two reasons. First, determining the nature and amount of dark matter in the universe is surely one of the most important unsolved problems in astronomy; second, it gives us the opportunity to focus on how we measure the masses of large-scale objects.

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 updated our discussion of mysterious expansion, renaming the section "The Fate of the Universe." New Figure 22.17 is a schematic illustration of the four basic expansion patterns. New Figure 22.18 shows some of the actual supernova data that favor an accelerating universe.

Teaching Notes (By Section)

Section 22.1 The Mystery of Dark Matter

This section introduces dark matter as one of the most fascinating and fundamentally important issues in astronomy.

- Because the rest of the chapter presumes that dark matter exists, we explain here a dilemma facing astronomers. Orbital velocity measurements in many different astronomical systems can be explained in only two ways: either dark matter exists, or we do not understand how gravity operates on large scales. Consider leading an in-class discussion about why most astronomers would rather believe in dark matter than discard our theory of gravity.

Section 22.2 Dark Matter in Galaxies

This section presents the evidence for dark matter in galaxies.

- Here we define the concept of a *mass-to-light ratio* and explain that high mass-to-light ratios indicate that most of the mass in galaxies is dimmer than stars; thus, we call it *dark matter*. The most general definition of dark matter is therefore anything that is not as bright as a star. Explaining that astronomers would consider the Earth and everything on it dark matter helps demystify the concept of dark matter for students.

Section 22.3 Dark Matter in Clusters

This section presents the evidence for dark matter in clusters of galaxies.

- Here is where we present the physics of clusters of galaxies. (Their observed properties are covered in Section 20.2.)
- We explain how the amount of dark matter in clusters can be measured in three different ways: by measuring the velocities of a cluster's galaxies, by measuring the temperature of a cluster's intracluster medium, and by measuring how severely a cluster's gravity lenses objects beyond it.
- If you have not covered Chapter S3, this is the first discussion of gravitational lensing in the book. We find that clusters are a good introduction to gravitational lensing because students can clearly see both the lensed objects and the cluster doing the lensing; the lensed images are often quite obviously distorted; and if multiple images exist, they are widely separated.

Section 22.4 Dark Matter: Ordinary or Extraordinary?

We do not yet know what dark matter is made of, but this section presents the available evidence.

- Here we define *ordinary matter* to be baryonic matter and *extraordinary matter* to be non-baryonic matter. We prefer to speak of ordinary matter and extraordinary matter when possible because these terms convey the proper impression to that large group of students who have trouble remembering what a baryon is.

- The search for dark matter in our own galaxy involves looking for gravitationally microlensed stars that are briefly amplified by MACHOs before returning to normal. Having introduced lensing via clusters in the previous section makes the more subtle concept of microlensing easier to grasp.

Section 22.5 Structure Formation

This section covers large-scale structure in the universe and the role of dark matter in creating it.

- Another advantage to bringing all the dark matter–related material together is that it creates a chapter devoted to large-scale gravitational effects in astronomy. Students who have just seen how dark matter binds galaxies and clusters together are well primed to learn about larger but less distinct structures that gravity is still in the process of creating.

Section 22.6 The Universe's Fate

This section explains how we try to assess the fate of the universe by measuring the amount of dark matter it contains and by measuring how the universe's expansion rate has changed through time.

- This section introduces the idea of critical density. We have found that the best way to show students how astronomers can measure this quantity is to apply the idea of a mass-to-light ratio to the universe as a whole. Astronomers measure the density of the universe in many other ways, of course, but those methods generally involve more advanced concepts.
- Recent supernova observations indicating that the universe's expansion is accelerating have become one of the biggest stories in science. We have elected to explain this finding by relating the brightness of a distant supernova to its lookback time. The overall geometry of the universe also plays a role in determining a supernova's apparent brightness, but we have omitted a discussion of that role in order to simplify the explanation.

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 22.2

- The distribution of matter in the Milky Way must not be centrally concentrated, because a centrally concentrated distribution would produce a sharply declining rotation curve like that of the solar system. Instead, the Milky Way's rotation curve is flat.
- The mass-to-light ratio of the red giant is $1M_{\text{Sun}}/100L_{\text{Sun}} = 0.01M_{\text{Sun}}/L_{\text{Sun}}$. The mass-to-light ratio of the red main-sequence star is $1M_{\text{Sun}}/0.001L_{\text{Sun}} = 1{,}000M_{\text{Sun}}/L_{\text{Sun}}$.

