Chapter-by-Chapter Guide

Part I: Developing Perspective

The remainder of this *Instructor Guide* reviews the book chapter by chapter. Within each chapter, it is organized as follows:

- A brief introduction with general comments about the chapter.
- Miscellaneous teaching notes organized section by section for the chapter that may be of use to you when teaching your course.
- Answers/discussion points for Think About It and See It For Yourself questions.
- Solutions to end-of-chapter problems.

Chapter 1. Our Place in the Universe

The purpose of this first chapter is to provide students with the contextual framework they need to learn the rest of the course material effectively: a general overview of our cosmic address and origins (Section 1.1), an overview of the scale of space and time (Section 1.2), and an overview of motion in the universe (Section 1.3). We often tell students that, after completing this first chapter, they have learned all the major ideas of astronomy, and the rest of the course will build the detailed scientific case for these general ideas.

As always, when you prepare to teach this chapter, be sure you are familiar with the relevant media resources and the online quizzes and other resources available on the MasteringAstronomy website.

Teaching Notes (By Section)

Section 1.1 Our Modern View of the Universe

This section provides a brief summary of our modern view of the universe, including its hierarchical structure (our cosmic address) and its history (our cosmic origins).

- We urge you to pay special attention to the full-page Figure 1.1 and the two-page Cosmic Context Figure 1.2. These figures should help your students keep our cosmic address and origins in context throughout the course, and you may wish to refer back to them often.
- Note the box Basic Astronomical Objects, Units, and Motion. Although some of the terms in this box are not discussed immediately, placing them in the beginning of the book should be helpful to students. All these terms also appear in the glossary, but they are so basic and important that we want to emphasize them here in Chapter 1.
- Note that we've chosen to use *light-years* rather than *parsecs* as our primary unit for astronomical distances for the following three reasons:

1. We have found that light-years are more intuitive than parsecs to most students because light-years require only an understanding of light travel times, not the more complex trigonometry of parallax.
2. Lookback time is one of the most important concepts in astronomy, and use of light-years makes it far easier to think about lookback times (e.g., when a student hears that a star is 100 light-years away, he/she can immediately recognize that we're seeing light that left the star 100 years ago).
3. Fortuitously, 1 light-year happens to be very close to 10^{13} kilometers (9.46×10^{12} km), making unit conversions very easy—this helps students remember that light-years are a unit of distance, not of time.

- FYI: The 2.5-million-light-year distance to the Andromeda Galaxy is based on results reported by K. Stanek and P. Garnavich, 1998, *Astrophysical Journal Letters*, 503, L131. They give the distance to Andromeda as 784 kiloparsecs, with a statistical error of ±13 and a systematic error of ±17. This distance is based on Hipparcos distances of red clump (helium core-burning) stars in the Milky Way and Hubble observations of red clump stars in Andromeda.
- We give the age of the universe as about 14 billion years based on the Wilkinson Microwave Anisotropy Probe (WMAP) results (http://map.gsfc.nasa.gov/). The WMAP results are consistent with an age of 13.7 billion years with a 1 sigma error bar of 0.2 billion years.

Section 1.2 The Scale of the Universe

We devote this section to the scale of space and time because our teaching experience tells us that this important topic generally is underappreciated by students. Most students enter our course without any realistic view of the true scale of the universe. We believe that it is a disservice to students to teach them about the content and physics of the universe without first giving them the large-scale context.

- We make use of the 1-to-10-billion scale of the Voyage scale-model solar system in Washington, D.C., a project that was proposed by *The Essential Cosmic Perspective* author Bennett. Voyage replicas are being developed for other science centers; if you are interested in learning more about how to get a Voyage replica in your town, please contact the author. (The same scale is also used in the Colorado Scale Model Solar System in Boulder.)
- With regard to counting to 100 billion, it can be fun in your lecture to describe what happens when you ask children how long counting that high would take. Young children inevitably say they can count much faster than one number per second. But what happens when they get to, say, "twenty-four billion, six hundred ninety-seven million, five hundred sixty-two thousand, nine hundred seventy-seven . . ."? How fast can they count now? And can they remember what number comes next?
- Regarding our claim that the number of stars in the observable universe is roughly the same as the number of grains of sand on all the beaches on Earth, here are the assumptions we've made:

- We are using 10^{22} as the number of stars in the universe. Assuming that grains of sand typically have a volume of 1 mm^3 (correct within a factor of two or three), 10^{22} grains of sand would occupy a volume of 10^{22} mm^3, or 10^{13} m^3.
- We estimate the depth of sand on a typical beach to be about 2–5 m (based on beaches we've seen eroded by storms) and estimate the width of a typical beach to be 20–50 m; thus, the cross-sectional area of a typical beach is roughly 100 m^2.
- With this 100 m^2 cross-sectional area, it would take a length of 10^{11} m, or 10^8 km, to comprise a volume of 10^{13} m^3. This is almost certainly greater than the linear extent of the sandy beaches on Earth.

- The idea of a "cosmic calendar" was popularized by Carl Sagan. Now that we've calibrated the cosmic calendar to have a cosmic age of 14 billion years, note that 1 average month = 1.17 billion years.

Section 1.3 Spaceship Earth

This section completes our overview of the big picture of the universe by focusing on motion in the context of the motions of Earth in space, using R. Buckminster Fuller's idea of *Spaceship Earth*.

- There are several different ways to define an average distance between Earth and the Sun (e.g., averaged over phase, over time, etc.). In defining an astronomical unit (AU), we use the term *average* to mean (perihelion + aphelion)/2, which is equivalent to the semimajor axis. This has advantages when it comes to discussing Kepler's third law, as it is much easier for students to think of a in the equation $p^2 = a^3$ as *average* rather than as *semimajor axis*.
- We use the term *tilt* rather than *obliquity* as part of our continuing effort to limit the use of jargon.
- We note that universal expansion generally is not discussed until very late in other books. However, it's not difficult to understand through the raisin cake analogy; most students have heard about it before (though few know what it means), and it's one of the most important aspects of the universe as we know it today. Given all that, there's no need to wait to introduce it.

Answers/Discussion Points for Think About It/See It For Yourself Questions

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

Section 1.1

- (p. 4) This question is, of course, very subjective, but it can make for a lively in-class debate.
- (p. 9) If people were looking from the Andromeda Galaxy at the Milky Way, they would see a spiral galaxy looking much like their galaxy looks

to us. They would see our galaxy as it was about 2.5 million years ago (due to light travel time) and thus could not know that our civilization exists here today.

Section 1.2

- (p. 10) This is another very subjective question, but it should get students thinking about the size of Earth in the cosmos. At the very least, most students will be very surprised at how small our planet seems in relation to the solar system. For most students, it makes Earth seem a little more fragile and often makes them think more about how we can best take care of our planet.
- (p. 14) This question also may be a great topic of debate. We've found that most students think it is inconceivable that we are the only intelligent beings. However, some religious students will assume we are alone based on their faith. In both cases, it can generate discussion about how science relies only on evidence. For example, we don't assume that others exist because we have no evidence that they do, and we don't assume we are alone for the same reason.

Section 1.3

- (p. 16) As we authors understand it, the only real reason that globes are oriented with north on top is that most of the early globe makers lived in the Northern Hemisphere. In any case, it is certainly equally correct to have the globe oriented in any other way.
- (p. 17) This question is easy to discuss if you refer to the 1-to-10-billion scale model developed earlier. On this scale, entire star systems (including all their planets) are typically only a few hundred meters in diameter, and they are separated from other systems by thousands of kilometers (at least in our vicinity of the galaxy).

Solutions to End-of-Chapter Problems (Chapter 1)

(Note: Solutions provided in the *Instructor Guide* are intended as samples only; individual answers may vary.)

