Part III: Learning from Other Worlds

Chapter 8. Welcome to the Solar System

This chapter offers an introduction to our solar system, with an emphasis on giving students a common background in the essential information about the planets that will allow a deeper look in coming chapters. We begin by imagining an alien spacecraft coming in from afar and mapping the broad features of the solar system. Then we focus in on individual worlds, taking a tour of the Sun and the nine planets. Finally, we discuss spacecraft exploration of the solar system.

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

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

This is an entirely new chapter, designed to give students a better sense of the solar system before diving into details in the chapters that follow. However, most of the material in this chapter will be familiar to you from other sections of the second edition. In particular, note that:

- The first two sections were essentially split out from the old Chapter 8 on the formation of the solar system, which has now become Chapter 9 in this edition.
- Section 8.3 is a modified version of the tour of the solar system that appeared in Chapter 1 of the second edition.
- Section 8.4 on spacecraft is adapted from the former Section 7.6 in the second edition.

Teaching Notes (By Section)

Section 8.1 Comparative Planetology

This section introduces and emphasizes the concept of comparative planetology, the idea that similarities and differences between the planets can be traced to common physical processes. This is the unifying theme behind all of Part III and should focus students on the importance of learning processes over facts.

Section 8.2 The Layout of the Solar System

This section introduces the "big picture" layout of the solar system in figures and tables, building up the students' mental picture of its properties.

- Note that we refer to residents of the Kuiper belt as *comets* in order to emphasize their icy compositions; not all planetary scientists refer to these objects in this way.

Section 8.3 A Brief Tour of the Solar System

This section offers our "tour" of the major worlds in the solar system. The Sun and each planet get a full page, with sizes and distances referenced to the same scale (the 1-to-10-billion Voyage scale) introduced in Section 1.2.

- FYI (relevant to the box on discovery of the outer planets): Uranus was discovered by Herschel when he saw that it appeared as a disk, rather than a point, through his telescope. However, it had been observed several times earlier and was recorded as a star (designated 34 Tauri) by Flamsteed.

Section 8.4 Exploring the Solar System

This section is designed to give students a brief overview of the use of spacecraft in planetary exploration.

- Note that we divide robotic spacecraft into four categories: Earth-orbiters, flybys, orbiters (of other worlds), and probes/landers. This helps focus students on the key differences between the types of missions.

Answers/Discussion Points for Think About It Questions

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

Section 8.2

- This question is designed to encourage students to discover patterns in the solar system instead of simply being told the answers. It is a good question to ask in class with Table 8.1 displayed—students will either remember the answers from reading the whole chapters, or will glean them from the table. The answers, of course, form the basis of this section and Chapter 9. The patterns of motion are listed in the bullets just following the "Think About It." The properties of the two groups of planets (best gleaned from Table 8.1) are summarized in Table 8.2. Most of the patterns and distinctions are clear-cut: no planets orbit the sun backwards, and all jovian planets are much larger than the largest terrestrial planet. All jovian planets have rings and moons. But some patterns are not "rules": not all planets rotate the same way, and many of the smaller moons orbit their planets backwards. Some terrestrial planets have moons, but not all.
- The asteroid belt would be a doughnut-shaped region lying between the orbits of Mars and Jupiter, the Kuiper belt is a much wider doughnut-shaped region extending from Neptune's orbit to about three times Neptune's distance from the Sun. Note that, whereas the asteroid belt and Kuiper belt are still on the National Mall on this scale, the Oort cloud is not: it comprises a spherical region that, to the west at least, extends as far as midwestern states. All of the individual objects in these three regions would be very tiny on this scale—none larger than Pluto, which is a barely visible dot (see Figure 1.8a), and most microscopic. Thus, while the regions contain numerous objects, they would be no more obvious to the eye than microscopic motes of dust.

Section 8.4

- No. Because of their differing orbital periods, they no longer have a simple alignment like they did during the 1980s. In particular, Uranus has caught up with Neptune by now, so we won't be able to visit both with a single slingshot from Saturn.

Solutions to End-of-Chapter Problems (Chapter 8)

1. Pluto orbits the Sun in the opposite direction of all the other planets. *False.*
2. If we were to discover a Kuiper-belt comet that is as large as the planet Mercury, we would classify it as a terrestrial planet. *False. Terrestrial planets are rocky and Kuiper-belt objects are icy.*
3. Comets in the Kuiper belt and Oort cloud have long, beautiful tails that we can see when we look through telescopes. *False. The vast majority of comets lie far from the Sun, too far to create tails, etc.*
4. Asteroids are made essentially of the same ingredients as the terrestrial planets. *True.*
5. The mass of the Sun compared to the mass of all the planets combined is like the mass of an elephant compared to the mass of a cat. *True.*

