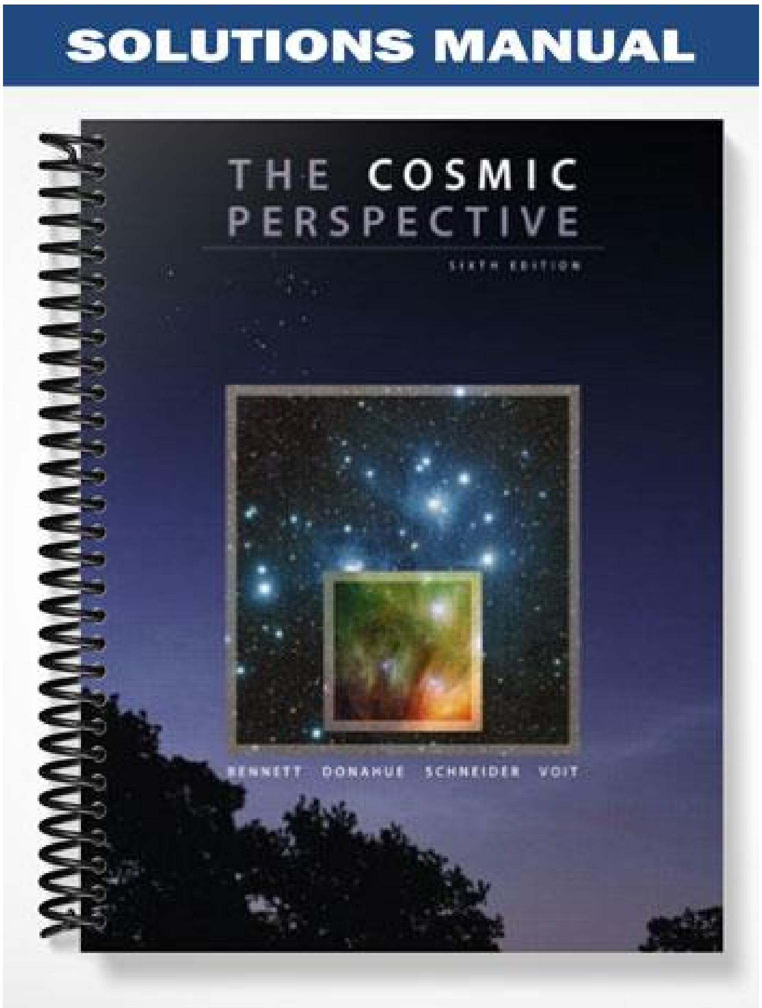
SOLUTIONS MANUAL
THE COSMIC
PERSPECTIVE
SIXTH EDITION
BENNETT DONAHUE SCHNEIDER VOIT

Chapter-by-Chapter Guide

Part I: Developing Perspective

The remainder of this Instructor Guide goes through the book chapter by chapter. Each chapter is organized as:

- A brief introduction with general comments about the chapter.
- Teaching Notes. Organized section by section for the chapter, these are essentially miscellaneous notes 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 essentially learned all the major ideas of astronomy, and the rest of their course will be building 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 (see the complete, section-by-section resource grid in Appendix 3 of this Instructor Guide) and the online quizzes and other study resources available on the MasteringAstronomy Web site.

Teaching Notes (By Section)

Section 1.1 Our Modern View of the Universe

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

- We urge you to pay special attention to the first two paintings (Figures 1.1 and 1.2). These pieces should help your students keep our cosmic address and origins in context throughout the course, and you may wish to refer to them often.
- Note the box on “Basic Astronomical Objects, Units, and Motion”: Although some of the terms in this box are not discussed immediately, having them here 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 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, and not of 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} kilometers), 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 in *Astrophysical Journal Letters*, 20 August 1998 (503, L131). They give the distance to Andromeda as 784 kiloparsec (kpc), 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/), which 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 all about the content and physics of the universe without first giving them the large-scale context.

- The "walking tour of the solar system" uses the 1-to-10-billion scale of the Voyage scale model solar system in Washington, D.C., a project that was proposed by Jeffrey Bennett, *The Cosmic Perspective*. 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, CO.)
- With regard to the count to 100 billion, it can be fun in lecture to describe what happens when you ask children how long it would take. Young children inevitably say they can count much faster than one 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 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 2 or 3), 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 meters (based on beaches we've seen eroded by storms) and estimate the width of a typical beach at 20–50 meters; 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} meters, or 10^8 kilometer, to make a volume of 10^{13} m^3. This is almost certainly greater than the linear extent of sandy beaches on Earth.
- The idea of a "cosmic calendar" was popularized by Carl Sagan. Now that we've calibrated the cosmic calendar to 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* 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 (although 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, why wait to introduce it?

Section 1.4 The Human Adventure of Astronomy

Although the philosophical implications of astronomical discoveries generally fall outside the realm of science, most students enjoy talking about them. This final section of Chapter 1 is intended to appeal to that student interest, letting them know that philosophical considerations are important to scientists as well.

- FYI: Regarding the Pope's apology to Galileo, the following is a quotation from *Time* magazine (Richard N. Ostling, John Moody, Rome and Amanv Radwan), December 28, 1992:

  > Popes rarely apologize. So it was big news in October when John Paul II made a speech vindicating Galileo Galilei. In 1633 the Vatican put the astronomer under house arrest for writing, against church orders, that Earth revolves around the sun. The point of the papal statement was not to concede the obvious fact that Galileo was right about the solar system. Rather, the Pope wanted to restore

and honor Galileo's standing as a good Christian. In the 17th century, said the Pope, theologians failed to distinguish between belief in the Bible and interpretation of it. Galileo contended that the Scriptures cannot err but are often misunderstood. This insight, said John Paul, made the scientist a wiser theologian than his Vatican accusers. More than a millennium before Galileo, St. Augustine had taught that if the Bible seems to conflict with "clear and certain reasoning," the Scriptures obviously need reinterpretation.

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. 2) This question is, of course, very subjective, but can make for a lively in-class debate.
- (p. 8) If people are 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 least, most students are 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 can be a great topic of debate. We've found that most students tend to think it is inconceivable that we could be the only intelligent beings. However, some religious students will assume we are alone on grounds of their faith. In both cases, it can generate discussion about how science goes only on evidence. For example, we don't assume there are others because we have no evidence that there are, and we don't assume we are alone for the same reason.

Section 1.3

- (p. 15) As we authors understand it, the only real reason that globes are oriented with north on top is because 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. 16) 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 are typically only a few hundred meters in diameter (including all their planets), while 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)

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 total 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 far enough back in time, the universe would be compressed until everything were 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 the stuff in our bodies was once part of the 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. So 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 planet 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 kilometers.

    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 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. Since 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 as great as 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 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.
39. 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.
40. 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.
41. 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.

42. a. This problem asks students to draw a sketch. Using the scale of 1 centimeter = 100,000 light-years, the sketches should show that each of the two galaxies is about 1 centimeter in diameter and that the Milky Way and M31 are separated by about 25 centimeters.

b. The separation between the Milky Way and M31 is only about 25 times their respective diameters—and other galaxies in the Local Group lie in between. In contrast, the model solar system shows that, on a scale where stars are roughly the size of grapefruits, a typical separation is thousands of kilometers (at least in our region of the galaxy). Thus, while galaxies can collide relatively easily, it is highly unlikely that two individual stars will collide. *Note:* Stellar collisions are more likely in places where stars are much closer together, such as in the galactic center or in the centers of globular clusters.

43. This is a subjective essay question. 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 kilometers per second, 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} kilometers, 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 kilometers per second according to Appendix A. (We choose the value in kilometers per second rather than meters per second 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 kilometers. 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 kilometers. 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 trying to convert this to minutes:

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

Since 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 will use the speed-time-distance relationship from the prior problem:

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

We also need the speed of light, which is 3×10^5 kilometers per second; the problem tells us that the distance from Earth to Mars varies from 56 million kilometers to 400 million kilometers. (Or 5.6×10^7 kilometers and 4×10^8 kilometers in scientific notation.)

a. Mars at its nearest is 56 million kilometers away, so the light travel time is:

$$\text{time of travel} = \frac{5.6 \times 10^7 \cancel{\text{km}}}{3.00 \times 10^5 \cancel{\text{km}}/\text{s}} = 187 \text{ s}$$

We would prefer this answer in minutes, so converting:

$$187 \cancel{\text{s}} \times \frac{1 \text{ min}}{60 \cancel{\text{s}}} = 3.11 \text{ min}$$

It takes a little over 3 minutes each way to communicate with a spacecraft on Mars at closest approach.

b. At the most distant, Mars is 400 million kilometers from Earth, so we can compute the travel time for light:

$$\text{time of travel} = \frac{4 \times 10^8 \cancel{\text{km}}}{3.00 \times 10^5 \cancel{\text{km}}/\text{s}} = 1330 \text{ s}$$

We would again prefer this in minutes, so we convert:

$$1330 \cancel{\text{s}} \times \frac{1 \text{ min}}{60 \cancel{\text{s}}} = 22.2 \text{ min}$$

It takes a little over 22 minutes each way to communicate with a spacecraft on Mars when Mars is at its farthest from Earth.

c. We will again use the speed-time-distance relationship:

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

In this case, we seek the time it takes light to travel from Earth to Pluto. Earth's average distance from the Sun is 1.496×10^8 kilometers and Pluto's average distance is 5.916×10^9 kilometers. If we assume the two problems are lined up on the same side of the Sun at their average distances, the distance between them is:

$$\begin{aligned}\text{Earth to Pluto distance} &= 5.916 \times 10^9 \text{ km} - 1.496 \times 10^8 \text{ km} \\ &= 5.766 \times 10^9 \text{ km}\end{aligned}$$

Using this value, the light travel time is:

$$\text{time of travel} = \frac{5.766 \times 10^9 \ \cancel{\text{km}}}{3.00 \times 10^5 \ \cancel{\text{km}}/\text{s}} = 1.922 \times 10^4 \ \text{s}$$

This is nearly 20,000 seconds, so let's try changing to more comprehensible units. We'll start by converting to minutes:

$$1.922 \times 10^4 \ \cancel{\text{s}} \times \frac{1 \ \text{min}}{60 \ \cancel{\text{s}}} = 320 \ \text{min}$$

That's a lot better, but it's still a lot more than 1 hour, so let's convert to hours:

$$320 \ \cancel{\text{min}} \times \frac{1 \ \text{hr}}{60 \ \cancel{\text{min}}} = 5.33 \ \text{hr}$$

It would take light 5.33 hours, or 5 hours and 20 minutes, to travel from Earth to Pluto under the alignment conditions and average distances we've assumed.