1. A geocentric universe is one in which Earth is assumed to be at the center of everything. In contrast, our current view of the universe suggests that Earth is a rather ordinary planet orbiting a rather ordinary star in an ordinary galaxy, and there is nothing "central" about Earth at all.
2. The largest scale is the universe itself, which is the sum of all matter and energy. The largest-known organized structures are superclusters of galaxies, then clusters and groups of galaxies, and then the roughly 100 billion individual galaxies, most of which are many thousands of light-years across. Each galaxy contains billions of stars and many or most stars may be orbited by planets.

3. When we say that the universe is expanding, we mean that the average distance between galaxies is increasing with time. If the universe is expanding, then if we imagine playing time backward, we'd see the universe shrinking. Eventually, if we went back far enough in time, the universe would be compressed until everything was on top of everything else. This suggests that the universe may have been very tiny and dense at some point in the distant past and has been expanding ever since. This beginning is what we call the *Big Bang*.
4. Most of the atoms in our bodies (all the elements except for hydrogen, since our bodies generally do not contain helium) were made by stars well after the Big Bang. So most of what makes up our bodies was once part of stars.
5. Light travels at 300,000 kilometers per second. A light-year is the distance that light travels in 1 year, which is about 9.46 trillion kilometers.
6. Because light travels at a fixed speed, it takes time for it to go between two points in space. Although light travels very quickly, the distances in the universe are so large that the time for light to travel between stars is years or longer. The farther away we look, the longer it takes light to have traveled to us from the objects being viewed. Thus, the light we see from more distant objects started its journey longer ago. This means that what we see when we look at more distant objects is how they looked longer ago in time. So looking farther away means looking further back in time.
7. The observable universe is the portion of the entire universe that we can, in principle, see. It is presumably about 14 billion light-years in radius because light from more than 14 billion light-years away could not yet have reached us during the 14 billion years since the Big Bang. Scientists currently think that the entire universe is larger than the observable universe.
8. On the 1-to-10-billion scale, the Sun is about the size of a grapefruit and the planets are the sizes of marbles or smaller. The distances between the planets are a few meters for the inner solar system to many tens of meters in the outer solar system. On the same scale, the nearest stars are thousands of kilometers away.
9. One way to understand the size of our galaxy is to note that if the Milky Way were the size of a football field, then the distance to the nearest star would be about 4 millimeters. One way to get a sense of the size of the observable universe is to note that the number of stars in it is comparable to the number of grains of sand on all of the beaches on the entire Earth.
10. There are numerous ways to describe how humanity fits into cosmic time, but here is one straight from the cosmic calendar: If the entire history of the universe were compressed into a single year, modern humans would have evolved only 2 minutes ago and the pyramids would have been built only 11 seconds ago.
11. Astronomical unit: The average distance between Earth and Sun, which is about 1.496×10^8 km.

    Ecliptic plane: The two-dimensional plane in which Earth orbits around the Sun. Most of the other planets orbit nearly in this same plane.

Axis tilt: The amount that a planet's rotation axis is tipped relative to a line *perpendicular* to the ecliptic plane.

12. The Milky Way Galaxy is a spiral galaxy, which means that it is disk-shaped, with a large bulge in the center. The galactic disk includes a few large spiral arms. Our solar system is located about 28,000 light-years from the center of the galaxy, or about halfway out to the edge of the galaxy. Our solar system orbits about the galactic center in a nearly circular orbit, making one trip around every 230 million years.
13. The disk of the galaxy is the flattened area where most of the stars, dust, and gas reside. The halo is the large, spherical region that surrounds the entire disk and contains relatively few stars and virtually no gas or dust. Dark matter resides primarily in the halo.
14. Edwin Hubble discovered that most galaxies are moving away from our galaxy, and the farther away they are located, the faster they are moving away. While at first this might seem to suggest that we are at the center of the universe, a little more reflection indicates that this is not the case. If we imagine a raisin cake rising, we can see that every raisin will move away from every other raisin. So each raisin will see all of the others moving away from it, with more distant ones moving faster—just as Hubble observed galaxies to be moving. Thus, just as the raisin observations can be explained by the fact that the raisin cake is expanding, Hubble's galaxy observations tell us that our universe is expanding.
15. *Our solar system is bigger than some galaxies.* This statement does not make sense because all galaxies are defined as collections of many (a billion or more) star systems, so a single star system cannot be larger than a galaxy.
16. *The universe is billions of light-years in age.* This statement does not make sense because it uses the term *light-years* as a time, rather than as a distance.
17. *It will take me light-years to complete this homework assignment.* This statement does not make sense because it uses the term *light-years* as a time, rather than as a distance.
18. *Someday, we may build spaceships capable of traveling a light-year in only a decade.* This statement is fine. A light-year is the distance that light can travel in 1 year, so traveling this distance in a decade would require a speed of 10% of the speed of light.
19. *Astronomers recently discovered a moon that does not orbit a planet.* This statement does not make sense because a moon is defined to be an object that orbits a planet.
20. *NASA soon plans to launch a spaceship that will photograph our Milky Way Galaxy from beyond its halo.* This statement does not make sense because of the size scales involved. Even if we could build a spaceship that traveled close to the speed of light, it would take tens of thousands of years to get high enough into the halo to photograph the disk and then tens of thousands of years more for the picture to be transmitted back to Earth.
21. *The observable universe is the same size today as it was a few billion years ago.* This statement does not make sense because the universe is growing larger as it expands.

22. *Photographs of distant galaxies show them as they were when they were much younger than they are today.* This statement makes sense because when we look far into space, we also see far back in time. Thus, we see distant galaxies as they were in the distant past, when they were younger than they are today.
23. *At a nearby park, I built a scale model of our solar system in which I used a basketball to represent the Earth.* This statement does not make sense. On a scale where Earth is the size of a basketball, we could not fit the rest of the solar system in a local park. (A basketball is roughly 200 times the diameter of Earth in the Voyage model described in the book. Because the Earth-Sun distance is 15 meters in the Voyage model, a basketball-size Earth would require an Earth-Sun distance of about 3 kilometers and a Sun-Pluto distance of about 120 kilometers.)
24. *Because nearly all galaxies are moving away from us, we must be located at the center of the universe.* This statement does not make sense, as we can tell when we think about the raisin cake model. Every raisin sees every other raisin moving away from it, so in this sense no raisin is any more central than any other. (Equivalently, we could say that every raisin—or galaxy—is the center of its own observable universe, which is true but very different from the idea of an absolute center to the universe.)
25. a; 26. b; 27. c; 28. b; 29. c;
30. b; 31. a; 32. a; 33. b; 34. a.
35. Major changes in scientific views are possible because science relies on physical evidence. Science must be backed by evidence from observations or experiments, and when the evidence does not back up the scientific story, the story is changed. That is what happened, for example, when belief in an Earth-centered universe gave way to the idea that Earth orbits the Sun. (In contrast, religious or cultural beliefs generally are less subject to change because they are based on faith or scriptures rather than on a search for physical evidence.)
36. Using the Voyage model scale (1 to 10 billion), Earth is barely 1 mm across, but is located 15 meters from the Sun. In other words, Earth's distance from the Sun is some 15,000 times greater than Earth's diameter. Given that fact, the difference in distance of the day and night sides of Earth is negligible, so it would be difficult to see how it could explain day and night temperature differences. If we had no other explanation for the temperature difference, then we might still be forced to consider whether there is some missing piece to our understanding. In this case, however, we have a much simpler alternative explanation: the day side is warm because it faces the Sun, and the night side is cooler because it faces away from the Sun.
37. Answers will vary. This question is designed to get students thinking about the nature of evidence and what it might take to get them to accept some scientific idea.
38. This is a new group work project.
39. This is a short essay question. Key points should include the fact that we are made of elements forged in past generations of stars and that those elements

were able to be brought together to make our solar system because of the recycling that occurs within the Milky Way Galaxy.