6. On average, Venus is the hottest planet in the solar system—even hotter than Mercury. *True.*
7. The weather conditions on Mars today are much different than they were in the distant past. *True.*
8. Moons cannot have atmospheres, active volcanoes, or liquid water. *False.*
9. Saturn is the only planet in the solar system with rings. *False.*
10. Several sample return missions are currently en route to the terrestrial planets. *False.*
11. a) Planets closest to the Sun are the warmest, as they absorb more solar energy (per unit area). Venus violates the trend, due to its greenhouse effect.
    b) Density: jovian planets are all less dense than 2 grams per cubic centimeter, while terrestrial planets are all more than 3 grams per cubic centimeter. Composition: jovian planets are all dominated by H, He and hydrogen compounds, while terrestrial planets are mostly rocks and metals. Distance: jovian planets are all 5AU and beyond, while terrestrial planets are all inside 2 AU. Pluto's misfit status is the subject of Problem 12.
    c) The column "Rotation Period" gives the time for a day—though note that it is a day relative to the stars (that is, a sidereal day—see Section S1.1), not the Sun. For all planets other than Mercury or Venus, the difference is small. Jovian planets have shorter days than terrestrial planets.
    d) The orbital periods increase with the planets' semimajor axes, according to Kepler's third law ($p^2=a^3$).
    e) Planets with significant axis tilts will have seasons: Earth, Mars, Saturn, Uranus, Neptune, Pluto.
    f) "Min/Max Distance from the Sun" shows the deviation from a circular orbit. Mercury and Pluto show the largest effects, with Mars next.
    g) The table shows that escape velocities are highest for the largest, most massive planets: Jupiter's is nearly 60 km/sec, while Pluto's is 1.25 km/sec. Escape velocity is higher for more massive planets because it depends on mass (see the formula in Chapter 5). It also depends on radius, but because mass and radius generally go together for planets in our solar system, it is not easy to separate the effects of mass and radius on escape velocity.
    h) Just multiply 100 pounds times the surface gravity relative to Earth, giving 38, 91, 100, 38, 253, 107, 91, 114 and 7 pounds as the weights on the planets.
12. Pluto has the size and mass of a very small terrestrial planet, as well as having a solid surface. But it lies at a distance (and hence has a temperature) more in line with the jovian planets. Its composition and density do not match either type of planet, though they do resemble jovian planet moons.
13. The chief difference (apart from their locations and orbits) is that comets are icy and asteroids are rocky. Comets are far more numerous.
14. Students should coherently summarize the patterns of motion listed as bullets on page 202, and make the basic observation that these patterns would not arise if every planet formed from a different cloud at a different time. There would be no reason for the motions of the planets to be similar. Students will gain a deeper understanding of the reasons in Chapter 9.
15. This question asks students to coherently rephrase Table 8.2 in their own words. Students should include a discussion of density, composition, and distance (see answer to 11b.)
16. Many possible answers, based on student interest.

Chapter 9. Formation of the Solar System

The chapter presents a single, unified theory for solar system formation. It essentially “builds” the solar system piece by piece so that the following chapters can look in detail at how those pieces work and interact with one another.

While there is some value in getting students to learn our modern theory of solar system formation itself, in the long run it is more important that they get a feel for what a theory is good for and how a theory should be judged. Note that, while we emphasize the evidence that supports our modern theory, we do not emphasize the contorted path followed in its development; you may therefore wish to emphasize the unresolved issues that we point out in this chapter and others. The difficulty in explaining many of the newly discovered extrasolar planets also provides a good example of how science works.

Note that this chapter also covers extrasolar planet detection and the implications of recently discovered planets to our theory of solar system formation.

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

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

This was Chapter 8 in the second edition, except that the first two sections of this chapter from the second edition have essentially moved to the new Chapter 8. This shortens the chapter and should help students focus on the key points.

- Although the basic content of this chapter remains the same as in the second edition, we have rewritten it completely—you’ll hardly find an unchanged sentence. The revised chapter should be much easier for your students to read and follow.
- Jargon reduction: We have eliminated the terms *jovian nebulae* and *nebular capture*, and now just talk about the *miniature solar nebulae* that presumably formed around each jovian world and describe the capture of gas without giving a name that students would have to memorize.
- Jargon reduction: We’ve also eliminated the term *magnetic braking* for the Sun’s slowing rotation, instead just describing the process. Again, the process should be clearer to students without adding the layer of jargon to memorize.
- Jargon change: We are now calling *radiometric dating* by its formal name, rather than *radioactive dating* as in the second edition.

Teaching Notes (By Section)

Section 9.1 The Origin of the Solar System: The Nebular Theory

This section sets the stage for the rest of the chapter by highlighting the key characteristics that must be answered by any theory that successfully explains the formation of the solar system. The four key characteristics are a review of those introduced in Chapter 8. We then outline a bit of the history of solar system formation theories, including an explanation of why the nebular theory gained credence over competing theories.

Section 9.2 Orderly Motion in a Collapsing Nebula

This section and the following two sections cover the nebular theory in detail, discussing how it explains each of the four characteristics summarized in Section 9.1.

- This section discusses how the nebular theory explains the generally orderly motion of large bodies in the solar system.

- Useful classroom demos include: (1) conservation of angular momentum, using a swivel chair or large turntable; (2) a "pepper-and-water" demonstration of random motions averaging out into regular motions through collisions. The latter demonstration can be done with a clear plastic tub on a viewgraph machine. Be sure to refocus the projector onto the pepper flakes on the water's surface.

Section 9.3 Two Types of Planets

This section covers how the planets were built from the raw materials of the solar nebula, with discussion centered on explaining why planets fall into the two main categories of terrestrial and jovian planets.