47. Since this question asks "how many times greater," the easiest way to solve it is with a ratio. We are asked how many times bigger Earth to Alpha Centauri distance is than the Earth-Moon distance, so we'll set this up with Earth-Alpha Centauri distance on the top of the ratio:

$$\text{ratio} = \frac{\text{Earth to Alpha Centauri distance}}{\text{Earth to Moon distance}}$$

Now all we need are the two distances. From Appendix E, the Earth-Moon distance is 3.844×10^5 kilometers. Both the problem and Appendix E tell us that the Earth-Alpha Centauri distance is 4.4 light-years, but we need that in kilometers in order to set up the ratio properly since the units have to be the same on the top and on the bottom. To find out how to make this conversion, we will look in Appendix A where we find that 1 light-year = 9.46×10^{12} kilometers. So converting:

$$4.4 \ \cancel{\text{light-years}} \times \frac{9.46 \times 10^{12} \ \text{km}}{1 \ \cancel{\text{light-year}}} = 4.2 \times 10^{13} \ \text{km}$$

Our ratio becomes

$$\text{ratio} = \frac{4.2 \times 10^{13} \ \cancel{\text{km}}}{3.844 \times 10^5 \ \cancel{\text{km}}} = 1.1 \times 10^8$$

We have found that Alpha Centauri is 110 million times farther away than the Moon.

48. 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} kilometers, 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:

$$\text{ratio} = \frac{\text{diameter of Milky Way}}{\text{diameter of Saturn's rings}}$$

$$= \frac{9.46 \times 10^{17}\ \cancel{\text{km}}}{2.7 \times 10^{5}\ \cancel{\text{km}}} = 3.5 \times 10^{12}$$

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

49. We are given the distance to Alpha Centauri as 4.4 light-years, but those units aren't very useful to us. So let's convert to kilometers. From Appendix A we see that 1 light-year = 9.46×10^{12} kilometers. So the distance to Alpha Centauri is

$$4.4\ \cancel{\text{light-years}} \times \frac{9.26 \times 10^{12}\ \text{km}}{1\ \cancel{\text{light-year}}} = 4.2 \times 10^{13}\ \text{km}$$

At a scale of 1 to 10^{19}, the distance to Alpha Centauri on this scale is

$$\frac{4.2 \times 10^{13}\ \text{km}}{10^{19}} = 4.2 \times 10^{-6}\ \text{km}$$

As numbers go, that one's not very easy to picture. So let's convert it to some smaller units. Since there are a thousand (10^3) meters to a kilometer and a thousand (10^3) millimeters to a meter, there are (10^6) millimeters to a kilometer. Those units seem about right for this distance, so let's convert:

$$4.2 \times 10^{-6}\ \cancel{\text{km}} \times \frac{10^{6}\ \text{mm}}{1\cancel{\text{km}}} = 4.2\ \text{mm}$$

From Appendix E, the Sun is 7.0×10^5 kilometers in radius, so the diameter is twice this, or 1.4×10^6 kilometers. On the 1-to-10^{19} scale, this is

$$\frac{1.4 \times 10^{6}\ \text{km}}{10^{19}} = 1.4 \times 10^{-13}\ \text{km}$$

We're asked to compare this to the size of an atom, 10^{-10} meter, so we had better convert one of the numbers. We'll convert from kilometers to meters:

$$1.4 \times 10^{-13}\ \cancel{\text{km}} \times \frac{1{,}000\ \text{m}}{1\ \cancel{\text{km}}} = 1.4 \times 10^{-10}\ \text{m}$$

Note that this is about the same size as a typical atom. In summary, we've found that on a scale on which the Milky Way Galaxy would fit on a football field, the distance from the Sun to Alpha Centauri is only about 4.2 millimeters—smaller than the width of a finger—and the Sun itself becomes as small as an atom.

50. a. First, we need to work out the conversion factor to use to go between the real universe and our model. We are told that the Milky Way Galaxy is to be about 1 centimeter in the new model. We know from this chapter that the Milky Way Galaxy is about 10^5 light-years across. We could convert this to kilometers, but looking at what we're asked to convert, it appears that all the numbers we'll be using will be given in light-years anyway. So our conversion factor is:

$$1\ \text{cm} = 10^{5}\ \text{light-years}$$

So for the first part, we need to figure out how far the Andromeda Galaxy (also known as M31) is from the Milky Way. The chapter tells us that their actual separation is 2.5 million light-years. So the distance on our scale is:

$$2.5 \times 10^6 \ \cancel{\text{light-years}} \times \frac{1 \text{ cm}}{10^5 \ \cancel{\text{light-years}}} = 25 \text{ cm}$$

The Andromeda Galaxy would be 25 centimeters away from our galaxy on this scale.

b. From Appendix E, we learn that Alpha Centauri is 4.4 light-years from the Sun. So using the conversion factor we developed in part (a), we convert this to the scale model distance:

$$4.4 \ \cancel{\text{light-years}} \times \frac{1 \text{ cm}}{10^5 \ \cancel{\text{light-years}}} = 4.4 \times 10^{-5} \text{ cm}$$

The separation between Alpha Centauri and our Sun is about 4.4×10^{-5} centimeter on this scale. As we will see in Chapter 6, this is comparable to the wavelength of blue light.

c. The observable universe is about 14 billion light-years in radius, so let's use that distance as an approximation to the distance of the most distant observable galaxies. Converting this distance to our model's scale:

$$14 \times 10^9 \ \cancel{\text{light-years}} \times \frac{1 \text{ cm}}{10^5 \ \cancel{\text{light-years}}} = 1.4 \times 10^6 \text{ cm}$$

That's more than a million centimeters, but it's difficult to visualize how far that is offhand. Let's convert that number to kilometers. We'll convert to meters first since we know how to go from centimeters to meters and meters to kilometers, but it's difficult to remember how to go straight from centimeters to kilometers:

$$1.4 \times 10^6 \ \cancel{\text{cm}} \times \frac{1 \ \cancel{\text{m}}}{100 \ \cancel{\text{cm}}} \times \frac{1 \text{ km}}{1000 \ \cancel{\text{m}}} = 14 \text{ km}$$

On a scale where our entire Milky Way Galaxy is the size of a marble, the most distant galaxies in our observable universe would be located some 14 kilometers away.

51. a. The circumference of Earth is $2\pi \times 6380$ km = 40,087 km. At a speed of 100 kilometers per hour, it would take:

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

to drive around Earth. That is, a trip around the equator at 100 kilometers per hour 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 kilometers per hour. 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 kilometers per hour. FYI: The following table shows the driving times from the Sun to each of the planets at a speed of 100 kilometers per hour.

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

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

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

At a speed of 100 kilometers per hour, the travel time to Proxima Centauri would be about:

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

It would take some 47 million years to reach Proxima Centauri at a speed of 100 kilometers per hour.

52. 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 kilometers per second or nearly 50 million kilometers per hour.

b. This is about 1000 times the speed of our fastest current spacecraft.

53. The average speed of our solar system in its orbit of the Milky Way is the circumference of its orbit divided by the time it takes for one orbit:

$$v = \frac{2\pi(28{,}000 \text{ lt-yr})}{2.3 \times 10^{8} \text{ yr}} = \frac{1.76 \times 10^{5} \cancel{\text{lt-yr}} \times 9.46 \times 10^{12} \frac{\text{km}}{\cancel{\text{lt-yr}}}}{2.3 \times 10^{8} \cancel{\text{yr}} \times 365 \frac{\cancel{\text{day}}}{\cancel{\text{yr}}} \times 24 \frac{\text{hr}}{\cancel{\text{day}}}} \approx 8.3 \times 10^{5} \frac{\text{km}}{\text{hr}}$$

We are racing around the Milky Way Galaxy at about 830,000 kilometers per hour, or about 510,000 miles per hour.

54. We'll use the relationship that says that

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

To compute each speed, we'll find the distance a person travels around Earth's axis in 1 day (24 hours). Using the hint from the problem, we can find the radius of the circle that a person at that latitude travels is $R_{Earth} \times \cos(\text{latitude})$, where $R_{Earth} = 6378$ km from Appendix E.

a. The radius of the circle that a person at latitude 30° travels is:

$$(6378 \text{ km}) \times \cos(30°) = 5534 \text{ km}$$

To get the distance traveled, we use the fact that a circle's circumference is given by $c = 2\pi r$, so in this case:

$$\text{distance} = 2\pi \ 5524 \times \text{km} = 34{,}700 \text{ km}$$

Using the relationship between speed, time, and distance given above, the speed is

$$\text{speed} = \frac{34{,}700 \text{ km}}{24 \text{ hr}} = 1446 \text{ km/hr}$$

A person at 30° latitude would be traveling at 1446 kilometers per hour around Earth's axis because of Earth's rotation.

b. The radius of the circle that a person at 60° travels is

$$(6378 \text{ km}) \times \cos(60°) = 3189 \text{ km}$$

The distance traveled is

$$\text{distance} = 2\pi(3{,}189 \text{ km}) = 20{,}040 \text{ km}$$

The speed is

$$\text{speed} = \frac{20{,}040 \text{ km}}{24 \text{ hr}} = 834 \text{ km/hr}$$

A person at 60° latitude travels around the axis at 834 kilometers per hour due to Earth's rotation.

c. Answers will vary depending on location.

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 (see the complete, section-by-section resource grid in Appendix 3 of this Instructor Guide) and the online quizzes and other study resources available on the MasteringAstronomy Web site.