40. This is a short essay question. Key points should include discussion of the difference in scale between interstellar travel and travel about our own world so that students recognize that alien technology would have to be far more advanced than our own to allow them to visit us with ease.

41. There is no danger of a collision between our star system and another in the near future. Such collisions are highly improbable in any event—remember that our Sun is separated from the nearest stars like grapefruits spaced thousands of miles apart. Moreover, we can observe the motions of nearby stars, and none of them are headed directly our way.

42. a. The diagrams should be much like Figure 1.16, except that the distances between raisins in the expanded figure will be 4 centimeters instead of 3 centimeters.

b.

Distances and Speeds of Other Raisins as Seen from the Local Raisin

Raisin Number	Distance Before Baking	Distance After Baking (1 hour later)	Speed
1	1 cm	4 cm	3 cm/hr
2	2 cm	8 cm	6 cm/hr
3	3 cm	12 cm	9 cm/hr
4	4 cm	16 cm	12 cm/hr
⋮	⋮	⋮	⋮
10	10 cm	40 cm	30 cm/hr
⋮	⋮	⋮	⋮

c. As viewed from any location inside the cake, more distant raisins appear to move away at faster speeds. This is much like what we see in our universe, where more distant galaxies appear to be moving away from us at higher speeds. Thus, we conclude that our universe, like the raisin cake, is expanding.

43. This is a subjective essay question. The grade should be based on clarity of the essay.

44. a. A light-second is the distance that light travels in 1 second. We know that light travels at a speed of 300,000 km/s, so a light-second is a distance of 300,000 kilometers.

b. A light-minute is the speed of light multiplied by 1 minute:

$$\begin{aligned} 1 \text{ light-minute} &= (\text{speed of light}) \times (1 \text{ min}) \\ &= 300{,}000 \frac{\text{km}}{\cancel{\text{s}}} \times 1 \cancel{\text{min}} \times \frac{60 \cancel{\text{s}}}{1 \cancel{\text{min}}} \\ &= 18{,}000{,}000 \text{ km} \end{aligned}$$

That is, "1 light-minute" is just another way of saying "18 million kilometers."

c. Following a similar procedure, we find that 1 light-hour is 1.08 billion kilometers; and

d. 1 light-day is 2.59×10^{10} km, or about 26 billion kilometers.

45. Recall that

$$\text{speed} = \frac{\text{distance traveled}}{\text{time of travel}}$$

We can rearrange this with only a little algebra to solve for time:

$$\text{time of travel} = \frac{\text{distance traveled}}{\text{speed}}$$

The speed of light is 3×10^5 km/s according to Appendix A. (We choose the value in km/s rather than m/s because, looking ahead, we see that the distances in Appendix E are in kilometers.)

a. According to Appendix E, the Earth-Moon distance is 3.844×10^5 km. Using this distance and the equation above for travel time, we get

$$\text{time of travel} = \frac{3.844 \times 10^5 \cancel{\text{km}}}{3.00 \times 10^5 \cancel{\text{km}}/\text{s}} = 1.28 \text{ s}$$

Light takes 1.28 seconds to travel from the Moon to Earth.

b. Appendix E also tells us that the distance between Earth and the Sun is 1.496×10^8 km. So we calculate:

$$\text{time of travel} = \frac{1.496 \times 10^8 \cancel{\text{km}}}{3.00 \times 10^5 \cancel{\text{km}}/\text{s}} = 499 \text{ s}$$

But most people don't really know how long 499 seconds is. It would be more useful if this number were in a more appropriate time unit. So we start by converting this to minutes:

$$499 \cancel{\text{sec}} \times \frac{1 \text{ min}}{60 \cancel{\text{sec}}} = 8.32 \text{ min}$$

Because 8 minutes is 480 seconds $\left(8 \text{ min} \times \frac{60 \text{ s}}{1 \text{ min}} = 480 \text{ s}\right)$, 499 seconds is also equivalent to 8 minutes and 19 seconds. Thus, light takes 8 minutes and 19 seconds to travel from the Sun to Earth.

46. We are asked to find how many times larger the Milky Way Galaxy is than the planet Saturn's rings. We are told that Saturn's rings are about 270,000 kilometers across and that the Milky Way is 100,000 light-years. Clearly, we'll have to convert one set of units or the other. Let's change light-years for kilometers. In Appendix A, we find that 1 light-year = 9.46×10^{12} km, so we can convert:

$$100{,}000 \cancel{\text{light-years}} \times \frac{9.46 \times 10^{12} \text{ km}}{1 \cancel{\text{light-year}}} = 9.46 \times 10^{17} \text{ Km}$$

We can now find the ratio of the two diameters:

$$\text{ratio} = \frac{\text{diameter of Milky Way}}{\text{diameter of Saturn's rings}}$$
$$= \frac{9.46 \times 10^{17} \text{ km}}{2.7 \times 10^{5} \text{ km}} = 3.5 \times 10^{12}$$

The diameter of the Milky Way Galaxy is about 3.5 trillion times as large as the diameter of Saturn's rings!

47. a. The circumference of Earth is $2\pi \times 6380$ km = 40,087 km. At a speed of 100 km/hr, it would take:

$$40{,}087 \text{ km} \div 100 \text{ km/hr} = 40{,}087 \text{ km} \times \frac{1 \text{ hr}}{100 \text{ km}} \times \frac{1 \text{ day}}{24 \text{ hr}} = 16.7 \text{ days}$$

to drive around Earth. That is, a trip around the equator at 100 km/hr would take a little under 17 days.

b. We find the time by dividing the distance to the planet from the Sun by the speed of 100 km/hr. It would take about 170 years to reach Earth and about 6700 years to reach Pluto (at their mean distances).

c. Similarly, it would take 6700 years to drive to Pluto at 100 km/hr. FYI: The following table shows the driving times from the Sun to each of the planets at a speed of 100 km/hr.

Planet	**Driving Time**
Mercury	66 years
Venus	123 years
Earth	170 years
Mars	259 years
Jupiter	888 years
Saturn	1630 years
Uranus	3300 years
Neptune	5100 years
Pluto	6700 years

d. We are given the distance to Alpha Centauri in light-years; converting to kilometers, we get:

$$4.4 \text{ light-years} \times \frac{9.46 \times 10^{12} \text{ km}}{1 \text{ light-year}} = 41.6 \times 10^{12} \text{ km}$$

At a speed of 100 km/hr, the travel time to Proxima Centauri would be about:

$$4.16 \times 10^{13} \text{ km} \div 100 \frac{\text{km}}{\text{hr}} = 4.16 \times 10^{13} \text{ km} \times \frac{1 \text{ hr}}{100 \text{ km}} \times \frac{1 \text{ day}}{24 \text{ hr}} \times \frac{1 \text{ yr}}{365 \text{ day}} = 4.7 \times 10^{7} \text{ yr}$$

It would take some 47 million years to reach Proxima Centauri at a speed of 100 km/hr.

48. a. To reach Alpha Centauri in 100 years, you would have to travel at 4.4/100 = 0.044 of the speed of light, which is about 13,200 km/s or nearly 50 million km/hr.
    b. This is about 1000 times the speed of our fastest current spacecraft.

Chapter 2. Discovering the Universe for Yourself

This chapter introduces major phenomena of the sky, with emphasis on:

- The concept of the celestial sphere.
- The basic daily motion of the sky, and how it varies with latitude.
- The cause of seasons.
- Phases of the Moon and eclipses.
- The apparent retrograde motion of the planets and how it posed a problem for ancient observers.

As always, when you prepare to teach this chapter, be sure you are familiar with the relevant media resources and the online quizzes and other study resources available on the MasteringAstronomy website.

Teaching Notes (By Section)

Section 2.1 Patterns in the Night Sky

This section introduces the concepts of constellations and the celestial sphere, and introduces horizon-based coordinates and daily and annual sky motions.