- Students often have difficulty with the concept of a frost line and how it influences the eventual size of planets. You are encouraged to verify your students' understanding of this key point before moving on. Also, despite our repeated emphasis of the point, when discussing accretion students sometimes lose sight of the fact that the vast majority of the material in the solar nebula is hydrogen and helium throughout. Take the opportunity to remind them of this fact.
- Planetary scientists often refer to materials such as methane, ammonia, and water as "ices." However, it is difficult to get students to think of ice as something that is not actually in the solid state. Therefore, we prefer the more accurate term *hydrogen compounds* for these materials. On a related note, we use the term "rocky material" to refer to elements and compounds that make rock when solid, but that can be in the gas state at high temperatures.
- The discussion of the four kinds of materials in the solar nebula—metal, rock, hydrogen compounds, and hydrogen and helium gas—will surface repeatedly in Part III, so it bears emphasis.
- Students are always excited to see meteorites, and this section begins to give them an appreciation of their importance. If you have access to meteorites, either pass them around or invite students to see them after class. For notes on acquiring meteorites for your school, see Section 13.3 in this Instructor's Guide.

Section 9.4 Explaining Leftovers and Exceptions to the Rules

This section discusses the final two challenges, both of which relate to the many small bodies in the solar system. First, we present a short discussion of the origin of asteroids and comets, with more detail to come in Chapter 13. Then we discuss impacts and the role they play in leading to "exceptions to the rules." Note that this is also where we discuss the giant impact hypothesis for the formation of our Moon.

- The fact that Earth probably did not form with much water helps students appreciate the importance of asteroids and comets. We've found that students love the idea that the water they drink likely came from comets.
- The giant impact hypothesis for the formation of the Moon is generally a favorite topic for many students. It's also a great place to discuss the nature of science, since science leads us to an idea that we may never be able to test directly.

Section 9.5 How Old is the Solar System?

This section addresses the important question of the age of the solar system and why we think we know it so well.

- This question can be answered only with a digression into radioactive decay. This section offers three ways of learning the concepts: text, graphs, and equations. While some students may appreciate the Mathematical Insight, the text and graphs will stand on their own for other students.

- The techniques of radiometric dating are far more sophisticated than described here, but they depend on a deeper understanding of chemistry than we can present at this level. Nevertheless, the principles are easy to understand, and should lend students some confidence in the idea that we really can know how old things are.

Section 9.6 Other Planetary Systems

The discovery of new planets around other stars is one of the hottest topics in astronomy, and students will probably be eager to hear the latest news.

- Although detection methods are not the main point of this section (the main point is implications to solar system formation theory), they are quite amazing—especially when you remind students of the scale of star systems and how challenging it is to find a planet.
- You should emphasize that, at least so far, all detections of planets have been indirect. Moreover, it is a good idea to remind students that these planets, at least so far, are *not* Earth-like.
- It's also worth a little time talking about upcoming missions, especially *Kepler*, that may tell us much more about planets around other stars.

Answers/Discussion Points for Think About It Questions

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

Section 9.2

- The random "strokes" in the water represent the gravitational influence of nearby stars stirring up the cloud from which we formed. The demonstration makes two main points: First, collisions average out the small random motions into large uniform motions. Second, it's very unlikely for random influences to exactly cancel out; the final rotation is always a bit one way or the other. Note that the experiment is not meant to reflect the shrinking of the cloud that formed the solar nebula, though it is likely that collisions were not able to average out random motions in the cloud until the cloud shrank. [Don't let students be confused by the clumping of pepper grains (surface tension) or the slowing of the rotation (friction with the tub).] We must always be on the lookout for aspects of the demonstration that might detract from the main point.

Section 9.3

- According to our theory, planets could not have formed along with the first generation of stars after the Big Bang. The Big Bang did not make the elements necessary for planets like ours.
- At 1300 K, almost all (at least 99.8%) of the nebula is gaseous. Only some of the different kinds of metals could condense, and they make up a maximum of 0.2% of the nebula. At 100 K, 2% of the nebula will be in solid form: metals, rocks and hydrogen compounds. The remaining 98% is hydrogen/helium gas that never condenses. The 100 K region is farther from the Sun.

Section 9.4

- Without Jupiter, comets and asteroids (which contain the ingredients for our oceans and atmosphere) would not have been deflected into the inner solar system. Earth would be made only of "dry" planetesimals that formed in our region of the solar system—no oceans or atmosphere.

Section 9.5

- In another 4.5 billion years, another half-life will have elapsed, for a total of about two half-lives. Only 1/4 of the original uranium will exist, and 3/4 will have been converted to lead.

- Their age would be "zero," even though the planet is 4.5 billion years old and the elements were made long before that. Age, in this context, means "time since the rock solidified."

Section 9.6

- This question should help students review the nature of science. The theory was not wrong, as it was supported by a large body of evidence that still stands. Rather, it was incomplete. In much the same way, Newton's theory of gravity is not "wrong," even though it has been supplanted by Einstein's general theory of relativity: rather, Newton's theory worked only in a limited range of circumstances, while Einstein's theory works in a broader range. A key idea here is that Newton's theory "falls out" from Einstein's theory when we make the approximation to the weak gravity conditions under which Newton's theory had been tested. In the same way, the "old" solar system formation is a valid approximation to the "new" one for circumstances in which substantial migration does not occur.