Teaching Notes (By Section)

Section 2.1 Patterns in the Night Sky

This section introduces the concepts of constellations and of 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 "dough." 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 dough 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 (e.g., latitude = altitude of NCP). 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 speaking 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 potential ambiguity with 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 it is linked to distance from the Sun, ask how seasons differ between the two hemispheres. They should then see for themselves that it 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 on the above note: Some students get confused by the fact that season diagrams (such as our Figure 2.15) 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 are at significantly different distances from the Sun. This is another reason why 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 at the same distance from the Sun at all times.

- 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 analogy to a spinning top.
- FYI 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. For a fuller treatment of issues associated with the scientific validity (or, rather, the lack thereof) of astrology, see Section 3.5.

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 of phases 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 that you'll find in almost every other text, which shows the Moon in eight different positions around Earth—students just don't get it, and the multiple moons confuse them. Instead, our Figure 2.22 shows how students can conduct a demonstration that will help them understand the phases. The Phases of the Moon tutorial on the MasteringAstronomy Web site has also proved very successful at 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 2.24 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. Hopefully 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 versus total) does not recur in each cycle is because 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 2.33, 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 at this point; that comes in Chapter 15.

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. 29) The simple answer is no, because a galaxy located in the direction of the galactic center will be obscured from view by the dust and gas of the Milky Way. Note, however, that this question can help you root out some student misconceptions. For example, some students might wonder if you could see the galaxy "sticking up" above our own galaxy's disk—illustrating a misconception about how angular size declines with distance. They might also wonder if a telescope would make a difference, illustrating a misconception about telescopes being able to "see through" things that our eyes cannot see through. Building on this idea, you can also foreshadow later discussions of nonvisible light by pointing out that while no telescope can help the problem in visible light, we CAN penetrate the interstellar gas and dust in some other wavelengths.

- (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 hopefully comes easily for college students!
- (p. 30) 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 like 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. Sample answer for latitude 40°N: 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. 33) It depends on the time of year; this question really just checks that students can properly interpret Figure 2.14. Sample answer for September 21: 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, since it is east of Virgo and therefore follows it around the sky.

Section 2.2

- (p. 35) Jupiter does not have seasons because of its lack of appreciable axis tilt. Saturn, with an axis tilt similar to Earth, does have seasons.
- (p. 40) In 2000 years, the summer solstice will have moved about the length of one constellation along the ecliptic. Since the summer solstice was in Cancer a couple thousand years ago (as you can remember from the Tropic of Cancer) and is in Gemini now, it will be in Taurus in about 2000 years.

Section 2.3

- (p. 42) A quarter moon visible in the morning must be third-quarter, since third-quarter moon rises around midnight and sets around noon.
- (p. 43) About 2 weeks each. Because the Moon takes about a month to rotate, your "day" would last about a month. Thus, you'd have about 2 weeks of daylight followed by about 2 weeks of darkness as you watched Earth hanging in your sky and going through its cycle of phases.
- (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. 50) 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 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, while 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 and so 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 would still be 180° away from the Sun's position.)

13. When we say that the Moon displays synchronous rotation, we mean that the Moon's spin period and its orbital period around Earth are the same. So from Earth, we always see the same side of the Moon and someone on the Moon always sees Earth in the same place in her local sky.
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, because 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 through 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. Since 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. Since 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. b; 35. a; 36. b
37. (a) Consistent with Earth-centered view, simply by having the stars rotate around Earth. (b) Consistent with 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) Consistent with Earth-centered view, since phases are caused by relative positions of Sun, Earth, and Moon—which are about the same with either viewpoint, since the Moon really does orbit Earth. (d) Consistent with 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. 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 Earth.
40. Answers will vary with location; the following is a sample answer for Boulder, CO.
    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.

41. 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.

42. You would not see the Moon go through phases if you were viewing it from the Sun. You would always see the sunlit side of the Moon, so it would always be "full." In fact, the same would be true of Earth and all the other planets as well.

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, although 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, since they are determined by the Moon's shadow on Earth.

45. This is an observing project that will stretch over several weeks.

46. This is a literary essay that requires reading the Mark Twain novel.

47. a. There are $360 \times 60 = 21{,}600$ arcminutes in a full circle.

b. There are $360 \times 60 \times 60 = 1{,}296{,}000$ arcseconds in a full circle.

c. The Moon's angular size of 0.5° is equivalent to 30 arcminutes or $30 \times 60 = 1800$ arcseconds.

48. a. We know that circumference = $2 \times \pi \times$ radius, so we can compute the circumference of Earth:

$$\begin{aligned} \text{circumference} &= 2 \times \pi \times (6370\ \text{km}) \\ &= 40{,}000\ \text{km} \end{aligned}$$

b. There are 90° of latitude between the North Pole and the equator. This distance is also one-quarter of Earth's circumference. Using the circumference from part (a), this distance is

$$\begin{aligned} \text{equator to pole distance} &= \frac{\text{circumference}}{4} \\ &= \frac{40{,}000\ \text{km}}{4} \\ &= 10{,}000\ \text{km} \end{aligned}$$

So if 10,000 kilometers is the same as 90° of latitude, then we can convert 1° into kilometers:

$$1° \times \frac{10{,}000\ \text{km}}{90°} = 111\ \text{km}$$

So 1° of latitude is the same as 111 kilometers on Earth.

c. There are 60 arcminutes in a degree. So we can find how many arcminutes are in a quarter-circle:

$$90° \times \frac{60 \text{ arcminutes}}{1°} = 5400 \text{ arcminutes}$$

Doing the same thing as in part (b):

$$1 \text{ arcminute} \times \frac{10{,}000 \text{ km}}{5400 \text{ arcminutes}} = 1.85 \text{ km}$$

Each arcminute of latitude represents 1.85 kilometers.

d. We cannot provide similar answers for longitude, because lines of longitude get closer together as we near the poles, eventually meeting at the poles themselves. So there is no single distance that can represent 1° of longitude everywhere on Earth.

49. a. We start by recognizing that there are 24 whole degrees in this number. So we just need to convert the 0.3° into arcminutes and arcseconds. So first converting to arcminutes:

$$0.3° \times \frac{60 \text{ arcminutes}}{1°} = 18 \text{ arcminutes}$$

Since there is no fractional part left to convert into arcseconds, we are done. So 24.3° is the same as 24° 18′ 0″.

b. Leaving off the whole degree, we convert the 0.59° to arcminutes:

$$0.59° \times \frac{60 \text{ arcminutes}}{1°} = 35.4 \text{ arcminutes}$$

So we have 35 whole arcminutes and a fractional part of 0.4 arcminute that we need to convert into arcseconds:

$$0.4 \cancel{\text{ arcminute}} \times \frac{60 \text{ arcseconds}}{1 \cancel{\text{ arcminute}}} = 24 \text{ arcseconds}$$

So 1.59° is the same as 1° 35′ 24″.

c. We have 0 whole degrees, so we convert the fractional degree into arcminutes:

$$0.1\cancel{°} \times \frac{60 \text{ arcminutes}}{1\cancel{°}} = 6 \text{ arcminutes}$$

Since there is no fractional part to this, we do not need any arcseconds to represent this number. So 0.1° is the same as 0° 6′ 0″.

d. We again have no whole degrees, so we start by converting 0.01° to arcminutes:

$$0.01° \times \frac{60 \text{ arcminutes}}{1°} = 0.6 \text{ arcminute}$$

There are no whole arcminutes here, either, so we have to convert 0.6 arcminute into arcseconds:

$$0.6\ \cancel{\text{arcminute}} \times \frac{60 \text{ arcseconds}}{1\ \cancel{\text{arcminute}}} = 36 \text{ arcseconds}$$

So 0.01° is the same as 0° 0′ 36″.

e. We again have no whole degrees, so we start by converting 0.001° to arcminutes:

$$0.001° \times \frac{60 \text{ arcminutes}}{1°} = 0.06 \text{ arcminute}$$

There are no whole arcminutes here, either, so we have to convert 0.06 arcminute into arcseconds:

$$0.06\ \cancel{\text{arcminute}} \times \frac{60 \text{ arcseconds}}{1\ \cancel{\text{arcminute}}} = 3.6 \text{ arcseconds}$$

So 0.01° is the same as 0° 0′ 3.6″.

50. a. We will start by converting the 42 arcseconds into arcminutes:

$$42\ \cancel{\text{arcseconds}} \times \frac{1 \text{ arcminute}}{60\ \cancel{\text{arcseconds}}} = 0.7 \text{ arcsecond}$$

So now we have 7° 38.7′. Converting the 38.7 arcminutes to degrees:

$$38.7\ \cancel{\text{arcminutes}} \times \frac{1°}{60\ \cancel{\text{arcminutes}}} = 0.645°$$

So 7° 38′ 42″ is the same as 7.645°.

b. We will start by converting the 54 arcseconds into arcminutes:

$$54\ \cancel{\text{arcseconds}} \times \frac{1 \text{ arcminute}}{60\ \cancel{\text{arcseconds}}} = 0.9 \text{ arcminute}$$

So now we have 12.9 arcminutes. Converting this to degrees:

$$12.9\ \cancel{\text{arcminutes}} \times \frac{1°}{60\ \cancel{\text{arcminutes}}} = 0.215°$$

So 12′ 54″ is the same as 0.215°.

c. We will start by converting the 59 arcseconds into arcminutes:

$$59\ \cancel{\text{arcseconds}} \times \frac{1 \text{ arcminute}}{60\ \cancel{\text{arcseconds}}} = 0.9833 \text{ arcminute}$$

So now we have 1° 59.9833′ arcminutes. Converting this to degrees:

$$59.9833\ \cancel{\text{arcminutes}} \times \frac{1°}{60\ \cancel{\text{arcminutes}}} = 0.9997°$$

So 1° 59′ 59″ is the same as 1.9997°, very close to 2°.

d. In this case, we need only convert 1 arcminute to degrees:

$$1\ \cancel{\text{arcminute}} \times \frac{1°}{60\ \cancel{\text{arcminutes}}} = 0.017°$$

So 1′ is the same as 0.017°.

e. We can convert this from arcseconds to degrees in one step since there are no arcminutes to add in:

$$1\ \cancel{\text{arcsecond}} \times \frac{1\ \cancel{\text{arcminute}}}{60\ \cancel{\text{arcseconds}}} \times \frac{1°}{60\ \cancel{\text{arcminutes}}} = 2.78 \times 10^{-4}°$$

So 1″ is the same as $2.78 \times 10^{-4}°$.