- Stars in the daytime: You may be surprised at how many of your students actually believe that stars disappear in the daytime. If you have a campus observatory or can set up a small telescope, it's well worth offering a daytime opportunity to point the telescope at some bright stars, showing the students that they are still there.
- In class, you may wish to go further in explaining the correspondence between the Milky Way Galaxy and the Milky Way in our night sky. Tell your students to imagine being a tiny grain of flour inside a very thin pancake (or crepe!) that bulges in the middle and a little more than halfway toward the outer edge. Ask, "What will you see if you look toward the middle?" The answer should be "batter." Then ask what they will see if they look toward the far edge, and they'll give the same answer. Proceeding similarly, they should soon realize that they'll see a band of batter encircling their location, but that if they look away from the plane, the pancake is thin enough that they can see to the distant universe.
- Sky variation with latitude: Here, the intention is only to give students an overview of the idea and the most basic rules (such as latitude = altitude of north celestial pole). Those instructors who want their students to be able to describe the sky in detail should cover Chapter S1, which covers this same material, but in much more depth.

- Note that in our jargon-reduction efforts, we do not introduce the term *asterism*; instead we speak of patterns of stars in the constellations. We also avoid the term *azimuth* when discussing horizon-based coordinates. Instead, we simply refer to *direction* along the horizon (e.g., south, northwest). The distinction of "along the horizon" should remove any potential ambiguity for direction on the celestial sphere (where "north" would mean toward the north celestial pole rather than toward the horizon).

Section 2.2 The Reason for Seasons

This section focuses on seasons and why they occur.

- In combating misconceptions about the cause of the seasons, we recommend that you follow the logic in the Common Misconceptions box. That is, begin by asking your students what they think causes the seasons. When many of them suggest that the seasons are linked to distance from the Sun, ask how seasons differ between the two hemispheres. They should then see for themselves that the reason can't be distance from the Sun or seasons would be the same globally rather than opposite in the two hemispheres.
- As a follow-up to the above note: Some students get confused by the fact that seasons diagrams (such as our Figure 2.13) cannot show the Sun-Earth distance and size of Earth to scale. Thus, unless you emphasize this point (as we do in the figure), it might actually look like the two hemispheres have significantly different distances from the Sun. This is another reason we believe it is critical to emphasize ideas of scale throughout your course. In this case, use the scale-model solar system as introduced in Section 1.2, and students will quickly see that the two hemispheres are effectively the same distance from the Sun at all times.
- The names of the solstices and equinoxes: We refer to names as they are known in the Northern Hemisphere. However, because of the confusion this sometimes causes for Southern Hemisphere observers, we have in this edition added parentheticals indicating alternate terms for dates; that is, the spring equinox becomes the *March equinox*, the summer solstice becomes the *June solstice*, etc.
- Note that we do not go deeply into the physics that causes precession, as even a basic treatment of this topic requires discussing the vector nature of angular momentum. Instead, we include a brief motivation for the cause of precession by the analogy to a spinning top.
- Regarding Sun signs: Most astrologers have "delinked" the constellations from the Sun signs. Thus, most astrologers would say that the vernal equinox still is in Aries—it's just that Aries is no longer associated with the same pattern of stars as it was in A.D. 150.

Section 2.3 The Moon, our Constant Companion

This section discusses the Moon's motion and its observational consequences, including the lunar phases and eclipses.

- For what appears to be an easy concept, many students find it remarkably difficult to understand the phases of the Moon. You may want to do an in-class demonstration by darkening the room, using a lamp to represent the Sun, and giving each student a Styrofoam ball to represent the Moon. If your lamp is bright enough, the students can remain in their seats and watch the phases as they move the ball around their heads.
- Going along with the above note, it is virtually impossible for students to understand phases from a flat figure on a flat page in a book. Thus, we have opted to eliminate the “standard” Moon phases figure found in almost every other text that shows the Moon in eight different positions around Earth. Students just don’t get it, and the multiple moons confuse them. Instead, our Figure 2.19 shows how students can conduct a demonstration that will help them understand the phases. The Phases of the Moon tutorial at **www.masteringastronomy.com** has also proven to be very successful in helping students understand phases.
- When covering the causes of eclipses, it helps to demonstrate the Moon’s orbit. Keep a model Sun on a table in the center of the lecture area; have your left fist represent Earth, and hold a ball in the other hand to represent the Moon. Then you can show how the Moon orbits your fist at an inclination to the ecliptic plane, explaining the meaning of the nodes. You can also show eclipse seasons by demonstrating the Moon’s orbit (with fixed nodes) as you walk around your model Sun. The students will see that eclipses are possible only during two periods each year. If you then add in precession of the nodes, students can see why eclipse seasons occur slightly more often than every 6 months.
- The *Moon Pond* painting in Figure 2.20 should also be an effective way to explain what we mean by *nodes* of the Moon’s orbit.
- FYI: We’ve found that even many astronomers are unfamiliar with the saros cycle of eclipses. We hope our discussion is clear, but some additional information may help you as an instructor. The nodes of the Moon’s orbit precess with an 18.6-year period; note that the close correspondence of this number to the 18-year, 11-day saros has no special meaning (it essentially is a mathematical coincidence). The reason that the same type of eclipse (e.g., partial vs. total) does not recur in each cycle is that the Moon’s line of apsides (i.e., a line connecting perigee and apogee) also precesses—but with a different period (8.85 years).
- FYI: The actual saros period is 6585.32 days, which usually means 18 years, 11.32 days, but instead is 18 years, 10.32 days if 5 leap years occur during this period.

Section 2.4 The Ancient Mystery of the Planets

This section covers the ancient mystery of planetary motion, explaining the motion, how we now understand it, and how the mystery helped lead to the development of modern science.

- We have chosen to refer to the westward movement of planets in our sky as *apparent* retrograde motion, in order to emphasize that planets only appear to go backward, but never really reverse their direction of travel in their orbits. This makes it easy to use analogies—for example, when students try the demonstration in Figure 2.27, they never say that their friend really moves backward as they pass by, only that the friend appears to move backward against the background.

- You should emphasize that apparent retrograde motion of planets is noticeable only by comparing planetary positions over many nights. In the past, we've found a tendency for students to misinterpret diagrams of retrograde motion and thereby expect to see planets moving about during the course of a single night.
- It is somewhat rare among astronomy texts to introduce stellar parallax so early. However, it played such an important role in the historical debate over a geocentric universe that we feel it must be included at this point. Note that we do *not* give the formula for finding stellar distances yet; that comes in Chapter 11.

Answers/Discussion Points for Think About It/See It For Yourself Questions

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

Section 2.1

- (p. 30) No. We can only describe angular sizes and distances in the sky, so physical measurements do not make sense. This is a difficult idea for many children to understand, but should come easily for college students!
- (p. 32) Yes, because it is Earth's rotation that causes the rising and setting of all the objects in the sky. *Note:* Many instructors are surprised that this question often gives students trouble, but the trouble arises from at least a couple misconceptions harbored by many students. First, even though students can recite the fact that the motion of the stars is really caused by the rotation of Earth, they haven't always absorbed the idea and therefore don't automatically apply it to less familiar objects such as galaxies. Second, many students have trouble visualizing galaxies as fixed objects on the celestial sphere like stars, perhaps because they try to see them as being "big" and therefore have trouble fitting them onto the sphere in their minds. Thus, this simple question can help you address these misconceptions and thereby make it easier for students to continue their progress in the course.
- (p. 33) This question is designed to make sure students understand basic ideas of the sky. Answers are latitude dependent. A sample answer for latitude 40°N would be: The north celestial pole is located 40° above the horizon, due north. You can see circumpolar stars by looking toward the north, anywhere between the north horizon and altitude 80°. The lower 40° of the celestial sphere is always below your horizon.