Section 22.3

- This is a good discussion question. Most astronomers find the agreement between these different mass measurement techniques reassuring. (They do not agree for all clusters, but as these techniques become more refined they agree for more and more clusters.)

Section 22.4

- This is another good discussion question. One pertinent example to mention is the discovery of Neptune, which was based solely on inferences from Newtonian gravity.

Section 22.6

- Robert Frost's poem that opens this section is a good departure point for a discussion of the philosophical implications of the universe's fate.

Solutions to End-of-Chapter Problems (Chapter 22)

1. Astronomers now believe that most of any galaxy's mass lies beyond the portions of the galaxy that we can see. *This statement is sensible, because the rotation curves of galaxies indicate that most of a galaxy's mass extends far beyond the region of the galaxies containing most of the stars.*

2. If our galaxy had less dark matter, its mass-to-light ratio would be lower. *This statement is sensible. If our galaxy had less dark matter, then the amount of mass divided by the amount of starlight would be lower.*
3. A cluster of galaxies is held together by the mutual gravitational attraction of all the stars in the cluster's galaxies. *This statement is not sensible. The amount of mass in a cluster's stars is much lower than the amount needed to hold the cluster together. That is why we believe that most of a cluster's matter is dark.*
4. We can estimate the total mass of a cluster of galaxies by studying the distorted images of galaxies whose light passes through the cluster. *This statement is sensible. Gravitational lensing is now commonly used to measure the masses of clusters.*
5. Clusters of galaxies are the largest structures that we have so far detected in the universe. *This statement is not sensible. Superclusters and voids are much larger than clusters of galaxies.*
6. Dark matter gets its name from the fact that it emits no detectable light. *This statement is sensible. We assume that dark matter exists because our measurements of gravity tell us that galaxies contain much more matter than can be seen in the form of stars.*
7. The primary evidence for an accelerating universe comes from observations of young stars in the Milky Way. *This statement is not sensible. In order to measure accelerating expansion, we need to measure distances to objects billions of light-years away.*
8. There is no doubt remaining among astronomers that the fate of the universe is to expand forever. *This statement is not sensible. Current evidence favors eternal expansion, but we have much more to learn about the universe before we can be certain of its fate.*

9–15. 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.

16. By accelerating expansion, we mean that the rate at which galaxies are moving apart is increasing with time. Recent measurements of supernovae suggest that today's expansion rate is indeed faster than the expansion rate that prevailed when the universe was half its current age. If the universe's expansion really is accelerating, then a mysterious repulsive force must be acting to push the universe's galaxies apart. If this repulsive force continues to push into the indefinite future, then the universe will never recollapse and all its galaxies will move extremely far apart.
17. If I discovered a galaxy with a mass-to-light ratio of 0.1 solar mass to 0.1 solar luminosity, I would be surprised. This ratio would indicate that the average star in this galaxy is 10 times more luminous per unit of mass than the Sun is. There are far more stars in our own galaxy that are dimmer than the Sun than there are stars that are more luminous than the Sun. Therefore, if a galaxy has a lower mass-to-light ratio than 1, then the ratio of massive hot stars to dim cool stars in this galaxy must be higher than that ratio in our own galaxy (or indeed in every other galaxy observed to date). If I had confidence in my observations, I might suspect that the star formation in this galaxy must have produced an unusual predominance of high mass stars.

18. We can derive a general-purpose formula for this problem and for the next problem by using the mass/velocity/radius relation and plugging in 100 km/sec for the velocity and 10,000 light-years for the radius. Then, for this and the next problem, we need to do fewer computations.

$$M_r = \frac{rv^2}{G} = \frac{\left[r \times \left(\frac{9.46 \times 10^{19}\,\text{m}}{10{,}000\ \text{ly}}\right)\right] \times \left[v^2 \times \left(\frac{1000\ \text{m}}{1\ \text{km}}\right)^2\right]}{\left(6.67 \times 10^{-11}\,\frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right) \times \left(2 \times 10^{30}\,\frac{\text{kg}}{M_{\text{Sun}}}\right)}$$

$$= 7.1 \times 10^5\, M_{\text{Sun}} \times \underbrace{r}_{r \text{ in } 10^4 \text{ ly}} \times \underbrace{v^2}_{v \text{ in km/s}}$$

$$= 7.1 \times 10^9\, M_{\text{Sun}} \times \left(\frac{r}{10{,}000\ \text{ly}}\right) \times \left(\frac{v}{100\,\frac{\text{km}}{\text{s}}}\right)^2$$