Solutions to End-of-Chapter Problems (Chapter 9)

1. A solar system has five terrestrial planets in its inner solar system and three jovian planets in its outer solar system. *This hypothetical solar system is consistent with our theory of solar system formation. The numbers of planets are different from our solar system, but that difference is not fundamental.*
2. A solar system has four large jovian planets in its inner solar system and seven small planets made of rock and metal in its outer solar system. *This discovery would be surprising, because solid objects that form beyond the jovian planets should include a great deal of ice, according to our current theories.*
3. A solar system has ten planets that all orbit the star in approximately the same plane. However, five planets orbit in one direction (e.g., counterclockwise) while the other five orbit in the opposite direction (e.g., clockwise). *The nebular theory cannot explain a "backward" planet, as all planets should form from the "forward"-moving nebula. A planet could conceivably be captured into such an orbit, if a planet ejected from another star system somehow entered our own solar nebula and was slowed down. This process is analogous to the capture of a retrograde satellite in a jovian nebula. However, it is extremely unlikely that half the planets in a solar system would have been captured in this way.*
4. A solar system has 12 planets that all orbit the star in the same direction and in nearly the same plane. The 15 largest moons in this solar system orbit their planets in nearly the same direction and plane as well. However, several smaller moons have highly inclined orbits around their planets. *This statement makes sense and in fact is similar to the situation in our solar system.*
5. A solar system has six terrestrial planets and four jovian planets. Each of the six terrestrial planets has at least five moons, while the jovian planets have no moons at all. *This statement does not make sense. Although the number of planets is not an issue, the presence of so many moons around terrestrial planets is hard to explain, as is the lack of moons around jovian planets. The capture of nebular gas should result in more jovian-planet satellites.*
6. A solar system has four Earth-size terrestrial planets. Each of the four has a single moon that is nearly identical in size to Earth's Moon. *This would be surprising. The formation of our Moon is thought to be the result of a rare random event, so it would not be expected to occur for all terrestrial planets.*
7. A solar system has many rocky asteroids and many icy comets. However, most of the comets orbit the star in a belt much like the asteroid belt of our solar system, while the asteroids inhabit regions much like the Kuiper belt and Oort cloud of our solar system. *This would be a surprise. Icy objects should appear outside the jovian planets, and rocky objects inside.*

8. A solar system has several planets similar in composition to our jovian planets, but similar in mass to our terrestrial planets. *This would be a surprise. We know of no process by which to make a jovian planet—with abundant hydrogen and helium gas—without first making a massive core of hydrogen compounds. It may be possible to have planets similar in size to terrestrial planets but made of hydrogen compounds.*

9–12. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

13. Ices would have condensed in the inner solar system, significantly increasing the size and mass (or possibly number) of terrestrial planets. Water and other hydrogen compounds would be much more abundant.

14. Without capture of nebular gas, jovian planets would not accumulate substantial amounts of material into the planets themselves or into the disks surrounding them. The jovian planets would consist of icy cores without the envelopes of light gases (H, He). No satellites would form, as no disk would have formed.

15. More than one correct answer: On one hand, more angular momentum might force more material into the solar nebula (instead of into the protosun). In this scenario, more planets or more massive ones might form. On the other hand, too much angular momentum might result in two protostars, possibly destabilizing the planet-forming process.

16. a. Following the method of Mathematical Insight 9.1, we calculate the age of the rock from the lunar highlands to be:

$$t = T_{\text{half}} \times \frac{\log_{10}\left(\frac{\text{current amount}}{\text{original amount}}\right)}{\log_{10}\left(\frac{1}{2}\right)}$$

$$= 4.5 \text{ billion yr} \times \frac{\log_{10}(0.55)}{\log_{10}\left(\frac{1}{2}\right)} = 3.9 \text{ billion yr}$$

b. The age of the rock from the lunar maria is:

$$t = T_{\text{half}} \times \frac{\log_{10}\left(\frac{\text{current amount}}{\text{original amount}}\right)}{\log_{10}\left(\frac{1}{2}\right)}$$

$$= 4.5 \text{ billion yr} \times \frac{\log_{10}(0.63)}{\log_{10}\left(\frac{1}{2}\right)} = 3.0 \text{ billion yr}$$

17. a. Based on the radioactive carbon content, the time since the cloth was painted is:

$$t = T_{\text{half}} \times \frac{\log_{10}\left(\frac{\text{current amount}}{\text{original amount}}\right)}{\log_{10}\left(\frac{1}{2}\right)}$$

$$= 5,700 \text{ yr} \times \frac{\log_{10}(0.77)}{\log_{10}\left(\frac{1}{2}\right)} = 2150 \text{ yr}$$

b. Based on the radioactive carbon content, the time since the wood was cut is:

$$t = T_{\text{half}} \times \frac{\log_{10}\left(\frac{\text{current amount}}{\text{original amount}}\right)}{\log_{10}\left(\frac{1}{2}\right)}$$

$$= 5,700 \text{ yr} \times \frac{\log_{10}(0.062)}{\log_{10}\left(\frac{1}{2}\right)} \approx 23,000 \text{ yr}$$

c. Carbon-14 is not useful for establishing the age of the Earth because its half-life is too short in comparison to the Earth's age; essentially all C-14 present when the Earth formed would have decayed long ago.