- (p. 34) It depends on the time of year. This question really just checks that students can properly interpret Figure 2.12. A sample answer for September 21 would be: The Sun appears to be in Virgo, which means you'll see the opposite zodiac constellation—Pisces—on your horizon at midnight. After sunset, you'll see Libra setting in the western sky, because it is east of Virgo and therefore follows it around the sky.

Section 2.2

- (p. 38) Jupiter does not have seasons because of its lack of appreciable axis tilt. Saturn, with an axis tilt similar to Earth's, does have seasons.

Section 2.3

- (p. 43) A quarter moon visible in the morning must be third quarter, because a third-quarter moon rises around midnight and sets around noon.
- (p. 47) Remember that each eclipse season lasts a few weeks. Thus, if the timing of the eclipse season is just right, it is possible for two full moons to occur during the same eclipse season, giving us two lunar eclipses just a month apart. In such cases, the eclipses will almost always be penumbral because the penumbral shadow is much larger than the umbral shadow. Thus, it's far more likely that the Moon will pass twice in the same eclipse season through the large penumbral shadow than through the much smaller umbral shadow.

Section 2.4

- (p. 51) Opposite ends of Earth's orbit are about 300 million kilometers apart, or about 30 meters on the 1-to-10-billion scale used in Chapter 1. The nearest stars are tens of trillions of kilometers away, or thousands of kilometers on the 1-to-10-billion scale, and they are typically the size of grapefruits or smaller. The challenge of detecting stellar parallax should now be clear.

Solutions to End-of-Chapter Problems (Chapter 2)

1. A constellation is a section of the sky, like a state within the United States. They are based on groups of stars that form patterns that suggested shapes to the cultures of the people who named them. The official names of most of the constellations in the Northern Hemisphere came from ancient cultures of the Middle East and the Mediterranean, whereas the constellations of the Southern Hemisphere got their official names from 17th-century Europeans.
2. If we were making a model of the celestial sphere on a ball, we would definitely need to mark the north and south celestial poles, which are the points directly above Earth's poles. Halfway between the two poles we would mark the great circle of the celestial equator, which is the projection of Earth's equator out into space. And we definitely would need to mark the

circle of the ecliptic, which is the path that the Sun appears to make across the sky. Then we could add stars and borders of constellations.

3. No, space is not really full of stars. Because the distance to the stars is very large, and because stars lie at different distances from Earth, stars are not really crowded together.
4. The local sky looks like a dome because we see half of the full celestial sphere at any one time.
   Horizon: The boundary line dividing the ground and the sky.
   Zenith: The highest point in the sky, directly overhead.
   Meridian: The semicircle extending from the horizon due north to the zenith to the horizon due south.
   We can locate an object in the sky by specifying its altitude and its direction along the horizon.
5. We can measure only angular size or angular distance on the sky because we lack a simple way to measure distance to objects just by looking at them. It is therefore usually impossible to tell if we are looking at a smaller object that's near us or a more distant object that's much larger.
   Arcminutes and arcseconds are subdivisions of degrees. There are 60 arcminutes in 1 degree, and there are 60 arcseconds in 1 arcminute.
6. Circumpolar stars are stars that never appear to rise or set from a given location, but are always visible on any clear night. From the North Pole, every visible star is circumpolar, as all circle the horizon at constant altitudes. In contrast, a much smaller portion of the sky is circumpolar from the United States, as most stars follow paths that make them rise and set.
7. Latitude measures angular distance north or south of Earth's equator. Longitude measures angular distance east or west of the Prime Meridian. The night sky changes with latitude because it changes the portion of the celestial sphere that can be above your horizon at any time. The sky does not change with changing longitude, however, because as Earth rotates, all points on the same latitude line will come under the same set of stars, regardless of their longitude.
8. The zodiac is the set of constellations in which the Sun can be found at some point during the year. We see different parts of the zodiac at different times of the year because the Sun is always somewhere in the zodiac, thus we cannot see that constellation at night at that time of the year.
9. If Earth's axis had no tilt, Earth would not have significant seasons because the intensity of sunlight at any particular latitude would not vary with the time of year.
10. The summer solstice is the day when the Northern Hemisphere gets the most direct sunlight and the Southern Hemisphere the least direct. Also, on the summer solstice, the Sun is as far north as it ever appears on the celestial sphere. On the winter solstice, the situation is exactly reversed: the Sun appears as far south as it will get in the year, and the Northern Hemisphere gets its least direct sunlight while the Southern Hemisphere gets its most direct sunlight.

On the equinoxes, the two hemispheres get the same amount of sunlight, and the day and night are the same length (12 hours) in both hemispheres. The Sun is found directly overhead at the equator on these days, and it rises due east and sets due west.

11. The direction in which Earth's rotation axis points in space changes slowly over the centuries, and we call this change *precession*. Because of this movement, the celestial poles and therefore the pole star changes slowly in time. So while Polaris is the pole star now, in 13,000 years the star Vega will be the pole star instead.
12. The Moon's phases start with the new phase when the Moon is nearest the Sun in our sky and we see only the unlit side. From this dark phase, one side of the Moon's visible face slowly becomes lit, moving to the first-quarter phase, when we see a half-lit moon. During the time when the Moon's illuminated fraction is increasing, we say that the Moon is waxing. When the entire visible face of the Moon is lit up and the Moon is visible all night long, we say that the Moon is in its full phase. The process then occurs in reverse over the second half of the month as the Moon's lit fraction decreases, through third quarter, when it is half-lit, back to new again. During the second half of the month when the Moon's illuminated fraction is decreasing, we say that the Moon is waning.

    We can never see a full moon at noon because, for the Moon to be full, it and the Sun must be on opposite sides of Earth. So as the full moon rises, the Sun must be setting, and when the Moon is setting, the Sun is rising. (*Exception*: At very high latitudes, there may be times when the full moon is circumpolar, in which case it could be seen at noon; but it would still be 180° away from the Sun's position.)
13. No. Viewed from the Sun, you would always see a full moon, because you'd always be looking at the side illuminated with sunlight.
14. While the Moon must be in its new phase for a solar eclipse or in its full phase for a lunar eclipse, we do not see eclipses every month. This is because the Moon usually passes to the north or south of the Sun during these times as its orbit is tilted relative to the ecliptic plane.
15. The apparent retrograde motion of the planets refers to the planets' behaviors when they sometimes stop moving eastward relative to the stars and move westward for a while. While the ancients had to resort to complex systems to explain this behavior, our Sun-centered model makes this motion a natural consequence of the fact that the different planets move at different speeds as they go around the Sun. We see the planets appear to move backward because we are actually overtaking them in our orbit (if they orbit farther from the Sun than Earth) or they are overtaking us (if they orbit closer to the Sun than Earth).
16. Stellar parallax is the apparent movement of some of the nearest stars relative to the more distant ones as Earth goes around the Sun. This is caused by our slightly changing perspective on these stars throughout the year. However, the effect is very small because Earth's orbit is much smaller than the distances to even the closest stars. Because the effect is so

small, the ancients were unable to observe it. However, they correctly realized that if Earth is going around the Sun, they should see stellar parallax. Because they could not see the stars shift, they concluded that Earth does not move.