51. From Appendix E, the Moon’s orbit has a radius of 384,400 kilometers. The distance that the Moon travels in one orbit is the circumference of the orbit:

$$\begin{aligned}\text{distance traveled} &= 2 \times \pi \times \text{radius}\\ &= 2 \times \pi \times (384{,}400\ \text{km})\\ &= 2{,}415{,}000\ \text{km}\end{aligned}$$

To find the Moon’s speed in kilometers per hour, we also need to find how many hours are in the Moon’s $27\frac{1}{3}$-day orbit:

$$27.3\ \cancel{\text{days}} \times \frac{24\ \text{hr}}{1\ \cancel{\text{day}}} \approx 656\ \text{hr}$$

The speed is the distance over the time,

$$\begin{aligned}\text{speed} &= \frac{\text{distance traveled}}{\text{time}}\\ &= \frac{2{,}415{,}000\ \text{km}}{656\ \text{hr}}\\ &\approx 3680\ \text{km/hr}\end{aligned}$$

The Moon orbits Earth at a speed of 3680 kilometers per hour.

52. Starting with the size of the Moon, we convert to the scale model distance by dividing by 10 billion:

$$\frac{3500\ \text{km}}{10^{10}} = 3.5 \times 10^{-7}\ \text{km}$$

This number is pretty hard to understand, so we should convert it to something more useful. Judging by the sizes of other objects in the model, let’s convert from kilometers to millimeters:

$$3.5 \times 10^{-7}\ \cancel{\text{km}} \times \frac{1000\ \cancel{\text{m}}}{1\ \cancel{\text{km}}} \times \frac{1000\ \text{mm}}{1\ \cancel{\text{m}}} = 0.35\ \text{mm}$$

The Moon’s size on this scale is 0.35 millimeter.

We perform the same conversion to get the Moon’s scale distance:

$$\frac{380{,}000\ \text{km}}{10^{10}} = 3.8 \times 10^{-5}\ \text{km}$$

Just as above, this number is hard to understand. We’ll also convert it to millimeters:

$$3.8 \times 10^{-5}\ \cancel{\text{km}} \times \frac{1000\ \cancel{\text{m}}}{1\ \cancel{\text{km}}} \times \frac{1000\ \text{mm}}{1\ \cancel{\text{m}}} = 38\ \text{mm}$$

The distance to the Moon on this scale is 38 millimeters. Since there are 10 millimeters to 1 centimeter, we can convert this to centimeters:

$$38\ \cancel{\text{mm}} \times \frac{1\ \text{cm}}{10\ \cancel{\text{mm}}} = 3.8\ \text{cm}$$

The Moon's scaled distance is 3.8 centimeters, which is less than 2 inches. It also means that the Moon's orbit is about half the size of the ball of the Sun. The ball of the Sun was the size of a grapefruit in this scale model, so sticking with fruit, we could say that the Moon's orbit has the diameter of a medium-size orange or an apple.

53. Following the method of Example 1 in Mathematical Insight 2.1, we can use the angular separation formula to find the Sun's actual diameter from its angular diameter of 0.5° and its distance of 1.5×10^8 kilometers:

$$\begin{aligned} \text{physical diameter} &= \text{angular diameter} \times \frac{2\pi \times \text{distance}}{360°} \\ &= 0.5\cancel{°} \times \frac{2\pi(1.5 \times 10^8\ \text{km})}{360\cancel{°}} \\ &\approx 1.3 \times 10^6\ \text{km} \end{aligned}$$

Using this very approximate value of 0.5° for the Sun's angular size, we find that the Sun's diameter is about 1.3 million kilometers—fairly close to the actual value of 1.39 million kilometers.

54. To solve this problem, we turn to Mathematical Insight 2.1, where we learn that the physical size of an object, its distance, and its angular size are related by the equation:

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

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:

$$\begin{aligned} \text{physical size} &= \frac{2\pi \times (150{,}000{,}000\ \text{km}) \times (0.5\cancel{°})}{360\cancel{°}} \\ &= 1{,}310{,}000\ \text{km} \end{aligned}$$

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.

55. To solve this problem, we use the equation relating distance, physical size, and angular size given in Mathematical Insight 2.1:

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

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. So we can calculate the size of Betelgeuse:

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

Clearly, we've chosen to express this in the wrong units: lights-years are too large to be convenient for expressing the size of stars. So 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 out of 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 kilometers. It is also almost six times the distance between Earth and Sun (1.5×10^8 kilometers, from Appendix E).

56. a. Using the small-angle formula given in Mathematical Insight 2.1, we know that:

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

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:

$$\text{angular size} = (3476\ \cancel{\text{km}}) \times \frac{360^\circ}{2\pi \times (356{,}400\ \cancel{\text{km}})} = 0.559^\circ$$

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

$$\text{angular size} = (3476\ \cancel{\text{km}}) \times \frac{360^\circ}{2\pi \times (406{,}700\ \cancel{\text{km}})} = 0.426^\circ$$

The Moon's angular diameter varies from 0.426° to 0.559° (at its farthest point 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. Since 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 development of science and how science works after they first have some idea of what science has accomplished. Thus, we find that covering the development of science at this point is more effective than introducing it earlier.

- If your course focuses on the solar system, you may wish to emphasize this material heavily in class, and perhaps supplement it with your favorite examples of ancient astronomy.
- If your course focuses on stars, galaxies, or cosmology, you may decide not to devote class time to this chapter at all, or to concentrate only on Section 3.4 on the nature of science. However, you may still wish to have your students read this chapter, as it may prove useful in later discussions about the nature of science.

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 Guide) and the online quizzes and other study resources available on the MasteringAstronomy Web site.

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 can focus on the examples generally without delving into the observational details; or (2) if you have more time available, you can emphasize the details of how observations allowed determination of the time and date, and of 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.

- 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, since 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. 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 "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.

Section 3.5 Astrology

Public confusion between astronomy and astrology is well known. To address this confusion, we end this chapter with a discussion 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. 56) 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.
- (p. 61) This question often generates interesting discussion, particularly if some of your students have read the claims that the Nazca lines have alien origins. We hope students will recognize that such claims shortchange the people who lived there by essentially claiming that they weren't smart enough to have created the lines and patterns themselves. In that way, students usually conclude that the arguments favoring alien origins do not make much sense.

Section 3.2

- (p. 66) 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 lost and also to discussion of whether the knowledge of our own civilization might suffer a similar fate.

Section 3.3

- (p. 71) Kepler's third law tells us that 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. 80) When someone says that something is "only a theory," they usually mean that it doesn't have a lot of evidence in its favor. However, according to the scientific definition, the term "only a theory" is an oxymoron, since a theory must be backed by extensive evidence. Nevertheless, even scientists often use the word in both senses, so you have to analyze the context to decide which sense is meant.

Section 3.5

- (p. 81) This question asks students to think about the type of prediction made by a newspaper horoscope, as opposed to the more specific prediction of a weather forecast. This can lead to an interesting discussion about what constitutes a testable prediction. In class, you may wish to bring examples of more detailed horoscopes or do an experiment to test astrology.

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. Some examples that students could use in this answer:

   Egyptians—Used 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—Were able to predict eclipses accurately.

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

   Polynesians—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. The ancient Egyptians used the shadows of the Sun, perhaps cast by obelisks, to measure the time of day. At night, they used the positions of the stars at different times of the year to do the same thing. The Anasazi used the way spirals in the "Sun Dagger" were illuminated to determine the time of year. In particular, on the solstices and equinoxes the illumination was special to mark those days. The Aztecs built the Templo Mayor so that on the equinoxes, the Sun would rise from exactly between two structures at the top when viewed from the opposite side of the plaza. Stonehenge may have been constructed for a similar purpose, with the Sun rising near certain stones on special days.
5. 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.

   The Metonic cycle is the 19-year cycle in which lunar phases recur on the same solar dates.

Ramadan shifts through the year because the Muslim calendar is a lunar calendar with 11 fewer days per year than a solar year. So the dates of Ramadan shift through the seasons (on which our calendar is based) from one year to the next. The Jewish holidays stay close to a single date on our calendar, however, because the calendar that produces them compensates for this 11-day shortage by adding a month in 7 years of the 19-year Metonic cycle.

6. A scientific model is conceptual rather than physical and is used to explain and predict natural phenomena.
7. The Greek geocentric model goes back a long way into the past. Early developments include the idea of the celestial sphere (5th century B.C., due to Anaximander), discovery that Earth is round (Eratosthenes was able to actually measure its radius around 240 B.C.), and the notion (due to Plato) that all of the celestial objects traveled in perfect circles. Eudoxus added separate spheres for each planet, as well as for the Sun and the Moon. Ptolemy incorporated all of this, as well as other ideas, into his model.
8. The Ptolemaic model is the model published by Claudius Ptolemy, a Greek astronomer who lived in the 2nd century B.C. He gathered together the works of many earlier Greek astronomers into his very successful model of the solar system. 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.
9. 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.
10. 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 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, which supported Copernicus's model and ruled out the basic tenets of the geocentric model.
11. 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: zero

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.)

12. 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 says that the only thing that affects the orbital period of the planets is the semimajor axis. So things like the mass of the planet and the orbital eccentricity do not matter.

13. The hallmarks of science are that it seeks explanations for phenomenon 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.

14. 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.

15. A pseudoscience is something that looks like a science but is not. For example, astrology is a pseudoscience because it makes predictions, but it does not reject models that make repeated inaccurate predictions. On the other hand, many fields do not make predictions and do not act likes sciences, so they are nonsciences but not pseudoscience. (For example, religions are ways of understanding the world around us, but because they do not generally make testable predictions, they are nonscience but not pseudoscience.)