For NGC7541 from Figure 21.4, the velocity at 30,000 light-years is 200 km/sec, and the velocity at 60,000 light-years is about 220 km/sec. Plugging into our handy formula, we can solve parts (a), (b), and (c).

a. Within 30,000 light-years:

$$M_r = 7.1 \times 10^9\, M_{\text{Sun}} \times \left(\frac{30{,}000\ \text{ly}}{10{,}000\ \text{ly}}\right) \times \left(\frac{200\,\frac{\text{km}}{\text{s}}}{100\,\frac{\text{km}}{\text{s}}}\right)^2 = 8.5 \times 10^{10}\, M_{\text{Sun}}$$

b. Within 60,000 light-years:

$$M_r = 7.1 \times 10^9\, M_{\text{Sun}} \times \left(\frac{60{,}000\ \text{ly}}{10{,}000\ \text{ly}}\right) \times \left(\frac{220\,\frac{\text{km}}{\text{s}}}{100\,\frac{\text{km}}{\text{s}}}\right)^2 = 2.1 \times 10^{11}\, M_{\text{Sun}}$$

c. The mass at 30,000 light-years is about half the mass at 60,000 light-years (since the velocity curve is flat, the velocity isn't much different, and thus the mass enclosed increases proportionally to the radius). The mass is not concentrated in the center of the galaxy.

19. For this problem, we assume that the cluster gas is all at one temperature (isothermal) and that we have X-ray data from the cluster out to at least 2 Mpc (= 6.2×10^{22} m). The temperature that we measure for the gas is 8×10^7 K. We can use the formula from Mathematical Insight 22.2 to compute an equivalent velocity for the particles in the gas; that is:

$$v_{\text{thermal}} = 100\,\frac{\text{m}}{\text{s}} \times \sqrt{T} = 8.94 \times 10^5\,\frac{\text{m}}{\text{s}}$$

We plug this velocity into the orbital velocity law to find the mass:

$$M = \frac{rv^2}{G} = \frac{\left(6.2 \times 10^{22}\,\text{m}\right) \times \left(8.94 \times 10^5\,\frac{\text{m}}{\text{s}}\right)^2}{\left(6.67 \times 10^{-11}\,\frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right)} = 7.4 \times 10^{44}\,\text{kg}$$

Dividing by 2×10^{30} kg/solar mass, we have 3.7×10^{14} solar masses inside 2 Mpc. (Note that this answer depends on the Hubble constant and maybe even other cosmological constants that must be assumed to figure out how "big" the cluster of galaxies is.)

20. If all the stars were identical, Sun-like stars, their mass-to-light ratios in solar units would be 1. If you measured a mass-to-light ratio of 30 solar masses per solar luminosity, you could find the amount of dark matter by assuming the dark matter contributes nothing to the luminosity. You can divide the total mass into stellar mass (M_*) and dark matter mass (M_{DM}). The galaxy has luminosity L, completely provided by stars. Therefore:

$$\frac{M_* + M_{\mathrm{DM}}}{L} = \frac{M_*}{L} + \frac{M_{\mathrm{DM}}}{L} = 30 \text{ (measured)}$$

$$\text{We estimate that, for stars: } \frac{M_*}{L} = 1$$

$$\text{So, } \frac{M_{\mathrm{DM}}}{L} = 29 \text{ and thus } \frac{M_{\mathrm{DM}}}{M_*} = \frac{29}{1} = 29$$

a. Therefore, the ratio of dark matter to "bright" matter in this case is 29:1.

b. If all of the dark matter is in Jupiter-size objects with 0.001 solar mass each, the number (N) of MACHOs per star is:

$$\frac{M_{DM}}{M_*} = \frac{N \times (0.001\, M_{\mathrm{Sun}})}{1\, M_{\mathrm{Sun}}} = 29$$

$$\text{so } N = \frac{29}{0.001} = 29{,}000$$

If MACHOs make up the dark matter in this hypothetical galaxy, there are 29,000 MACHOs per star.