18. The age of this meteorite is:

$$t = T_{\text{half}} \times \frac{\log_{10}\left(\frac{\text{current amount}}{\text{original amount}}\right)}{\log_{10}\left(\frac{1}{2}\right)}$$

$$= 14 \text{ billion yr} \times \frac{\log_{10}(0.94)}{\log_{10}\left(\frac{1}{2}\right)} = 1.25 \text{ billion yr}$$

Because this time is much less than the age of the solar system, the meteorite cannot be a leftover from the solar system formation. The rock must have formed more recently, indicating that Mars must have had geological activity relatively recently.

19. The planet around 51 Pegasi has an orbital period of 4.23 days. Because the star has about the same mass as the Sun, we can find the planet's distance from its star by using Kepler's third law in its original form. But first we must convert the period of 4.23 days into units of years:

$$p = 4.23 \text{ day} \times \frac{1 \text{ yr}}{365 \text{ day}} = 0.0116 \text{ yr}$$

Now we can use Kepler's third law to find the planet's distance in AU:

$$p^2 = a^3 \quad \Rightarrow \quad a = \sqrt[3]{p^2} = \sqrt[3]{0.0116^2} = 0.0512 \text{ AU}$$

The planet around 51 Pegasi orbits with an average distance (semimajor axis) of 0.051 AU—much closer to its star than Mercury is to our Sun.

At 0.6 times the mass of Jupiter, the planet in 51 Pegasi seems likely to be a jovian planet. In the nebular theory, jovian planets form outside the "frost line," which in our solar system is outside the orbit of Mars (1.5 AU). Thus, it is surprising to find a jovian planet that is located closer to its star than Mercury is to our Sun.

20. a. If the planet blocks 0.017 of the star's area, it must have a radius 0.13 times that of the star, or about 91,000 km.

b. The planet's volume will be $4/3\ \pi\ r^3 = 3.13 \times 10^{15}$ km^3 or 3.13×10^{30} cm^3. The mass of the planet is $0.6 \times 1.9 \times 10^{27}$ kg $= 1.14 \times 10^{30}$ g (using data from Table C-1 in the appendix). Dividing mass by volume gives density = 0.36 g/cm^3. The planet has a lower density than any in our solar system but clearly is closer to jovian in nature. (The low density is actually a result of its having retained much of the heat of formation due to its proximity to the star.)

Chapter 10. Planetary Geology: Earth and the Other Terrestrial Worlds

This chapter begins our true comparative planetology with a general introduction to planetary geology. Note that, while the focus is on processes, we still use features on Earth (and occasionally on other worlds) to give concrete examples of each process at work. Once students learn the basic ideas, we apply them to each of the terrestrial planets in the "geological tour" sections (10.4 through 10.7) that conclude the chapters.

- Note that, while we use Earth as our prototype for most of the features and processes introduced in this chapter, we discuss in depth only those aspects of Earth that have counterparts on other worlds. Unique aspects of Earth's geology, such as plate tectonics, are mentioned for their uniqueness but not discussed in depth until Chapter 14.
- If you are more accustomed to teaching with a planet-by-planet approach than the comparative planetology approach, you may wish to emphasize Sections 10.4 through 10.7, which go through a geological tour of the terrestrial worlds. Indeed, you can feel free to use the earlier sections only as references, focusing on the worlds individually if you wish.
- Throughout this chapter, it is useful to ask "what if" questions in class. For example, ask how terrestrial planets would be different if they were larger, older, younger, and so on.
- Note that we do not introduce jargon that will not be useful elsewhere. For example, we do not use the terms *scarp, graben,* or *regolith*—instead, we describe such things using familiar words from everyday English.

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

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

Like the other chapters of Part III, this chapter has been completely rewritten for this edition in order to make it simpler and clearer to students. Note the following content changes:

- Perhaps even more so than in other chapters of Part III, we rearranged content to simplify the flow, reduced jargon, clarified key points, and added figures to enhance explanations. The changes are too numerous to list individually.
- The "concept map" figures (with lots of arrows and interconnections) from the second edition have been replaced with several new "summary figures" that make the same points in a much more visual and easily understood way.
- We have enhanced the geological tour of the individual worlds, so that they now stand as self-contained sections on each planet (except for the Moon and Mercury handled together). This should also make it much easier to present this material in class.

Teaching Notes (By Section)

Section 10.1 Planetary Surfaces

This section provides an overview of what we will be learning in this chapter, and why it is relevant to understanding our own planet.

Section 10.2 Inside the Terrestrial Worlds

This section presents the key features of planetary interiors that are important to understanding surface geology.

- Note that most students are familiar with the Earth's structure in terms of core, mantle, and crust, but are unfamiliar with the important term *lithosphere*. You should check to be sure your students understand this term clearly before continuing.
- Most students have heard of seismology but do not know how it can be used to explore a planet's interior. This is discussed in a Thinking About box.
- Note that this is the first section in which we introduce the idea of convection—a topic that will come up again and again throughout the remainder of the book.
- The discussion of planetary cooling might benefit from a simple demonstration of large and small objects—potatoes, rocks, ice cubes, or whatever is handy—cooling down or warming up.
- The discussion of magnetic fields also lends itself to a demonstration with iron filings and magnets.