16. The basic idea of astrology is that the positions of objects in the sky (the Sun, Moon, planets, and so forth) can affect our lives or predict our futures. For the ancients, astrology probably seemed to make sense because the Sun and Moon really do have effects on our lives: The changing of the seasons and the coming and going of the tides are tied to the Sun and Moon, after all. So it might seem natural to guess that other bodies in the sky might affect us as well. Today, however, we

understand that the Sun and Moon influence our lives through gravity (and light in the case of the Sun), and that the gravity of the planets is too weak to influence us at the distances at which they are located. Moreover, repeated tests have always shown astrological predictions to be no more accurate than would be expected by pure chance.

17. *The Yankees are the best baseball team of all time.* Nonscience, since it is based on personal opinion.
18. *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.
19. *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.
20. *There is no liquid water on the surface of Mars today.* Can be evaluated scientifically. This idea has been tested by study of Mars.
21. *Dogs are smarter than cats.* This question might be argued both ways, but probably is nonscience, since "smarter" is not well-defined.
22. *Children born when Jupiter is in the constellation Taurus are more likely to be musicians than other children.* Can be evaluated scientifically by finding the astrological signs of musicians. In fact, it has been tested, and turns out not to be true—making continued belief in it nonscience.
23. *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.
24. *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.
25. *God created the laws of motion that were discovered by Newton.* Nonscience, since it is an idea that cannot be tested scientifically.
26. *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.
27. b; 28. a; 29. c; 30. b; 31. b; 32. c; 33. c; 34. b; 35. c; 36. b
37. 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.
38. 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 (i.e., 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 show that Earth has spherical symmetry rather than some other shape.
39. This question involves independent research. Answers will vary.

40. 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 one that applies to them.
41. The dates will vary depending on the year. The key points are: (a) Chanukah stays within a few-week range, because its date is chosen on a calendar that follows the Metonic cycle. (b) Ramadan moves through the year, because it is tied to a “pure” lunar calendar (one that does not use the Metonic cycle).
42. 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.
43. 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.

44–46. These questions involve independent research. Answers will vary.

47. First, we calculate the number of days in 19 years, given that there are 365.2422 days in a year:

$$19 \cancel{\text{yr}} \times \frac{365.2422 \text{ days}}{1 \cancel{\text{yr}}} = 6939.60 \text{ days}$$

We can compare this to the number of days in 235 months, given that there are 29.5306 days in a month:

$$235 \cancel{\text{months}} \times \frac{29.5306 \text{ days}}{1 \cancel{\text{month}}} = 6939.69 \text{ days}$$

Clearly, these two numbers are very close, less than a tenth of a day different. So 19 years is almost exactly 235 months.

We can use this fact to keep lunar calendars roughly synchronized with the seasons by making sure to add an extra month in several years out of every 19. By doing this, we ensure that there are 235 months in each 19-year cycle so that the lunar calendar is well synchronized with the seasons.

48. First, let us calculate how many months are in 60 years in the Chinese calendar. We are told that the typical year is 12 months long and that there are 22 years with an extra month. Using this information, we see that there are 22 years with 13 months and the remaining 38 years (60 years – 22 years) have 12 months. So the total number of months is:

$$38 \cancel{\text{yr}} \times \frac{12 \text{ months}}{1 \cancel{\text{yr}}} + 22 \cancel{\text{yr}} \times \frac{13 \text{ months}}{1 \cancel{\text{yr}}} = 742 \text{ months}$$

In Problem 47 we are told that the average month has 29.5306 days. So we can calculate the number of days in those 742 months:

$$742 \cancel{\text{months}} \times \frac{29.5306 \text{ days}}{1 \cancel{\text{month}}} = 21{,}912 \text{ days}$$

In Problem 47 we also see that there are 365.2422 days in 1 solar year, so we can also calculate how many days would be in 60 solar years:

$$60\ \cancel{\text{yr}} \times \frac{365.2422\text{ days}}{1\ \cancel{\text{yr}}} = 21{,}915\text{ days}$$

The Chinese calendar differs from a precise solar calendar by 3 days in every 60 years. This scheme is similar to the method discussed in Problem 47 and in the text (where there are 7 years with 13 months in every 19 years) because both add extra months to some years to compensate for the shift of the lunar calendars relative to the seasons.

49. We will follow Eratosthenes's method, from the Special Topic 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. So we can set up the same type of relationship as Eratosthenes did:

$$\frac{10\cancel{°}}{360\cancel{°}} \times (\text{circumference of Nearth}) = 1000\text{ km}$$

We solve for the circumference of Nearth:

$$\begin{aligned}\text{circumference of Nearth} &= 1000\text{ km} \times \frac{360\cancel{°}}{10\cancel{°}} \\ &= 36{,}000\text{ km}\end{aligned}$$

The circumference of Nearth is 36,000 kilometers.

50. We will follow Eratosthenes's logic from the Special Topic box. In the case of Tirth, we learn that the Sun is straight overhead at Tyene at the same time that it is 4° from the zenith at Alectown and that the two cities are 1000 kilometers apart. So we can set up the same sort of relationship as Eratosthenes did:

$$\frac{4\cancel{°}}{360\cancel{°}} \times (\text{circumference of Tirth}) = 400\text{ km}$$

We solve for the circumference of Tirth:

$$\begin{aligned}\text{circumference of Tirth} &= 400\text{ km} \times \frac{360\cancel{°}}{4\cancel{°}} \\ &= 36{,}000\text{ km}\end{aligned}$$

The circumference of Tirth is 36,000 kilometers.

51. We are told in Mathematical Insight 3.2 that the perihelion and aphelion distances between the Sun and a planet are, respectively:

$$\text{perihelion distance} = a(1 - e)$$

$$\text{aphelion distance} = a(1 + e)$$

where a is the semimajor axis and e is the eccentricity.

From Appendix E, Mars's orbital eccentricity is 0.093 and its semimajor axis is 1.524 AU. So we get:

$$\begin{aligned}\text{perihelion distance} &= (1.524\text{ AU}) \times (1 - 0.93) \\ &= 1.382\text{ AU}\end{aligned}$$

and

$$\text{aphelion distance} = (1.524\text{ AU}) \times (1 + 0.93)$$
$$= 1.666\text{ AU}$$

Mars's minimum distance from the Sun is 1.382 AU and its maximum distance is 1.666 AU.

52. From Appendix E, Pluto has the largest eccentricity of the planets, at 0.248. (Note that we are ignoring the recently discovered dwarf planet Eris, which is apparently larger than Pluto and has a greater eccentricity.) Given its semimajor axis, 39.54 AU, we can use the formulas from Mathematical Insight 3.2 to calculate its perihelion and aphelion distances from the Sun:

$$\text{perihelion distance} = a(1 - e)$$
$$= 39.54\text{ AU} \times (1 - 0.248)$$
$$= 29.73\text{ AU}$$

and

$$\text{aphelion distance} = a(1 + e)$$
$$= 0.723\text{ AU} \times (1 + 0.248)$$
$$= 0.718\text{ AU}$$

Pluto's perihelion distance from the Sun is 29.73 AU, and its aphelion distance from the Sun is 49.35 AU.

53. From Appendix E, Venus has the smallest eccentricity of the planets, at 0.007. Given its semimajor axis, 0.723 AU, we can use the formulas from Mathematical Insight 3.2 to calculate its perihelion and aphelion distances from the Sun:

$$\text{perihelion distance} = a(1 - e)$$
$$= 0.723\text{ AU} \times (1 - 0.007)$$
$$= 0.718\text{ AU}$$

and

$$\text{aphelion distance} = a(1 + e)$$
$$= 0.723\text{ AU} \times (1 + 0.007)$$
$$= 0.728\text{ AU}$$

Venus's perihelion distance from the Sun is 0.718 AU, and its aphelion distance from the Sun is 0.728 AU.

54. 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 its average distance in AU:

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

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

55. Since the mass of this new star is the same as the mass of the Sun, we can use Kepler's third law. According to Kepler's third law:

$$a^3 = p^2$$

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

$$p = \sqrt{a^3}$$

We do not need the eccentricity at all (notice that it does not appear in Kepler's third law), but we do need to convert the new planet's semimajor axis into AU to use this formula. So converting 112,000,000 kilometers into AU:

$$112{,}000{,}000\ \cancel{\text{km}} \times \frac{1\ \text{AU}}{150{,}000{,}000\ \cancel{\text{km}}} = 0.747\ \text{AU}$$

Using this in Kepler's third law:

$$\begin{aligned} p &= \sqrt{(0.747)^3} \\ &= 0.645\ \text{yr} \end{aligned}$$

The new planet has an orbital period of 0.645 year, or about $7\frac{3}{4}$ months.

56. 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:

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

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

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

Comet Halley has a semimajor axis of 17.9 AU.

b. We use the formulas from Mathematical Insight 3.2. We are told that Halley's comet has an eccentricity of 0.97 and in part (a), we calculated its semimajor axis to be 17.9 AU:

$$\begin{aligned} \text{perihelion distance} &= 17.9\ (1 - 0.97) \\ &= 0.537\ \text{AU} \end{aligned}$$

and

$$\begin{aligned} \text{aphelion distance} &= 17.9\ (1 + 0.97) \\ &= 35.3\ \text{AU} \end{aligned}$$

Halley's comet comes as close as 0.537 AU to the Sun and travels as far away as 35.3 AU from the Sun.

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. Since it is moving most slowly there, Halley's comet also spends more time in that part of its orbit.

Chapter S1. Celestial Timekeeping and Navigation

This is a supplementary chapter, meaning that coverage is optional—nothing in this chapter is prerequisite for the rest of the book. This final chapter of Part I provides details about apparent motions of the sky that have not already been covered in the first three chapters. Note that, although it covers fairly "basic" ideas about the sky, this material is often quite difficult for students. Understanding motions of the sky requires visualizing three-dimensional geometry, which some students simply cannot grasp in just a week or so. It certainly helps if you have access to a planetarium when covering the motions of the sky.

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 Guide) and the online quizzes and other study resources available on the MasteringAstronomy Web site.

Teaching Notes (By Section)

Section S1.1 Astronomical Time Periods

This section introduces basic astronomical periods: the solar versus the sidereal day, the synodic versus the sidereal month, the tropical versus the sidereal year, and synodic versus sidereal periods of the planets.