Chapter 23. The Beginning of Time

This chapter concentrates on the Big Bang model for the universe's origin and presents the evidence in favor of it.

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:

- Our section on inflation contains the WMAP results announced in early 2003. New Figure 23.16 shows the all-sky map and the dependence of temperature differences on angular separation within that map. The text has been updated to connect the cosmological model favored by that experiment with cosmological measurement covered elsewhere in the book.

Teaching Notes (By Section)

Section 23.1 Running the Expansion Backwards

This section prepares students to learn about the universe by showing how extreme the temperature of the early universe becomes if we extrapolate the present expansion of the universe into the past.

Section 23.2 A Scientific History of the Universe

This section outlines the scientific history of the universe according to the Big Bang theory.

- If you are pressed for time or do not want to devote time to deeper cosmological issues, this section may be the only one you want to cover.
- Many aspects of the early universe will be clearer to students who have studied the material on elementary particles and quantum physics in Chapter S4.
- Inflation of the universe does not necessarily coincide with the end of the GUT era, but we discuss it here because the idea of inflation arose out of GUT physics.
- The mass-energy density of the universe goes from radiation-dominated to matter-dominated at $z \approx 10{,}000$. While the distinction between a matter-dominated universe and a radiation-dominated universe is important to astronomers, causing a change in the relation between time and redshift, it is a relatively subtle concept to explain to students. We chose not to mention it here because it does not bring about a qualitative change in the contents of the universe and because the students already have enough eras to keep in mind.

Section 23.3 Evidence for the Big Bang

In this section, we present the two strongest pieces of evidence in favor of the Big Bang theory: the cosmic background radiation and the helium abundance of the universe.

- The relationship between the microwave background fluctuations seen by COBE and the underlying mass distribution is less direct than it might seem at first glance. In perturbations larger than the cosmological horizon, matter and radiation go hand in hand. As time passes, the horizon grows to encompass ever vaster perturbations, and at $z > 1{,}000$, perturbations of ordinary matter that have just become smaller than the horizon start to oscillate because the trapped photons resist gravitational compression. However, if structure formation in the early universe involves WIMPs, as many astronomers suspect, the dark-matter components of these perturbations continue to grow. The temperature fluctuations recorded in the microwave background therefore depend on the phase of the oscillating compression waves at the time of recombination as well as the gravitational redshift owing to the growing dark-matter potential wells.
- The moment at which microwave background photons begin to stream freely across the universe is often said to be simultaneous with the moment of recombination. However, while most electrons are captured into photons at $z \approx 1{,}500$, the remaining free electrons in the universe continue to scatter background photons until $z \approx 1{,}000$. We do not draw attention to this discrepancy in the text, but it leaves us with two different redshifts to choose from when defining the end of the era of nuclei. We have chosen to define the end of this era to be at $z \approx 1{,}000$ because it makes the arithmetic and memorization easier for students (i.e., 3 K now implies 3,000 K at the time of last scattering.)

Section 23.4 Inflation

This section presents three well-known problems with the Big Bang model—the origin of structure, the smoothness problem, and the flatness problem—and then discusses how an early episode of inflation might solve all three.

- We pay little attention to the steady state theory of the universe in this chapter because it is no longer a viable alternative to the Big Bang theory; we now have ample evidence that galaxies in the universe evolve in rough synchronization. A more current controversy to focus on is the question of whether inflation really happened. Should we prefer the classic Big Bang theory, with its attendant problems, or the inflation-modified Big Bang theory, which might solve these problems but has little hard evidence in its favor?

- Density perturbations in the early universe must all have had roughly the same amplitude when first encompassed by the cosmological horizon. This type of uniformity arises naturally in inflationary models—a point in their favor. However, naive models of inflation overpredict the amplitudes of these fluctuations by a few orders of magnitude—a strike against them.
- Inflation naturally explains the uniformity of the microwave background temperature. This is perhaps the most significant success of inflation theory, because there is currently no other plausible explanation.
- Increasingly sophisticated observations of variations in the microwave background temperature across the sky will test the idea of inflation over the next several years. We encourage students to be on the lookout for news items about these experiments.

Section 23.5 Did the Big Bang Really Happen?