Section 10.3 Shaping Planetary Surfaces: The Four Basic Geological Processess

This section introduces the four basic geological processes—impact cratering, volcanism, tectonics, and erosion—with concrete examples of each. A key intention in this section is to enable students to connect the presence or absence of the geological processes to basic planetary properties such as size, distance from the Sun, and rate of rotation.

Sections 10.4 through 10.6 Geological Tours: The Moon and Mercury, Mars, and Venus

These sections provide an up-to-date and fairly comprehensive geological tour of each of the terrestrial worlds, except Earth. Please remember that our key objective is for students to *understand* the features we see on each world, not to memorize the names or characteristics of these features.

Section 10.7 Earth and Geological Destiny

This final section explains why we need to save detailed discussion of Earth for later and summarizes what we have learned about geological density, based on the properties with which a planet is born.

Answers/Discussion Points for Think About It Questions

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

Section 10.1

Typical globes have relief of one-to-several mm, which is out of proportion to their size—a factor of several too large. If the bumps were to scale, they would hardly be discernable.

Section 10.2

- Mercury has a far higher proportion of metal than the Moon, since it has a huge iron core. With more metal and less rock, Mercury should have proportionally less heat from radioactive decay. (Some students may think about the amount of heat in absolute terms, not relative, in which case Mercury's larger size acts against the smaller proportion of rock.)
- More similar to Earth's, since Venus is almost Earth's size—much larger than the Moon. Mars' interior temperature should be intermediate between Earth and the Moon.
- The smallest: It has lost the most interior heat, and thus its lithosphere has thickened the most. Note that a smaller planet will have a thicker lithosphere both in relative terms (% of radius) and in km.
- Faster rotation.

Section 10.3

- Mercury, with more ancient craters, has an older surface. The planets are the same age, i.e., the planets as a whole formed roughly simultaneously. Geological processes have been active on Venus, remaking the surface over billions of years.

- The lack of volcanism on the Moon and Mercury mean a lack of outgassing, so there is no source for substantial atmospheric gas. The weak gravity and relatively high temperature on these planets also enabled the gas emitted long ago to have escaped.
- No. Size affects volcanism and tectonics, so at Mercury's size the Earth would have lacked outgassing and would lack an atmosphere. With no atmosphere, there's no erosion, regardless of other properties.

Section 10.5

- Size. Earth's large size has sustained widespread, global, and ongoing volcanism and tectonics, preventing any part of the surface from still showing the scars of the heavy bombardment.

Section 10.6

- Volcanism and tectonics ought to be essentially unchanged, as they depend primarily on planetary size. But fast rotation would create winds in Venus's thick atmosphere, leading to more erosion.

Solutions to End-of-Chapter Problems (Chapter 10)

1. The next mission to Mercury photographs part of the surface never seen before and detects vast fields of sand dunes. *This discovery would be a big surprise, because Mercury never had an atmosphere sufficient for significant erosional activity.*
2. New observations show that several of the volcanoes on Venus have erupted within the past few million years. *This would not be surprising. Venus is thought to be sufficiently active for new eruptions to occur and create lava flows.*
3. A Venus radar mapper discovers extensive regions of layered sedimentary rocks, similar to those found on Earth and Mars. *This discovery would be very surprising. Erosion is virtually negligible on Venus, due to the lack of liquid water and significant winds. Even if Venus had more water early in its existence, more recent geological activity has wiped out every trace of such ancient surfaces.*
4. Radiometric dating of rocks brought back from one lunar crater shows that the crater was formed only a few tens of millions of years ago. *This would not be surprising. Craters are continuing to form throughout the solar system, as there are still plenty of impactors around. Meteor Crater is an example of a recent crater—only a few tens of thousands of years old.*
5. Seismographs placed on the surface of Mercury reveal frequent and violent earthquakes. *This would be surprising, as the kind of tectonic activity responsible for earthquakes occurred very long ago.*
6. New orbital photos of craters on Mars that have gullies also show pools of liquid water to be common on the crater bottoms. *This would be surprising. Under the current conditions of Mars' atmosphere, pools of liquid water should rapidly freeze and/or evaporate.*
7. Clear-cutting in the Amazon rain forest exposes vast regions of ancient terrain that is as heavily cratered as the lunar highlands. *This would be surprising. Erosion has been so strong in that region that no ancient terrain would be recognizable. Furthermore, Earth had little continental crust so long ago, so South America wouldn't even have existed as a large land mass at that time.*
8. Drilling into the Martian surface, a robotic spacecraft discovers liquid water a few meters beneath the slopes of a Martian volcano. *This would be exciting, but not surprising. "Geothermal" heat from Martian volcanoes may well be enough to melt water under the Mars surface.*

9–14. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

15. The Earth was once heavily cratered, but other geological processes (especially erosion and plate tectonics) have erased the vast majority of craters. Earth's larger size is responsible: larger planets have hotter interiors and therefore more tectonic activity. Furthermore, larger planets create more atmosphere (through more volcanic activity from a warmer interior) and retain the atmosphere better (through higher gravity).