17. *The constellation of Orion didn't exist when my grandfather was a child.* This statement does not make sense because the constellations don't appear to change on the time scales of human lifetimes.
18. *When I looked into the dark lanes of the Milky Way with my binoculars, I saw what must have been a cluster of distant galaxies.* This statement does not make sense because we cannot see through the band of light we call the Milky Way to external galaxies; the dark fissure is gas and dust blocking our view.
19. *Last night the Moon was so big that it stretched for a mile across the sky.* This statement does not make sense because a mile is a physical distance, and we can measure only angular sizes or distances when we observe objects in the sky.
20. *I live in the United States, and during my first trip to Argentina I saw many constellations that I'd never seen before.* This statement makes sense because the constellations visible in the sky depend on latitude. Because Argentina is in the Southern Hemisphere, the constellations visible there include many that are not visible from the United States.
21. *Last night I saw Jupiter right in the middle of the Big Dipper. (Hint: Is the Big Dipper part of the zodiac?)* This statement does not make sense because Jupiter, like all the planets, is always found very close to the ecliptic in the sky. The ecliptic passes through the constellations of the zodiac, so Jupiter can appear to be only in one of the 12 zodiac constellations—and the Big Dipper (part of the constellation Ursa Major) is not among these constellations.
22. *Last night I saw Mars move westward through the sky in its apparent retrograde motion.* This statement does not make sense because the apparent retrograde motion is noticeable only over many nights, not during a single night. (Of course, like all celestial objects, Mars moves from east to west over the course of *every* night.)
23. *Although all the known stars appear to rise in the east and set in the west, we might someday discover a star that will appear to rise in the west and set in the east.* This statement does not make sense. The stars aren't really rising and setting; they only appear to rise in the east and set in the west because *Earth* rotates.
24. *If Earth's orbit were a perfect circle, we would not have seasons.* This statement does not make sense. As long as Earth still has its axis tilt, we'll still have seasons.
25. *Because of precession, someday it will be summer everywhere on Earth at the same time.* This statement does not make sense. Precession does not change the tilt of the axis, only its orientation in space. As long as the tilt remains, we will continue to have opposite seasons in the two hemispheres.

26. *This morning I saw the full moon setting at about the same time the Sun was rising.* This statement makes sense because a full moon is opposite the Sun in the sky.
27. c; 28. a; 29. a; 30. a; 31. a;
32. b; 33. b; 34. c; 35. a; 36. b.
37. (a) This is consistent with the Earth-centered view, simply by having the stars rotate around Earth. (b) This is consistent with the Earth-centered view by having Sun actually move slowly among the constellations on the path of the ecliptic so that its position north or south of the celestial equator is thought of as "real" rather than as a consequence of the tilt of Earth's axis. (c) This is consistent with the Earth-centered view, because phases are caused by relative positions of Sun, Earth, and Moon—which are about the same with either viewpoint, because the Moon really does orbit Earth. (d) This is consistent with the Earth-centered view; as with (c), eclipses depend only on the Sun-Earth-Moon geometry. (e) In terms of just having the "heavens" revolve around Earth, apparent retrograde motion is inconsistent with the Earth-centered view. However, this view was not immediately rejected because the absence of parallax (and other beliefs) caused the ancients to go to great lengths to find a way to preserve the Earth-centered system. As we'll see in the next chapter, Ptolemy succeeded well enough for the system to remain in use for another 1500 years. Ultimately, however, the inconsistencies in predictions of planetary motion led to the downfall of the Earth-centered model.
38. The shadow shapes are wrong. For example, during gibbous phase, the dark portion of the Moon has the shape of a crescent, and a round object could not cast a shadow in that shape. You could also show that the crescent moon, for example, is nearly between Earth and the Sun, so Earth can't possibly cast a shadow on it.
39. This is a new group work project.
40. The planet will have seasons because of its axis tilt, even though its orbit is circular. Because its 35° axis tilt is greater than Earth's 23.5° axis tilt, we'd expect this planet to have more extreme seasonal variations than does Earth.
41. Answers will vary with location; the following is a sample answer for Boulder, Colorado.
    a. The latitude in Boulder is 40°N and the longitude is about 105°E.
    b. The north celestial pole appears in Boulder's sky at an altitude of 40° in the direction due north.
    c. Polaris is circumpolar because it never rises or sets in Boulder's sky. It makes a daily circle less than 1° in radius around the north celestial pole.
42. a. When you see a full Earth, people on Earth must have a new moon.
    b. At full moon, you would see new Earth from your home on the Moon. It would be daylight at your home, with the Sun on your meridian and about a week until sunset.
    c. When people on Earth see a waxing gibbous moon, you would see a waning crescent Earth.

d. If you were on the Moon during a total lunar eclipse (as seen from Earth), you would see a total eclipse of the Sun.

43. If the Moon were twice as far from Earth, its angular size would be too small to create a total solar eclipse. It would still be possible to have annular eclipses, though the Moon would cover only a small portion of the solar disk.
44. If Earth were smaller in size, solar eclipses would still occur in about the same way because they are determined by the Moon's shadow on Earth.
45. This is an observing project that will stretch over several weeks.
46. a. There are 360 × 60 = 21,600 arcminutes in a full circle.
    b. There are 360 × 60 × 60 = 1,296,000 arcseconds in a full circle.
    c. The Moon's angular size of 0.5° is equivalent to 30 arcminutes or 30 × 60 = 1800 arcseconds.
47. To solve this problem, we turn to Cosmic Calculations 2.1, where we learn that the physical size of an object, its distance, and its angular size are related by the equation:

$$\text{physical size} = \frac{2\pi \times (\text{distance}) \times (\text{angular size})}{360^\circ}$$

We are told that the Sun is 0.5° in angular diameter and is about 150,000,000 kilometers away. So we put those values in:

$$\text{physical size} = \frac{2\pi \times (150{,}000{,}000\text{ km}) \times (0.5^\circ)}{360^\circ}$$
$$= 1{,}310{,}000\text{ km}$$

For the values given, we estimate the size to be about 1,310,000 kilometers. We are told that the actual value is about 1,390,000 kilometers. The two values are pretty close, and the difference can probably be explained by the Sun's actual diameter not being exactly 0.5° and the distance to the Sun not being exactly 150,000,000 kilometers.

48. To solve this problem, we use the equation relating distance, physical size, and angular size given in Cosmic Calculations 2.1:

$$\text{physical size} = \frac{2\pi \times (\text{distance}) \times (\text{angular size})}{360^\circ}$$

In this case, we are given the distance to Betelgeuse as 427 light-years and the angular size as 0.044 arcsecond. We have to convert this number to degrees (so that the units in the numerator and denominator cancel), so:

$$0.044\ \cancel{\text{arcsecond}} \times \frac{1\ \cancel{\text{arcminute}}}{60\ \cancel{\text{arcseconds}}} \times \frac{1^\circ}{60\ \cancel{\text{arcminutes}}} = 1.22 \times 10^{-5\circ}$$

We can leave the distance in light-years for now. Thus, we can calculate the size of Betelgeuse:

$$\text{physical size} = \frac{2\pi \times (427\text{ light-years}) \times (1.22 \times 10^{-5\circ})}{360^\circ}$$
$$= 9.1 \times 10^{-5}\text{ light-years}$$

Clearly, we've chosen to express this in the wrong units: light-years are too large to be convenient for expressing the size of stars. Thus, we convert to kilometers using the conversion factor found in Appendix A:

$$9.1 \times 10^{-5} \ \cancel{\text{light-years}} \times \frac{9.46 \times 10^{12} \ \text{km}}{1 \ \cancel{\text{light-year}}} = 8.6 \times 10^{8} \ \text{km}$$

(Note that we could have converted the distance to Betelgeuse to kilometers before we calculated Betelgeuse's size and gotten the diameter in kilometers from our formula for physical size.)

The diameter of Betelgeuse is about 860 million kilometers, which is more than 600 times the Sun's diameter of 1.39×10^6 km. It is also almost six times the distance between Earth and Sun (1.5×10^8 km, from Appendix E).