In this section, the last on cosmology and the universe, we want to leave the students looking up at the sky and thinking for themselves, so we pose the question "Why is the night sky dark?" This leads to a discussion of Olbers' paradox and its implications about the evolution of the universe.

- The text states that the darkness of the night sky implies that "the universe has either a finite number of stars, or it changes in time in some way that prevents us from seeing an infinite number of stars." Note that while the gross characteristics of the universe in the steady state model do not change with time, the universe does change on smaller scales in a way that solves Olbers' paradox. Old galaxies are flying apart and are redshifted out of view with the expansion of the universe, while new galaxies appear in the growing gaps. For more on the subject of Olbers' paradox, consult Edward Harrison's excellent book, *Darkness at Night.*

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 23.3

- A variety of stars and galaxies spanning a wide range of redshifts would produce thermal radiation at many different temperatures, quite unlike the pure thermal spectrum we observe. However, the Big Bang theory successfully predicts that the universe should be permeated by thermal radiation at a uniform temperature.
- The Big Bang fused 25% of the normal matter in the universe into helium. Galaxies that have not cycled very much of their gas through stars should not have much more than 25% helium. No galaxies should have less than this amount, because stars can only increase the helium fraction—they cannot diminish it.
- The density of normal matter we infer from the abundances of deuterium and other light elements is a few times less than the density of dark matter we infer from mass-to-light ratios and other techniques. That is why astronomers suspect that the majority of the mass in the universe is made up of weakly interacting particles. However, our estimates of the overall density of the universe are still somewhat uncertain, so we cannot be absolutely sure that WIMPs or something like them really pervades the cosmos.

Solutions to End-of-Chapter Problems (Chapter 23)

1. According to the Big Bang theory, the universe's temperature was greater than 10 billion (10^{10}) K when the universe was less than one-ten-billionth (10^{-10}) of a second old. *This statement is sensible. Figure 22.1 shows just such a relationship between time and temperature.*
2. Although the universe today appears to be made mostly of matter and not antimatter, the Big Bang theory suggests that the early universe had nearly equal amounts of matter and antimatter. *This statement is sensible. According to the Big Bang theory, the universe was hot enough to generate matter–antimatter pairs of particles very early in time, ensuring that the amounts of matter and antimatter were virtually equal.*
3. According to the Big Bang theory, the cosmic microwave background was created when energetic photons ionized the neutral hydrogen atoms that originally filled the universe. *This statement is not sensible. On the contrary, the cosmic microwave background was created when there were too few energetic photons in the universe to keep the hydrogen ionized. After the transition from ionized hydrogen to neutral hydrogen, the universe became much more transparent, and the photons that eventually became the cosmic microwave background began to stream freely across the universe.*
4. While the existence of the cosmic microwave background is consistent with the Big Bang theory, it is also easily explained by assuming that it comes from individual stars and galaxies. *This statement is not sensible. The cosmic microwave background is extremely smooth across the sky, and its blackbody spectrum corresponds to a very precise temperature. The characteristics of this background would not be so uniform if it came from many different objects.*
5. According to the Big Bang theory, most of the helium in the universe was created by nuclear fusion in the cores of stars. *This statement is not sensible. According to the Big Bang theory, most of the helium in the universe was created by fusion in the uniform gas that filled the universe during the first few minutes after the Big Bang.*
6. The theory of inflation suggests that the structure in the universe today may have originated as tiny quantum fluctuations. *This statement is sensible. If inflation really happened, then tiny quantum fluctuations present in the universe before inflation were stretched to enormous size during the episode of inflation. These fluctuations would then be large enough to eventually grow into galaxies and clusters of galaxies.*
7. Within the next decade, observations of the cosmic microwave background will prove definitively whether inflation really occurred in the early universe. *This statement is not sensible. Proving that inflation really happened will be extremely difficult. However, experiments now under way could prove that inflation did* not *happen. If inflation keeps passing such tests, then our confidence in it will grow.*
8. The fact that the night sky is dark tells us that the universe cannot be infinite, unchanging, and everywhere the same. *This statement is sensible. Olbers' paradox states that if the universe were infinite, unchanging, and everywhere the same, then the entire sky would blaze as brightly as the Sun.*
9. The ideal story will begin with the genesis of a proton as a partner in a proton–antiproton pair shortly after the Big Bang and will include incorporation into a star massive enough to create oxygen nuclei.