16. Mars has had the greatest erosional activity, because it once had liquid water on its surface and it now has wind and dust storms. Its size—large compared to the three other words considered—is the main reason. Mars outgassed more, and was able to retain its atmosphere due to stronger gravity.

    Mercury has a negligible atmosphere from the point of view of erosion, primarily due to its high temperature related to its distance from the Sun. Its relatively small size also led to only a small amount of outgassing to form an atmosphere in the first place.

    The Moon also has a negligible atmosphere, primarily related to the inability of such a small world to create or retain an atmosphere.

    Venus has a great deal of atmosphere but very little erosion. Water erosion doesn't occur because the planet is too hot, a condition related to its distance from the Sun. More straightforward, it lacks significant wind erosion because its slow rotation rate leads to very slow winds.

17. If Mars were smaller, it would have undergone less volcanic and tectonic activity because its interior would have cooled more. With less atmosphere from less outgassing, it is likely that erosion would be less important as well. As a result, craters would be more widespread on the Martian surface. With less atmosphere, Mars would have been a less hospitable place for life.

18. Extrapolating from the Moon to Earth and beyond, we would predict very high rates of volcanic and tectonic activity which would have completely erased evidence of past cratering. We'd expect it to have a substantial atmosphere, but one cannot actually predict its erosional activity without knowing more about it, such as its surface temperature and rotation rate.

19. a. The spacecraft should include a magnetic field detector, because the size and rapid rotation of the planet would be expected to cause a magnetic field if the core is metallic. The spacecraft should also measure the gravitational pull of the planet on the spacecraft (giving the mass) and the size of the planet; together these quantities provide the planet's density.

    b. Given the planet's size and rotation rate, erosional features should be present if there is an atmosphere.

20. Radiometric dating is usually considered more reliable than measuring crater abundances, partly because it is much more precise. In addition, cratering is somewhat random and more likely to be misleading. Moreover, the precise time at which the early bombardment ended is not well known. Crater abundances are easier to measure on other planets, because it is much cheaper to take photographs than to land on the surface and analyze rocks for radioactivity—either with an intelligent robot or by returning the sample to Earth.

21. The pressure from the textbook will squash a 2-cm ball of Silly Putty at room temperature to about 1 cm in 5 seconds. A warmer ball of Silly Putty will squash to about 0.5 cm in the same amount of time, and a chilled ball to about 1.5 cm. Actual measurements may vary due to the temperatures used and the size of the ball. Opinions may vary as to whether the differences are large or small effects, though we feel they are large given the small range in temperatures used. The geological connection is that warmer rocks deform more easily than cooler rocks.

22. Answers will vary depending on the size and shape of the containers used. Complete freezing will normally take hours. Measurement of the "lithospheric thickness" will be difficult in some cases. The main result—that larger containers take longer to freeze—should be quite obvious, and its relationship to small bodies cooling off faster than larger bodies should be clear.
23. Observations of the Moon should be feasible with virtually any small telescope. Answers will vary depending on the phase of the Moon and the interest of the student, but virtually any attempt that has engaged the student's mind in active observation should be considered a success.

Chapter 11. Planetary Atmospheres: Earth and the Other Terrestrial Worlds

This chapter continues our focus on the terrestrial worlds, this time with emphasis on their atmospheres. As in the previous chapter, we introduce important ideas and processes with concrete examples from Earth. The final section contrasts how the climate histories of Venus, Earth, and Mars have differed, along with current understanding of why these differences arose. Again, if you are more comfortable with a planet-by-planet approach than a comparative planetology approach, you could consider focusing on Section 11.6 first and bringing in supporting material from other sections as needed.

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

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

Like the other chapters of Part III, this chapter has been completely rewritten for this edition in order to make it simpler and clearer to students. Note the following content changes:

- As with Chapter 10, the specific organizational changes are too numerous to list here. But, in general, you'll find the same basic material covered as in the second edition, but in a way that should be much easier for you to teach and for your students to follow.
- Note that the greenhouse effect now gets its own full section (11.2).
- We have expanded the final section on comparative climate histories of Venus, Earth, and Mars to include discussion of the runaway greenhouse effect on Venus. This topic came in Chapter 13 of the second edition.
- We have replaced the jargon term *albedo* with *reflectivity*, which students will instantly understand (and never get confused over which is high and which is low).

Teaching Notes (By Section)

Section 11.1 Atmospheric Basics

We begin with an overview of the terrestrial atmospheres, focusing on the effects that atmospheres have on planets. This should provide motivation for why the material in this chapter is important.

Section 11.2 The Greenhouse Effect and Planetary Temperature

This section focuses on the important role of the greenhouse effect.

- The concept of the "no greenhouse" temperature—the temperature a planet would have in the absence of greenhouse gases—is introduced qualitatively in the text and in a more mathematical way in Mathematical Insight 11.1. This concept helps students understand the importance of the greenhouse effect.

Section 11.3 Atmospheric Structure

This section focuses on how interactions between light and gases determine a planet's basic atmospheric structure. The ideas involve some physics, but once students understand them they should be able to follow the idea of atmospheric structure easily. Students may find the discussion of why the sky is blue to be particularly interesting.