- You may wish to do the demonstration described in the text to show the difference between a sidereal and a solar day; it's easy for students to watch you rotating as you walk around an object that represents the Sun.
- Technical note: The true rotation period of Earth differs from the sidereal day by a few thousandths of a second because of the precession of Earth's axis.
- If your campus has a sundial, take a class field trip or ask your students to investigate it on their own.
- Many students will find the issues of calendar reform quite interesting from a historical point of view, especially the fact that, for centuries, not all countries agreed on the date, even if they were ostensibly using the same "Christian" calendar.

Section S1.2 Celestial Coordinates and Motion in the Sky

This section covers the coordinates of right ascension and declination and the variation in sky motions with latitude.

- In class, you may want to emphasize that these coordinates are easier to understand if we think of them as "celestial latitude" and "celestial longitude."

- If possible, it really helps if you can visit a planetarium to demonstrate the motions described in this section. In that case, you may wish to begin by pointing out how its dome distorts what we see in the real sky. In particular, the point in the planetarium representing the zenith generally is directly over the projector, rather than over any audience member's head. As a result, the planetarium sky looks most distorted above wherever you are sitting. The other major distortion is the smaller angular size of everything viewed in the planetarium compared to the real sky.
- We've found that the order in which sky motions at different latitudes are described is very important in helping students understand what is going on. The order we've chosen begins with the simplest latitudes—the North Pole and then the equator. In class, you should next do your own latitude, then generalize.
- Keep in mind that some otherwise bright students will have difficulty with this three-dimensional geometry regardless of what you do. Such students may simply have to memorize the rules rather than truly understand the geometry.

Section S1.3 Principles of Celestial Navigation

This section gives a brief overview of techniques of celestial navigation.

- The idea of determining your longitude by calling a friend in Greenwich may seem a bit far-fetched, especially in historical context, but we've found it effective at getting students to realize that it's really pretty easy to determine longitude—the only trick is that you need a clock to tell you the time someplace else.
- *Technical note:* Common Misconceptions: Compass Directions. In this box, we say "magnetic north" to mean the magnetic pole located in the Northern Hemisphere. In terms of response to magnetism, the magnetic pole in the Northern Hemisphere is a south magnetic pole; that is why the north end of a magnet is attracted in this direction. Similarly, by "south magnetic pole" we really mean the magnetic pole located in the Southern Hemisphere—which is a north magnetic pole, according to its magnetic properties.

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 S1.1

- (p. 90) At midnight, looking toward the meridian means looking in a direction 180° away from the Sun. Neither Mercury nor Venus ever ventures anywhere close to this far from the Sun as viewed from Earth; neither, therefore, ever appears on the meridian at midnight.
- (p. 91) 12:01 A.M. is 1 minute after midnight, while 12:01 P.M. is 1 minute after noon.

Section S1.2

- (p. 96) This exercise asks students to continue work with their own model of the celestial sphere, which we explain how to make in the main text (a few paragraphs earlier). On April 21, the Sun is about $\frac{1}{12}$ of the way around the ecliptic from the spring equinox. On November 21, it is about $\frac{1}{12}$ of the way short of being at the winter solstice.
- (p. 98) This exercise again asks students to continue building their own model of the celestial sphere.
- (p. 99) Again, students will mark their models of the celestial sphere. They should now be able to locate the Sun for any day, including their birthdays.
- (p. 101) No stars are circumpolar at the equator, and all portions of the celestial sphere become visible over the course of the day.
- (p. 103) At 30°S latitude, the celestial equator crosses the meridian at altitude 90° – 30° = 60° in the northern half of the sky. Stars with positive declinations follow short tracks across the northern sky. Stars with negative declinations follow long tracks across the southern sky (crossing into the north if they have a declination between 0° and –30°). Stars with declinations more negative than –60° are circumpolar.

Solutions to End-of-Chapter Problems (Chapter S1)

1. A sidereal day is shorter than a solar day because as Earth spins, it also moves around the Sun. So for each complete rotation, Earth must rotate a little extra before the Sun returns to the same place in the local sky.
2. A sidereal month is the time it takes for the Moon to go around Earth relative to the background stars. This is shorter than a synodic month, which is the time it takes the Moon to go from new phase to the next new phase. The synodic month is longer than the sidereal month due to Earth's orbital motion, which means that the Moon must travel more than one complete orbit from new moon to new moon.

   A sidereal year is the time it takes Earth to complete an orbit relative to the positions of distant stars. This is about 20 minutes longer than a tropical year, which is the time between two successive vernal (spring) equinoxes. The difference is due to the precession of Earth's spin axis.

   A planet's sidereal period is the time it takes the planet to go around the Sun. (From the Sun's point of view, the planet would come back to the same stars. But don't try to stand on the Sun and check.) The planet's synodic period is the time it takes the planet to go from a particular alignment with Earth back to that same relative alignment—for example, the time it takes Mars to go from being opposition to opposition again.
3. Opposition occurs when a planet is on the opposite side of Earth from the Sun. This can only happen for planets located farther than Earth from the Sun. (So Venus and Mercury are *never* in opposition.)

A conjunction occurs when a planet is aligned with the Sun in our sky, either between the Sun and Earth or on the opposite side of the Sun from Earth. For planets beyond Earth, only a superior conjunction (when the planet is on the opposite side of the Sun from Earth) is possible. For Mercury and Venus, which orbit closer to the Sun than we do, an inferior conjunction (when the planet is between the Sun and Earth) also occurs.

Greatest elongation only occurs for planets closer to the Sun than Earth—that is, for Mercury and Venus. This is the arrangement where the planet will appear to be as far from the Sun in our sky as it will get during an orbit.

4. We will see a transit only for the planets Mercury and Venus (at least for planets within our solar system). A transit occurs when a planet appears to pass in front of the Sun's disk as seen from Earth, so it can occur only when the planet is in inferior conjunction. Moreover, because Mercury and Venus's orbits are tilted relative to Earth's orbit, the planets usually are slightly north or south of the Sun at inferior conjunction. However, when the planet's orbits line up just right, we get a transit. Transits of Mercury occur about a dozen times a century, while Venus transits occur in pairs separated by more than 100 years, with the second transit of a pair occurring about 8 years after the first.

5. Apparent solar time is the time based on the actual location of the Sun in the sky, while mean solar time is based on making all days 24 hours long. The two differ because of the tilt of Earth's spin access and because Earth moves at different speeds in its orbit as it gets slightly closer to or farther from the Sun, so that the actual length of a day based on the Sun's position in the sky actually varies over the course of the year, with 24 hours as the average. Apparent solar time can be read directly from a sundial, while mean solar time is easier to obtain with mechanical or electronic clocks because all days are the same length.

   Standard time is the mean solar time over an east-west swath of Earth known as a time zone. Daylight saving time is simply standard time advanced by 1 hour. Universal Time (UT) is the mean solar time for Greenwich, England.

6. The Julian calendar was developed at Julius Caesar's orders to correct problems with the older Roman calendar. It added an extra day every 4 years to keep the calendar more closely synchronized with the seasons. However, over many years this was still not quite accurate enough, and the Julian calendar drifted relative to the seasons. Pope Gregory XIII ordered the calendar to be fixed. His Gregorian calendar modified the leap-year pattern so that while it still normally occurs every 4 years, we do not have leap year in century years, except for years that are divisible by 400. Today we use the Gregorian calendar.

7. When we describe equinoxes and solstices as points on the celestial sphere, we refer to the positions among the stars that the Sun actually occupies on those days. For example, the spring equinox in the sky is the point in the constellation Pisces at which the Sun is located on the day of the spring equinox.

8. Declination and right ascension are the coordinates we use to pinpoint positions on the celestial sphere. These are quite similar to latitude and longitude: Like latitude, declination is zero at the equator and is measured in degrees. But rather than say "north" or "south," we assign declinations positive or negative values. Right

ascension is like longitude, except that it is usually measured in hours, minutes, and seconds rather than in degrees.

9. The Sun's celestial coordinates change over the year because, as we orbit the Sun, the Sun appears to drift eastward around the celestial sphere at a rate of about 2 hours of right ascension per month. It also moves somewhat north and south with the seasons (due to Earth's tilt), so that the Sun has its largest positive (northernmost) declination on the summer solstice and its largest negative (southernmost) declination on the winter solstice, and is at 0° declination on the equinoxes.

10. At the North Pole, the north celestial pole is directly overhead and the celestial equator circles the horizon.

    At the equator, the north celestial pole is on the northern horizon, and the celestial equator runs from due east to due west and through the zenith.

    At 40° north latitude, the north celestial pole is due north, 40° above the horizon. The celestial equator runs from due east to due west, passing through an altitude of 50° due south.

11. At 40°N latitude, the Sun will rise due east and set due west on the equinoxes. On these days it will cross the meridian at altitude 50° due south. On the summer solstice, the Sun will rise north of due east, cross the meridian at altitude 73.5° due south, and set north of due west. On the winter solstice, the Sun rises south of due east, crosses the meridian at altitude 26.5° due south, and sets south of due west.

    At the equator on the equinoxes, the Sun will rise due east, pass directly overhead, and set due west. On the summer solstice, the Sun will rise north of due east, cross the meridian at 66.5° to the *north* and set north of due west. On the winter solstice, the mirror image will occur: The Sun will rise south of due east, cross the meridian at 66.5° altitude to the south, and set south of due west.

    At the North Pole on the equinoxes, the Sun will skim the horizon, making a circle all around the horizon each day. On the summer solstice, the Sun will circle 23.5° above the horizon all day. On the winter solstice, we would not see the Sun at all.

    At the South Pole on the equinoxes, the Sun will skim the horizon, making a circle all around the horizon each day. On the summer solstice, the Sun would not appear at all. On the winter solstice, the Sun will circle 23.5° above the horizon all day.

12. The tropics of Cancer and Capricorn are the most extreme latitudes (farthest north and south) where the Sun can ever be seen directly overhead. On the solstices (summer for Cancer, winter for Capricorn), the Sun will rise north of due east (south, for winter at Capricorn), pass directly overhead, and set north of due west (south, for winter at Capricorn).