10–16. 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.

17. a. The wavelength of maximum intensity for thermal radiation with a temperature of 3,000 K is:

$$\lambda_{\max} = \frac{2.9\times10^6}{T(\mathrm{K})}\ \mathrm{nm} = \frac{2.9\times10^6}{3000\ \mathrm{K}}\ \mathrm{nm} = 970\ \mathrm{nm}$$

b. If the current temperature of the microwave background is 2.73 K:

$$\lambda_{\max} = \frac{2.9\times10^6}{T(\mathrm{K})}\ \mathrm{nm} = \frac{2.9\times10^6}{2.73\ \mathrm{K}}\ \mathrm{nm} = 1.06\times10^6\,\mathrm{nm} = 1.06\ \mathrm{mm}$$

The peak of the microwave background is near 1 mm.

c. The ratio between the peak wavelength at the time of recombination, when the universe was at 3,000 K, and now is:

$$\frac{\lambda_{\max,\,T=2.73}}{\lambda_{\max,\,T=3000}} = \frac{1.1\times10^6\,\mathrm{nm}}{970\ \mathrm{nm}} = \frac{3000\ \mathrm{K}}{2.73\ \mathrm{K}} \approx 1000$$

This change is consistent with an expansion factor (or $1 + z$) of 1,000. (Hence you may hear astronomers talking about the recombination epoch at $z = 1{,}000$.) As the universe expands, so does the wavelength of the photons in the microwave background.

18. Answers may vary, but students should at least be able to state that inflation is being tested using observations of temperature differences in the cosmic microwave background.

19. a. This problem might help students only a very little in "visualizing" 10^{100} years, but it helps some students to practice with scientific notation and powers of 10. A trillion years is 10^{12} years, 100 times longer than 10^{10} years (10 billion years). A quadrillion years, 10^{15} years, is 100,000 times longer than 10 billion years, and 10^{20} years is 10 billion times longer than 10 billion years.

b. If protons have a half-life of 10^{32} years, the number of remaining protons will be one-half the current number in 10^{32} years; this is the definition of a half-life. The number of remaining protons will be one-fourth the current number in 2×10^{32} years. By 10^{34} years, 100 half-lives of 10^{32} years will have gone by. By that time, $(1/2)^{100} = 7.9 \times 10^{-31}$ of the original protons exist. By 10^{40} years, 10^8 half-lives will have gone by. The fraction 1/2 raised to the power of 100 million is a very small number, so 100 million half-lives is more than sufficient for all of the protons in the universe to be gone.

c. 10^{100} zeros are a lot of zeros. If one zero could be written into 1 cubic micrometer, how many zeros could fit into the observable universe? One cubic micrometer is $10^{-6}\ \mathrm{m} \times 10^{-6}\ \mathrm{m} \times 10^{-6}\ \mathrm{m} = 10^{-18}\ \mathrm{m}^3$, a very small thing. How many cubic micrometers are there in the observable universe? If we take the approximate size of the universe to be 15 billion light-years in radius, then the volume of the universe in cubic micrometers is:

$$\frac{4}{3}\pi r^3 = \frac{4}{3}\pi\left[1.5\times10^{10}\mathrm{ly}\times\left(9.46\times10^{15}\,\frac{\mathrm{m}}{\mathrm{ly}}\right)\times\left(10^6\,\frac{\mu\mathrm{m}}{\mathrm{m}}\right)\right]^3 \approx 10^{97}\,\mu\mathrm{m}^3$$

So only 1/1000 of 10^{100} zeros of one cubic micrometer would fit into the observable universe. (*Note:* Carl Sagan performed a short "skit" illustrating this point in his *Cosmos* series.)

Chapter 24. Life Beyond Earth: Prospects for Microbes, Civilizations, and Interstellar Travel

This final chapter discusses the fascinating topic of life in the universe, and includes discussion of SETI and prospects for interstellar travel. ***Note that although this chapter is included in Part VI, it can be covered independently of all the other chapters in Parts IV through VI. In particular, if you have a course on the solar system, you may wish to cover this chapter immediately after Chapter 14.*** *Note 2:* This chapter is essentially a very condensed version of topics covered in the text *Life in the Universe*, by Bennett, Shostak, and Jakosky. That text can be used for a full-semester course on life in the universe.

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?