49. a. Using the small-angle formula given in Cosmic Calculations 2.1, we know that:

$$\text{angular size} = \text{physical size} \times \frac{360°}{2\pi \times \text{distance}}$$

We are given the physical size of the Moon (3476 kilometers) and the minimum orbital distance (356,400 kilometers), so we can compute the angular size:

$$\text{angular size} = (3{,}476 \ \cancel{\text{km}}) \times \frac{360°}{2\pi \times (356{,}400 \ \cancel{\text{km}})} = 0.559°$$

When the Moon is at its most distant, it is 406,700 kilometers, so we can repeat the calculation for this distance:

$$\text{angular size} = (3{,}476 \ \cancel{\text{km}}) \times \frac{360°}{2\pi \times (406{,}700 \ \cancel{\text{km}})} = 0.426°$$

The Moon's angular diameter varies from 0.426° to 0.559° (at its farthest distance from Earth and at its closest, respectively).

b. We can do the same thing as in part (a), except we use the Sun's diameter (1,390,000 kilometers) and minimum and maximum distances (147,500,000 kilometers and 152,600,000 kilometers) from Earth. At its closest, the Sun's angular diameter is:

$$\text{angular size} = (1{,}390{,}000 \ \cancel{\text{km}}) \times \frac{360°}{2\pi \times (147{,}500{,}000 \ \cancel{\text{km}})} = 0.540°$$

At its farthest from Earth, the Sun's angular diameter is:

$$\text{angular size} = (1{,}390{,}000 \ \cancel{\text{km}}) \times \frac{360°}{2\pi \times (152{,}600{,}000 \ \cancel{\text{km}})} = 0.522°$$

The Sun's angular diameter varies from 0.522° to 0.540°.

c. When both objects are at their maximum distances from Earth, both objects appear with their smallest angular diameters. At this time, the Sun's angular diameter is 0.522°, and the Moon's angular diameter is 0.426°. The Moon's angular diameter under these conditions is significantly smaller than the Sun's, so it could *not* fully cover the Sun's disk. Because it cannot completely cover the Sun, there can be no total eclipse under these conditions. There can be only an annular or partial eclipse under these conditions.

Chapter 3. The Science of Astronomy

Most students do not really understand how science works, and our aim in this chapter is to edify them in an interesting and multicultural way. If you are used to teaching from other textbooks, you may be surprised that we have chosen to wait until Chapter 3 to introduce this material. However, we have found that students are better able to appreciate the scientific method and the development of science after they first have some idea of what science has accomplished. Thus, we find covering the development of science at this point to be more effective than introducing it earlier.

As always, when you prepare to teach this chapter, be sure you are familiar with the relevant media resources and the online quizzes and other study resources available on the MasteringAstronomy website.

Teaching Notes (By Section)

Section 3.1 The Ancient Roots of Science

This section introduces students to the development of astronomy by discussing how ancient observations were made and used by different cultures. We stress that these ancient observations helped lay the groundwork for modern science. The particular examples cited were chosen to give a multicultural perspective on ancient astronomy; instructors may wish to add their own favorite examples of ancient observations. In teaching from this section, you can take one of two basic approaches, depending on how much time you have available: (1) If you have little time to discuss the section in class, you may focus on the examples generally without delving into the observational details; or (2) if you have more time available, you may emphasize the details of how observations allowed determination of the time and date and how lunar cycles are used to make lunar calendars.

Section 3.2 Ancient Greek Science

This section focuses on the crucial role of the ancient Greeks in the development of science. We focus on the idea of creating scientific models through the example of the gradual development of the Ptolemaic model of the universe. The section concludes with discussion of the Islamic role in preserving and expanding upon Greek knowledge, setting the stage for discussion of the Copernican revolution in the next section.

- The flat Earth: There’s a good article about the common misconception holding that medieval Europeans thought Earth to be flat in *Mercury*, Sept/Oct 2002, page 34.

Section 3.3 The Copernican Revolution

With the background from the previous two sections, students now are capable of understanding how and why the geocentric model of the universe was abandoned. We therefore use this section to discuss the unfolding of the Copernican revolution by emphasizing the roles of each of the key personalities involved.

- Note that Kepler's laws are introduced in this section in their historical context.
- Note that we present Galileo's role by focusing on how he overcame remaining objections to the Copernican model. This is a particularly good example of the working of science, because it shows both that old ideas were *not* ridiculous while also showing how new ideas gained acceptance.

Section 3.4 The Nature of Science

The historical background of the previous sections has students ready to discuss just what science really is. Here are a few notes:

- We emphasize that the traditional idea of a "scientific method" is a useful idealization, but that science rarely proceeds so linearly.
- The most important part of this section is the concept of *hallmarks of science*. We have developed these three hallmarks through extensive discussions with both scientists and philosophers of science, and we believe they represent a concise summary of the distinguishing features of science.
- One of the key reasons that the hallmarks are useful is that they make it relatively easy for students to distinguish between science and nonscience.
- We include only a brief discussion of the idea of scientific paradigms; you may wish to supplement this discussion with your favorite examples of paradigm shifts.
- Public confusion between astronomy and astrology is well known. To address this confusion, we include a short Special Topic box designed to help students distinguish between the two. We have tried to avoid direct criticism of astrology and astrologers, even while pointing out that it is clearly not a science. Nevertheless, we suggest that you treat this topic carefully. A fair number of students are hard-core believers in astrology, and an attempt to dissuade them may backfire by making them dislike you and/or your course. If you can at least get such students to ask a few questions of themselves and their beliefs, you will have achieved a great deal.

Answers/Discussion Points for Think About It/See It For Yourself Questions

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

Section 3.1

- (p. 58) This question simply asks students to think about the process of learning by trial and error. If you use this question for in-class discussion, you should encourage students to think about how this process is similar to the process of thinking used in science.

Section 3.2

- (p. 61) The intent of this question is to help students gain appreciation for the accomplishments of ancient Greece. In class, this question can lead to further discussion of how much was lost when the Library of Alexandria was destroyed and also to discussion of whether the knowledge of our own civilization might someday suffer a similar fate.

Section 3.3

- (p. 68) Kepler's third law tells us that an orbital period depends only on average distance, so the comet with an average distance of 1 AU would orbit the Sun in the same time that Earth orbits the Sun: 1 year. Kepler's second law tells us that the comet would move fast near its perihelion and slow near its aphelion, so it would spend most of its time far from the Sun, out near the orbit of Mars.

Section 3.4

- (p. 77) When someone says that something is "only a theory," he/she usually means that it doesn't have a lot of evidence in its favor. However, according to the scientific definitions, "only a theory" is an oxymoron, because a theory must be backed by extensive evidence. Nevertheless, even scientists often use the phrase in both senses, so you have to analyze the context to decide which sense is meant.

Solutions to End-of-Chapter Problems (Chapter 3)

1. We all use the trial-and-error methods used in science frequently in our lives. Science is more systematic in its approach than we tend to be in more ordinary situations.
2. Ancient cultures studied astronomy to track the changes of the seasons. They needed this information to help them plant, grow, and harvest crops each year.

   Egyptians: Used the Sun and stars to tell time, giving us our 12-hour day and 12-hour night.

   Anasazi: Created the Sun Dagger, which marks the solstices and equinoxes with special illuminations on those days. Understood lunar cycles.

   Babylonians: Predicted eclipses accurately.

   Chinese: Kept detailed records of the skies for thousands of years.

Polynesians: Were experts at navigation, including celestial navigation.

3. The days of the week are named for the seven wandering objects in the sky that the ancients knew: the Sun and Moon and the planets Mercury, Venus, Mars, Jupiter, and Saturn.
4. A lunar calendar is a calendar in which the months are tied to the Moon's 29-day cycle. As a result, a lunar calendar has 11 fewer days per year than a calendar that is based on Earth's orbital period. Lunar calendars are still used for many religious and cultural purposes.
5. A scientific model is conceptual rather than physical and is used to explain and predict natural phenomena. The Greek geocentric model is the ancient model that placed Earth at the center of a great celestial sphere.
6. The Ptolemaic model was the Greek geocentric model made specifically by Claudius Ptolemy in the 2nd century B.C. His model was able to explain retrograde motion by having the planets move on smaller circles attached to the larger circles on which they went around Earth.
7. The Copernican revolution was the overthrowing of the Ptolemaic model of the solar system, essentially changing the human view of the universe from one in which Earth was imagined to be central to one in which Earth is just one of many similar planets.
8. The Copernican model was not immediately accepted because it didn't do any better at predicting the motions of the planets than the Ptolemaic model did. It was also about equally complex, so there were few advantages to changing models.