    The Arctic and Antarctic Circles are the northernmost and southernmost points where the Sun will be seen at least briefly on every day of the year. Alternatively, these are the southernmost and northernmost latitudes where the Sun will appear above the horizon for an entire 24-hour day at least once a year. So on the summer solstice at the Arctic Circle, the Sun will be due north at midnight, just at the horizon. It will work its way east, growing higher in the sky, until it comes around to the meridian to the south, when it will be at 47° above the horizon. It will then continue off to the west, then north, sinking back toward the horizon. On the winter solstice, the Sun will just barely appear above the horizon due south at noon. For the Antarctic circle, this situation is exactly reversed.

13. If we know the time and date, we can use the Sun to determine our latitude and longitude. The Sun's declination on a given date is well known, so based on the Sun's altitude when it's on the meridian, we can work out our latitude. We could alternately use a star at night to do the same thing. Longitude is trickier. To do this, we need a clock that keeps UT accurately. However, if we have this, we can use when a given star crosses the meridian (or when the Sun does, although we have to account for the Sun's variations with the day of the year) to tell our longitude.
14. The Global Positioning System is a set of satellites designed to allow people on Earth to determine their locations with extreme accuracy.
15. *Last night I saw Venus shining brightly on the meridian at midnight.* This statement does not make sense, because it would require that Venus be at opposition to the Sun in the sky—and, because Venus is closer to the Sun than is Earth, it is never at opposition.
16. *The apparent solar time was noon, but the Sun was just setting.* This statement does not make sense, because apparent solar noon is defined as the time when the Sun is at its highest point on the meridian. If the Sun is at its highest point, it cannot be setting.
17. *My mean solar clock said it was 2:00 P.M., but my friend who lives east of here had a mean solar clock that said it was 2:11 P.M.* Mean solar time is different for every different longitude, so this statement makes sense if the friend lives the equivalent of 11 minutes of longitude east of you.
18. *When the standard time is 3:00 P.M. in Baltimore, it is 3:15 P.M. in Washington, D.C.* This statement does not make sense, because standard time zones must be 1 hour apart, not 15 minutes apart. (Also, Baltimore and Washington, D.C., are in the same time zone.)
19. *Last night around 8 P.M., I saw Jupiter at an altitude of 45° in the south.* This statement makes sense, because it describes the position of Jupiter in your local sky.
20. *The latitude of the stars in Orion's belt is about 5°N.* This statement does not make sense; Orion's belt is not on Earth, and hence does not have a latitude.
21. *Today the Sun is at an altitude of 10° on the celestial sphere.* This statement does not make sense, because altitude is a coordinate of the local sky, not of the celestial sphere.
22. *Los Angeles is west of New York by about 3 hours of right ascension.* This statement does not make sense, because right ascension is a coordinate of the celestial sphere, not of Earth.
23. *The summer solstice is east of the vernal equinox by 6 hours of right ascension.* This statement is true at all times.
24. *Even though my UT clock had stopped, I was able to find my longitude by measuring the altitudes of 14 different stars in my local sky.* This statement does not make sense, because longitude determination requires comparing the positions of stars (or the Sun) in your location with their positions in a known location, and the latter requires knowing the time in that location. Thus, without a clock, you can't determine your longitude.

25. b; 26 a; 27. c; 28. b; 29. a; 30. a; 31. c; 32. c; 33. a; 34. c

35. Transits would not have provided evidence against the geocentric universe; transits would have been consistent with the Earth-centered view, since Mercury and Venus lay between Earth and the Sun in this model (see Figure 3.24). However, just as there are occasional transits, there are occasional times when Mercury or Venus pass directly behind the Sun as seen from Earth; we say that they are eclipsed by the Sun—and such eclipses could not have occurred in the geocentric system in which Mercury and Venus were always between Earth and the Sun.

36. The mathematics was just one step in the longer process of the Copernican revolution, but it helped scientists make precise predictions that could therefore be tested much more carefully than vague or imprecise statements. Precision testing of mathematically based predictions is a key ingredient of modern science.

37. Congress's goal in extending the period of daylight saving time was supposedly to save energy. However, studies are ambiguous as to whether the change actually saves energy (e.g., less lighting needed in the evening) or costs energy (e.g., businesses stay open later, so people drive more). So if there's any real science behind it, it's difficult to see.

38. If Earth rotated in the opposite direction, our orbit around the Sun would mean we'd need to turn through *less* than one full rotation from noon one day to noon the next, so the solar day would be *shorter* than the sidereal day.

39. If Earth's axis did not precess, there would be no difference between the sidereal and tropical years.

40. Answers will vary with latitude (except for part (b)); the following is a sample answer for 40°N latitude:

    a. The north celestial pole appears in your sky at an altitude of 40°, in the direction due north.

    b. The meridian is a half-circle that stretches from the point due south on the horizon, through the zenith, to the point due north on the horizon.

    c. The celestial equator is a half-circle that stretches from the point due east on the horizon, through an altitude of 50° due south, to the point due west on the horizon.

    d. The Sun can appear at the zenith only in the tropics. At latitude 40°N, the Sun is never at the zenith.

    e. Because the north celestial pole appears due north at an altitude of 40°, a star is circumpolar if it is within 40° of the north celestial pole. The north celestial pole has a declination of +90°, so within 40° means declinations greater than +50°.

    f. The celestial equator reaches a maximum altitude of 50° in the southern sky. Thus, any star that is more than 50° south of the celestial equator is never visible above the horizon. More than 50° south of the celestial equator means declinations more negative than –50°.

41. For Sydney, 34°S latitude:

    a. The south celestial pole appears in your sky at an altitude of 34°, in the direction due south.

b. The meridian is a half-circle that stretches from the point due south on the horizon, through the zenith, to the point due north on the horizon.

c. The celestial equator is a half-circle that stretches from the point due east on the horizon, through an altitude of 56° due north, to the point due west on the horizon.

d. The Sun can appear at the zenith only in the tropics. At latitude 34°S, the Sun is never at the zenith.

e. Because the south celestial pole appears due south at an altitude of 34°, a star is circumpolar if it is within 34° of the south celestial pole. The south celestial pole has a declination of –90°, so within 34° means declinations more negative than –56°.

f. The celestial equator reaches a maximum altitude of 56° in the northern sky. Thus, any star that is more than 56° north of the celestial equator is never visible above the horizon. More than 56° north of the celestial equator means declinations greater than +56°.

42. Answers will vary with latitude; the following is a sample answer for 40°N latitude:

a. On the spring or fall equinox, the Sun rises due east, reaches an altitude of 50°S on the meridian, and sets due west.

b. On the summer solstice, the Sun rises more than 23.5° north of due east, reaches an altitude of 50° + 23.5° = 73.5° on the meridian in the south, and sets more than 23.5° north of due west.

c. On the winter solstice, the Sun rises more than 23.5° south of due east, reaches an altitude of 50° – 23.5° = 26.5° on the meridian in the south, and sets more than 23.5° south of due west.

d. Answers depend on the date.

43. In Sydney (34°S latitude): The celestial equator goes due east, through 90° – 34° = 56° in the north, to due west.

a. On the spring or fall equinox, the Sun rises due east, reaches an altitude of 56°N on the meridian, and sets due west.

b. On the summer solstice, the Sun rises more than *23.5*° north of due east, reaches an altitude of 56° – 23.5° = 32.5° on the meridian in the north, and sets more than 23.5° north of due west.

c. On the winter solstice, the Sun rises more than 23.5° south of due east, reaches an altitude of 56° + 23.5° = 79.5° on the meridian in the north, and sets more than 23.5° south of due west.

d. Answers depend on the date.

44. a. Your latitude is 15°N. Because it is the vernal equinox, the Sun follows the path of the celestial equator through the sky. Thus, the Sun's meridian altitude of 75°S tells you that this also is the altitude at which the celestial equator crosses the meridian. Because we know that the celestial equator crosses the meridian at 90°– [your latitude], your latitude is 90° – 75° = 15°; it is north latitude because the celestial equator is in your southern sky.

b. Your longitude is 150°W. The Sun is on your meridian, so it is noon for you. The UT clock reads 22:00, or 10 P.M., so Greenwich is 10 hours ahead of you. Each hour represents 15° of longitude, so 10 hours means 150°; you are west of Greenwich because your time is behind.

c. You are very close to Hawaii.

45. a. You are on the equator. Because it is the summer solstice, the Sun crosses the meridian 23.5° north of the celestial equator. Thus, the Sun's meridian altitude of 67.5°N tells you that the celestial equator is passing through your zenith and hence that you are on Earth's equator.

b. Your longitude is 90°E. The Sun is on your meridian, so it is noon for you. The UT clock reads 06:00, or 6 A.M., so Greenwich is 6 hours behind you. Each hour represents 15° of longitude, so 6 hours means 90°; you are east of Greenwich because your time is ahead.

c. You are in the Indian Ocean, not too far west of the island of Sumatra.

46. a. Your latitude is within 1° of 67°N, which you know because that is the altitude of Polaris in your sky.

b. Your longitude is 15°W. Your local time is midnight and the UT clock reads 01:00, or 1 A.M., so Greenwich is 1 hour ahead of you. Thus, you are 15° west of Greenwich.

c. You are just off the northern coast of Iceland.

47. a. Your latitude is 33°S, which you know because that is the altitude of the south celestial pole in your sky.

b. Your longitude is 75°W. Your local time is 6 A.M. and the UT clock reads 11:00, or 11 A.M., so Greenwich is 5 hours ahead of you. Thus, you are $5 \times 15° = 75°$ west of Greenwich.

c. You are off the coast of Chile, nearly due west of Santiago.

48. The range of latitudes for which the Sun can reach the zenith on Mars is very slightly larger, as is the range of latitudes for which the Sun can be circumpolar. Both ranges increase with axis tilt, so the slightly larger axis tilt of Mars means slightly greater ranges. (Sketch not shown.)