This is an entirely new chapter for the third edition, though some parts of it formerly appeared in Chapters 13 and S5 of the second edition.

Teaching Notes (By Section)

Section 24.1 The Possibility of Life Beyond Earth

"Astrobiology" is a relatively new term and new field of study, and this section briefly describes why it has become such a hot topic of late.

Section 24.2 Life in the Solar System

This section covers possibilities for finding life elsewhere in our solar system, with the greatest emphasis on Mars and Europa. Note that it also includes a discussion of *Viking* results from Mars and of controversy over whether a martian meteorite contains evidence of past life on Mars.

Section 24.3 Life Around Other Stars

This section considers prospects for life on planets around other stars. We also discuss the "rare Earth hypothesis" in this section, emphasizing that arguments can be made on both sides of this hypothesis, and therefore that we cannot reach any conclusions about it until more data are available.

Section 24.4 The Search for Extraterrestrial Intelligence

This section provides a very short discussion of SETI efforts.

- Note that we use a modified version of the Drake equation that is easier for students to understand. We still call it the "Drake equation," thanks to approval from Frank Drake himself!
- We recommend to our students that they watch the movie *Contact*, or read the book by Carl Sagan. The movie can generate very interesting class discussions.

Section 24.5 Interstellar Travel

This section offers a brief overview of the difficulty of interstellar travel and several potential technologies for interstellar travel.

- For each technology described, we also state an approximate speed (as a percentage of the speed of light) that this technology could reach. Precise calculations of these speeds depend on many variables, including the mass of the spacecraft payload; obviously, a lower-mass payload

can reach a higher speed with the same technology. The values we have given for speeds are based on assuming large payloads that could support many crew members.
- The box about UFOs (Are Aliens Already Here?) should be interesting to many students, and can be discussed thoughtfully once students understand something about the challenge of interstellar travel.

Section 24.6 A Paradox: Where Are the Aliens?

This final section discusses Fermi's question "where is everybody?" We find that students are particularly intrigued by this paradox and its astonishing implications. This discussion also makes a nice wrap-up to a course.

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 24.1

- This is a subjective question, but arguably the weakest link is taking the rapid appearance of life on Earth to imply that life can arise relatively easily. With statistics of one, it's always possible that the Earth was the beneficiary of some extraordinarily good luck, and that the overall probability of life arising with hundreds of millions of years is very small. The assumption that the Earth's case is "typical" is a common one in science, but until we have other cases we cannot be sure it is correct.

Section 24.2

- If Martian life shares a common ancestor with Earth life, it should have many chemical similarities, such as DNA as its hereditary material, a similar or identical genetic code, similar metabolism, etc. If the Martian life has very different chemistry, then it probably arose independently.
- A full discussion of this topic would require more chemistry than students have learned in this book, but students can still respond by thinking about the importance of water for transporting chemicals within living organisms. In that case, those who argue that a liquid is not necessary must come up with alternative ideas about how the life "lives" (e.g., metabolizes, reproduces, evolves). A survey of science fiction will show no shortage of ideas, so a class discussion may be interesting to see whether students consider such ideas plausible. *Note:* One of the flaws of many science fiction life forms is that they make sense as described, but there's no way to see how they could have evolved in the first place from the basic chemical constituents we might find anyplace in the universe. If students propose such ideas, ask them to consider how the lifeforms came to exist.

Section 24.3

- There is no definitive answer to this question, but it can generate interesting discussion. Certainly, it can be argued that evolution might have proceeded more rapidly with more impacts. On the other hand, if the impacts are large enough to be sterilizing, that would be very bad for extant life. Similarly, it is hard to believe that a large impactor every 10,000 years would be good. Perhaps there is some optimum impact rate that would have the maximum positive effects on evolution.

Section 24.4

- For this example we have $N_{HP} = 1{,}000$; $f_{\text{life}} = 1/10$; $f_{\text{civ}} = 1/4$, and $f_{\text{now}} = 1/5$. In that case, we find: number of civilizations = $1{,}000 \times 1/10 \times 1/4 \times 1/5 = 5$. That is, with these numbers, the

Drake equation tells us that there are 5 civilizations (with which we could potentially communicate) out there now.