   Tycho collected new, more precise data on the positions of the planets. When Johannes Kepler was able to look at these data, he realized that he could improve on Copernicus's basic model by making the orbits elliptical rather than circular, with the Sun at one focus rather than at the center of the orbit. These improvements, coupled with his other two laws, led to a substantially simpler model of the solar system that was also more accurate than the Ptolemaic model. This new model faced considerable resistance from some people, but it was strongly supported by influential scientists of the day. Most notably, Galileo not only advocated the Copernican model (with Kepler's improvements), but he also used the newly invented telescope to study the sky. In doing so, he made discoveries, such as the phases of Venus and the moons of Jupiter, that supported Copernicus's model and ruled out the basic tenets of the geocentric model.
9. An ellipse is an oval-like figure. We can draw an ellipse by putting two tacks down into a piece of paper and then running a loop of string around both of them. If we hook a pencil inside the string, pull the loop tight, and then drag the pencil around, keeping the string taut, we get our ellipse. The foci of the ellipse are the locations of the tacks. The eccentricity is a measure of how noncircular the ellipse is: 0 eccentricity is a circle, while higher values of the eccentricity make more stretched-out ellipses. (The maximum value of eccentricity for an ellipse is 1.)
10. (i) Planets move in elliptical orbits around the Sun, with the Sun at one focus. This describes the shape of the orbits (ellipses rather than the circles

used by most previous models) and where the Sun is located relative to the orbits (at a focus rather than in the center).
(ii) A line from the planet to the Sun sweeps out equal areas in equal amounts of time. This law describes how fast the planets move in their orbits. When they are close to the Sun, they move faster, and when they are far away they move slower.
(iii) The law $p^2 = a^3$ relates the period, p, with the semimajor axis, a. This law says that the more distant planets orbit more slowly than the ones that are closer to the Sun. It also states that the only thing that affects the orbital period of the planets is the semimajor axis. Thus, things like the mass of the planet and the orbital eccentricity do not matter.

11. The hallmarks of science are that it seeks explanations for phenomena using natural causes, relies on the creation and testing of models (and that the models should be as simple as possible), and uses testable predictions to determine if a model should be kept or discarded. In the Copernican revolution, the first hallmark shows in the way Tycho's data led Kepler to look for a natural explanation for the observations. The second shows in the way the Copernican model, with Kepler's improvements, proved better than any competing model, such as that of Ptolemy. The third shows in the way the models were carefully tested by looking for observations that each model predicted. The Ptolemaic model was then rejected, and we do not use it today.

    Occam's razor is the idea that, when faced with more than one model that seems to match the data, we should use the simplest one.

    Personal testimony does not count as evidence in science because it is impossible for other people to verify the testimony independently.
12. A hypothesis in science is essentially an educated guess about why or how some phenomenon happens. If the hypothesis survives repeated tests and explains a broad enough range of phenomena, it may be elevated to the status of theory.
13. *The Yankees are the best baseball team of all time.* Nonscience, because it is based on personal opinion.
14. *Several kilometers below its surface, Jupiter's moon Europa has an ocean of liquid water.* Can be evaluated scientifically because the idea can, in principle, be tested by future spacecraft.
15. *My house is haunted by ghosts who make the creaking noises I hear each night.* Nonscience. The noises may be real, but no evidence is offered for concluding that they are caused by ghosts.
16. *There is no liquid water on the surface of Mars today.* Can be evaluated scientifically. This idea has been tested by study of Mars.
17. *Dogs are smarter than cats.* This statement might be argued both ways, but probably is nonscience, because "*smarter*" is not well-defined.
18. *Children born when Jupiter is in the constellation Taurus are more likely to be musicians than other children.* Can be evaluated using scientific testing to find the astrological signs of musicians. In fact, it has been tested, and turns out not to be true—making continued belief in it nonscience.

19. *Aliens can manipulate time so that they can abduct people and perform experiments on them without the people ever realizing they were taken.* Nonscience, because it offers no way to test whether the abductions really occur.
20. *Newton's law of gravity works as well for explaining orbits of planets around other stars as it does for explaining the planets in our own solar system.* Can be evaluated scientifically by observing extrasolar planets.
21. *God created the laws of motion that were discovered by Newton.* Nonscience, because it is an idea that cannot be tested scientifically.
22. *A huge fleet of alien spacecraft will land on Earth and introduce an era of peace and prosperity on January 1, 2020.* Can be evaluated scientifically by seeing whether or not the aliens show up on the appointed date.
23. b; 24. a; 25. c; 26. b; 27. b;
28. c; 29. c; 30. b; 31. c; 32. b.
33. Answers will vary depending on the idea chosen. The key in grading is for students to explain themselves clearly and to defend their opinions well.
34. More than one answer is possible for each part of this question, but here are some samples: (a) Observing changes in the sky with latitude would show that Earth is not flat. (b) Showing that the Sun is in different positions (that is, at different times of day) for different longitudes would show that Earth is curved east-west in addition to north-south. (c) Showing that changes in the sky with latitude and longitude are independent of where you start would demonstrate that Earth has spherical symmetry rather than some other shape.
35. This is a new group work project.
36. This problem requires students to devise their own scientific test of astrology. One example of a simple test is to cut up a newspaper horoscope and see whether others can correctly identify the horoscope that applies to them.
37. This question asks students to make a bulleted "executive summary" of the Copernican revolution. Answers will vary, so grades should be based on the clarity, conciseness, and completeness of the list.
38. This essay question can generate interesting responses. Of course, the impacts of the Copernican revolution involve opinion, so grade essays based on how well they are written and defended.
39. This question involves independent research. Answers will vary.
40. We will follow Eratosthenes's method, as seen in the Cosmic Calculations box. In the case of Nearth, we learn that the Sun is straight overhead at Nyene at the same time that it is 10° from the zenith at Alectown and that the two cities are 1000 kilometers apart. We can set up the same type of relationship as Eratosthenes did:

$$\frac{10\not{^\circ}}{360\not{^\circ}} \times \text{(circumference of Nearth)} = 1{,}000 \text{ km}$$

We solve for the circumference of Nearth:

$$\text{circumference of Nearth} = 1{,}000 \text{ km} \times \frac{360^\circ}{10^\circ}$$
$$= 36{,}000 \text{ km}$$

The circumference of Nearth is 36,000 kilometers.

41. Kepler's third law states:

$$a^3 = p^2$$

where *a* is the semimajor axis in AU and *p* is the period in years. Solving for the average distance *a*, we find:

$$a = \sqrt[3]{p^2}$$

We now put in Eris's period of p = 560 years to find the average distance in AU:

$$a = \sqrt[3]{560^2} = 67.9 \text{ AU}$$

Eris has an average distance (semimajor axis) of 67.9 AU.

42. a. We can use Kepler's third law to find the semimajor axis of Halley's comet. Kepler's third law states that:

$$a^3 = p^2$$

where *a* is the semimajor axis in AU and *p* is the period in years. We are asked to find the semimajor axis, so we can solve for *a* by taking the cube root of both sides:

$$a = \sqrt[3]{p^2}$$

Because Halley has an orbital period of 76 years, we can calculate the semimajor axis:

$$a = \sqrt[3]{76^2}$$
$$= 17.9 \text{ AU}$$

Comet Halley has a semimajor axis of 17.9 AU.

b. Halley's comet spends most of its time far from the Sun near aphelion. We know this from Kepler's second law, which tells us that bodies move faster when they are closer to the Sun in their orbits than when they are farther away. So Halley's comet moves most slowly at aphelion. Because it is moving most slowly there, Halley's comet also spends more time in that part of its orbit.