49. If Earth went around the Sun in 6 months rather than a year, we would travel twice as great of an angle around the Sun in 1 day as we do now. Right now, we travel about 1° around the Sun in our orbit, so we'd travel 2° per day in the 6-month year. The solar day would have to be longer than the sidereal day by enough for Earth to spin an extra 2°. How long would this take? Well, Earth spins 360° in about 24 hours (actually, in 23 hours and 56 minutes, but this should be good enough). So converting from degrees to hours, we get:

$$2\cancel{°} \times \frac{24 \text{ hr}}{360\cancel{°}} = 0.13 \text{ hr}$$

We had better convert this to minutes, though:

$$0.13 \cancel{\text{hr}} \times \frac{60 \text{ min}}{1 \cancel{\text{hr}}} = 8 \text{ min}$$

So Earth's solar day would be 8 minutes longer than the sidereal day. Since the sidereal day is 23 hours and 56 minutes, that comes out to 24 hours and 4 minutes.

Note that the extra 8 minutes is exactly twice the 4-minute difference we experience with the 12-month year. Since we'd be traveling twice as far per day (in angle) in the 6-month year, this should make sense.

50. In Mathematical Insight S1.1, we learn that the orbital period for planets farther from the Sun than Earth is related to the synodic period by the relationship:

$$P_{\text{orb}} = P_{\text{syn}} \times \frac{1 \text{ yr}}{(P_{\text{syn}} - 1 \text{ yr})}$$

where P_{orb} is the sidereal orbital period and P_{syn} is the synodic orbital period.

So we just need to get Saturn's synodic period in years so that the units match up. So we convert from days to years:

$$378.1 \cancel{\text{days}} \times \frac{1 \text{ yr}}{365.25 \cancel{\text{days}}} = 1.0352 \text{ yr}$$

Plugging this value for P_{syn}, we get:

$$P_{\text{orb}} = 1.0352 \cancel{\text{yr}} \times \frac{1 \text{ yr}}{(1.0352 - 1 \cancel{\text{yr}})}$$
$$= 29.41 \cancel{\text{yr}}$$

Saturn's orbital period must be 29.41 years. Note that our answer agrees quite well with the value in Appendix E of 29.42 years.

51. In Mathematical Insight S1.1, we learn that the orbital period for planets closer to the Sun than Earth is related to the synodic period by the relationship:

$$P_{\text{orb}} = P_{\text{syn}} \times \frac{1 \text{ yr}}{(P_{\text{syn}} + 1 \text{ yr})}$$

where P_{orb} is the sidereal orbital period and P_{syn} is the synodic orbital period.

We need to convert Mercury's synodic period into years so that the units match up:

$$115.9 \cancel{\text{days}} \times \frac{1 \text{ yr}}{365.25 \cancel{\text{days}}} = 0.3173 \text{ yr}$$

Plugging in to the formula, we get:

$$P_{\text{orb}} = 0.3173 \cancel{\text{yr}} \times \frac{1 \text{ yr}}{(0.3173 + 1 \cancel{\text{yr}})}$$
$$= 0.2409 \text{ yr}$$

Mercury's orbital period is 0.2409 year, which is in excellent agreement with the value in Appendix E.

52. Because the synodic period of the asteroid is longer than Earth's orbital period, it must orbit farther from the Sun than Earth does. In this case, we will use the relationship for synodic and sidereal orbital periods for those planets:

$$P_{\text{orb}} = P_{\text{syn}} \times \frac{1 \text{ yr}}{(P_{\text{syn}} - 1 \text{ yr})}$$

where P_{orb} is the sidereal orbital period and P_{syn} is the synodic orbital period.

So we just need to get the asteroid's synodic period in years so that the units match up. So we convert from days to years:

$$429\ \cancel{\text{days}} \times \frac{1\text{ yr}}{365.25\ \cancel{\text{days}}} = 1.17\text{ yr}$$

Plugging this value for P_{syn}, we get

$$P_{orb} = 1.17\ \cancel{\text{yr}} \times \frac{1\text{ yr}}{(1.17 - 1\ \cancel{\text{yr}})}$$
$$= 6.88\text{ yr}$$

The asteroid's orbital period is 6.88 years.

53. To answer this, we will need to use the equation of time plot (Figure 2 in Special Topic: Solar Days and the Analemma). Reading off of the graph for February 15, we see that mean solar time is ahead of the apparent solar time by about 14 minutes. So if the sundial says that the time is 18 minutes until noon, we have to add 14 minutes to this to get a mean solar time of 4 minutes to noon, or 11:56 A.M.

54. To answer this, we will need to use the equation of time plot (Figure 2 in Special Topic: Solar Days and the Analemma). Reading off of the graph for July 1, we see that the mean solar time is about 5 minutes ahead of apparent solar time. So if the sundial says 3:30 P.M., the mean solar time would be 5 minutes later, or 3:35 P.M.

55. On the day of the spring equinox, the Sun is located at the position of the spring equinox in the sky. Thus, at 4 P.M., both the Sun and the spring equinox are 4 hours past the meridian, so the local sidereal time is 4 hours.

56. Vega has RA = $18^h\ 35^m$. Thus, at LST = 19:30, Vega's hour angle is:

$$HA_{Vega} = LST - RA_{Vega} = 19{:}30 - 18{:}35 = 00{:}55$$

Vega crossed your meridian about 55 minutes ago, which means it will cross again in about 23 hours 5 minutes.

57. We are given HA_{star} = 3 hr and LST = 8:15. Thus, we have the equation:

$$HA_{star} = LST - RA_{star}$$

Solving for the RA of the star, we find:

$$RA_{star} = LST - HA_{star} = 08{:}15 - 03{:}00 = 05{:}15$$

The star has a right ascension of 5 hours 15 minutes.

58. We are told in Mathematical Insight S1.2 that

$$HA_{object} = LST - RA_{object}$$

where HA_{object} is the hour angle, LST is the local sidereal time, and RA_{object} is the object's right ascension. We are told that the local sidereal time is 7:00 and that the Orion Nebula has a right ascension of $5^h\ 25^m$, so the hour angle of the Orion Nebula must be $1^h\ 35^m$. This puts the Orion Nebula west of the meridian by about 25°. Since the Orion Nebula has a declination of –5.5°, it is near the celestial equator. At our latitude, the celestial equator has an altitude of 50° (90° latitude) where it crosses the meridian in the south. The Orion Nebula will have sunk a bit lower since then, so we should look for it at about 40° altitude, somewhere in the southeast.

59. We will compute this in a way similar to the way in which we found the difference between the mean solar and sidereal days. The Moon's orbital period is about

27.5 days. In this time, it travels 360° around the celestial sphere. Thus, each day, it travels relative to the stars through an angle of:

$$1 \ \cancel{\text{day}} \times \frac{360°}{27.3 \ \cancel{\text{days}}} = 13.2°$$

We now need to figure out how long it takes Earth to cover this angle it rotates. Since Earth spins 360° in 24 hours, we can use this to convert:

$$13.2\cancel{°} \times \frac{24 \text{ hr}}{360\cancel{°}} = 0.88 \text{ hr}$$

This number would probably be better if it were in minutes, so we convert:

$$0.88 \ \cancel{\text{hr}} \times \frac{60 \text{ min}}{1 \ \cancel{\text{hr}}} \approx 53 \text{ min}$$

The synodic period of the Moon is about 24 hours and 53 minutes.

Doing the same for Phobos, we see from Appendix E that its orbital period is 0.319 Earth day. First, we should convert this to Martian days. Appendix E also tells us that Mars spins on its axis every 1.026 Earth days. So Phobos's orbital period in Martian days is:

$$0.319 \ \cancel{\text{Earth day}} \times \frac{1 \text{ Martian day}}{1.026 \ \cancel{\text{Earth days}}} = 0.327 \text{ Martian day}$$

In this time, it travels 360° around the Martian sky. However, this time Mars has spun a around a bit so now Phobos has to catch up to be back on the meridian. How far has Mars spun? Well, Mars spins 360° in 1 Martian day, so we convert 0.327 Martian day to degrees:

$$0.327 \ \cancel{\text{Martian day}} \times \frac{360°}{1 \ \cancel{\text{Martian day}}} = 118°$$

How long does it take Phobos to cover that extra distance? Well, if it travels 360° in 0.327 day, then we can convert 118° into the time it takes for Phobos to cover that distance:

$$118\cancel{°} \times \frac{0.327 \text{ Martian day}}{360\cancel{°}} = 0.107 \text{ Martian day}$$

So adding this to the orbital period, we discover that Phobos takes 0.434 Martian day to go from the meridian back around to the meridian again—which means that Phobos circles the Martian sky more than twice with each Martian day.

60. Let's see how far Mercury's local meridian has to move to catch the Sun after one orbit. The Sun moves at 360° per 88 days. So we can find out how far it has moved in on a 58.6-day spin period:

$$58.6 \ \cancel{\text{days}} \times \frac{360°}{88 \ \cancel{\text{days}}} = 240°$$

So Mercury's spin has to catch up 240°. But wait! The Sun will still be moving at its 360°/88-day rate across the sky while Mercury's meridian tries to catch up at its

360°/58.6-day rate. (For Earth, we didn't include this because Earth spins so much faster than it orbits. But for Mercury, the two speeds are too close to ignore this effect.) So we can set up a relationship between how fast Mercury's meridian moves in time *t* and how far it has to go to catch up:

$$\frac{360°}{58.6 \text{ days}} t = \frac{360°}{88 \text{ days}} t + 240°$$

We can group the terms with *t*:

$$\frac{360°}{58.6 \text{ days}} t - \frac{360°}{88 \text{ days}} t = 240°$$

$$\left(\frac{360°}{58.6 \text{ days}} - \frac{360°}{88 \text{ days}} \right) t = 240°$$

and then solve for *t*:

$$t = \frac{240\cancel{°}}{\left(\frac{360\cancel{°}}{58.6 \text{ days}} - \frac{360\cancel{°}}{88 \text{ days}} \right)}$$

$$= 117 \text{ days}$$

We have to add this to our 58.6-day spin period, which already happened, so we get 176 days for the solar day. That's exactly twice the orbital period. The solar day on Mercury is twice the length of the year!