- This is a subjective question that should get students discussing evolutionary imperatives. For example, many biologists see advantages in two eyes (e.g., depth perception) and an opposable thumb, and sexual reproduction is an efficient way of shuffling genes. Students can debate whether the same "solutions" to problems of survival are likely to have evolved on other worlds.
- This is a very subjective question that can generate a good discussion about SETI efforts. You might point students to the book or movie *Contact* as a way of thinking about the question.

Section 24.5

- This question (Would you go on a long interstellar trip?) can be interesting to discuss in terms of who would and would not go.
- The question of whether an interstellar civilization is extinction-proof can generate a lot of discussion. For discussion of a related issue, we often recommend that students read the science fiction novel *The Forever War,* by Joe Haldeman.

Solutions to End-of-Chapter Problems (Chapter 24)

1. The first human explorers on Mars discover that the surface is littered with the ruins of an ancient civilization, including remnants of tall buildings and temples. *This statement is fantasy. If any such civilization ever existed on the surface of Mars, we would know about it by now.*
2. The first human explorers on Mars drill a hole into a Martian volcano to collect a sample of soil from several meters underground. Upon analysis of the soil, they discover that it holds living microbes resembling terrestrial bacteria but with a different biochemistry. *This statement is science fiction: it could actually happen, since there could be microbes on Mars and, if so, Martian life could have a different biochemistry from life on Earth.*
3. In 2020, a spacecraft lands on Europa and melts its way through the ice into the Europan ocean. There, it finds numerous strange, living microbes, along with a few larger organisms that feed on the microbes. *This statement is science fiction because it could really happen, assuming we are correct about the existence of an ocean under the icy surface of Europa.*
4. It's the year 2075. A giant telescope on the Moon, consisting of hundreds of small telescopes linked together across a distance of 500 kilometers, has just captured a series of images of a planet around a distant star on which we can clearly see seasonal changes in vegetation. *This could really happen if we really build such large sets of interlinked telescopes (interferometers).*
5. A century from now, after completing a careful study of planets around stars within 100 light-years of Earth, we've discovered that the most diverse life exists on a planet orbiting a young star that formed just 100 million years ago. *This could not happen according to our present understanding of the origin of planets and life, because during the first 100 million years of a star system's history we expect the planet to be pelted by many large impacts. If life could arise so quickly at all, it would almost certainly be extinguished.*
6. In 2030, a brilliant teenager discovers a way to build a rocket that burns coal as its fuel and can travel at half the speed of light. *This statement is fantasy, because chemical burning cannot possibly release enough energy to achieve such speeds.*
7. In the year 2750, we receive a signal from a civilization around a nearby star telling us that the *Voyager 2* spacecraft recently crash-landed on their planet. *This statement is fantasy, because* Voyager *will take tens of thousands of years to reach the distance of even the nearest stars.*

8. Crew members of the matter-antimatter spacecraft *Star Apollo*, which left Earth in the year 2165, returns to Earth in the year 2450, looking only a few years older than when they left. *This is possible on a spacecraft that travels at a speed very close to the speed of light, thanks to effects of time dilation as explained by Einstein's theory of relativity.*
9. By traveling through a wormhole apparently constructed by an advanced civilization, future explorers can journey from our solar system to a star system near the center of the galaxy in just a few hours. *Students could argue this one either way, but based on present knowledge it seems that this could be true, at least in principle. Indeed, it was a premise of the book/movie* Contact, *by Carl Sagan. However, many scientists suspect that we'll someday learn reasons why this could not really be possible.*
10. Aliens from a distant star system invade the Earth with the intent to destroy us and occupy our planet, but we successfully fight them off with a great effort by our best scientists and engineers. *This is fantasy. The ability to travel through interstellar space requires technology far beyond that which we possess today. Clearly, a war between us and such advanced aliens would be a terrible mismatch—and not in our favor.*
11. The galaxy is divided into a series of empires, each having arisen from a different civilization, that hold each other at bay through the threat of military action. *This statement is almost certainly fantasy, because the chance of multiple civilizations having emerged close enough together in time to share similar levels of technology is vanishingly small.*
12. A single, great galactic civilization exists. It originated on a single planet long ago but is now made up of beings from many different planets, each of which was assimilated into the galactic culture in turn. *Based on what we know today, this certainly seems like it could be possible—and how amazing it would be if it turns out to be true!*

13–16. These are all essay questions, in which the key is for students to explain their answers and defend their opinions well.