Section 11.4 Weather and Climate

After distinguishing between weather and climate, the section proceeds to delve into both.

- In terms of material that will be important to understanding later sections, the most important part of this section is the short discussion of long-term climate change that comes at its end. This sets the stage for understanding the mechanisms of long-term atmospheric gain and loss in the next section, and for understanding the climate histories of the planets that follow in the final section.

Section 11.5 Sources and Losses of Atmospheric Gas

This section covers the processes that add or remove gas from planetary atmospheres, which are very important to understanding the climate histories of the terrestrial worlds. Note that this section includes our brief discussion of the exospheres of the Moon and Mercury.

Section 11.6 The Climate Histories of Mars, Venus, and Earth

The chapter concludes by exploring how Venus and Mars have ended up so different from Earth. For most students, this is the highlight of the chapter.

Answers/Discussion Points for Think About It Questions

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

Section 11.1

- Lower. Gravity is weaker on Mars, so the same amount of air would weigh less and press down less hard, leading to lower pressure.

Section 11.2

- On clear nights, the thermal radiation from the surface can escape to space, cooling the planet rapidly. If it's cloudy, the thermal radiation is reflected back down and keeps the troposphere warmer.
- The high-reflectivity (white) shirt absorbs less sunlight, so you'll be cooler than the person in black.
- Since nitrogen and oxygen make up most of the Earth's atmosphere, the greenhouse effect would be far stronger if they were greenhouse gases, and so the Earth would be much hotter.

Section 11.3

- Moon: Yes, since there's not enough atmosphere to absorb solar X rays. Mars: No; X rays are absorbed in the thermosphere.
- The solar wind buffets Earth's magnetosphere, accelerating particles to high energy—high enough to impact Earth's atmosphere and cause the aurora.

Section 11.4

- The route from North America to Asia should go nearer the equator, catching the winds from the east. The route from Asia to North America should go farther north to catch the prevailing winds from the west.

- Aim to the left. Put yourself in the place of the person near the outer perimeter of the merry-go-round in Figure 11.14. To end up "straight north," i.e., along the line to the pole at the center, you'll have to aim a bit left.

Section 11.5

- Because of their small size, Mercury and the Moon lack volcanism and therefore lack a source for atmospheric gas.

Section 11.6

- The answer should be clear from study of Figure 11.29. With the same atmosphere as Earth, the temperature on Venus would be the 45°C that Earth would get if it moved to Venus's distance. Thus, it would be cool enough for liquid water. (*Note:* Although not asked in the question, students might wonder if this new Venus would undergo a runaway greenhouse effect. The answer is probably not, at least if it is only the atmosphere that magically changed. Venus has no water to evaporate and no carbonate rock to release CO_2, so the higher temperature would not cause any additional greenhouse gases to enter the atmosphere.)

Solutions to End-of-Chapter Problems (Chapter 11)

1. If the Earth's atmosphere did not contain molecular nitrogen, X rays from the Sun would reach the surface. *False. Almost any atmospheric ingredient will stop X rays.*
2. When Mars had a thicker atmosphere in the past, it probably also had a stratosphere. *False; not all atmospheric ingredients can absorb UV as ozone does on Earth.*
3. If the Earth rotated faster, storms would probably be more common and more severe. *True. Weather gets much of its energy from Earth's rotation.*
4. Mars would still have seasons even if its orbit around the Sun were perfectly circular rather than elliptical. *This statement is true. Mars' tilt is comparable to Earth's, so seasons would still be important. A circular orbit would have the effect of making seasons similar in the two hemispheres.*
5. If the solar wind were much stronger, Mercury might develop a carbon dioxide atmosphere. *False. CO_2 comes from volcanic outgassing, not bombardment of a rocky surface.*
6. The Earth's oceans probably formed at a time when no greenhouse effect operated on Earth. *False. Oceans always put water vapor, which is a very strong greenhouse gas, into the atmosphere.*
7. Mars may once have been warmer, but because it is farther from the Sun than Earth, it's not possible that it could ever have been warmer than the Earth. *This statement is incorrect. With enough greenhouse gasses, or even reflectivity differences, it's possible that Mars could have been warmer than Earth. Temperature depends on more than distance.*
8. If Earth had as much carbon dioxide in its atmosphere as Venus, our planet would be too hot for liquid water to exist on the surface. *True.*

9–11. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

12. a. Venus's cloudiness causes it to reflect so much sunlight that it actually absorbs less than the Earth.
    b. In the absence of clouds, Venus's dark surface would lead to the absorption of much more sunlight and higher temperatures. Without performing a calculation, it's debatable whether Venus would be warmer with the low reflectivity or the greenhouse effect. (A calculation would show that the low reflectivity would not warm the planet as much as the current greenhouse effect.)

c. The clouds contain sulfuric acid probably derived from volcanic outgassing. If outgassing ceased, the amount of sulfur compounds—and therefore clouds—would probably decrease.

13. a. With no greenhouse gases, the troposphere would not be warmer at the bottom.

b. Without UV light, no stratosphere would form.

c. With greater X-ray output, the thermosphere and exosphere would be warmer.

14. No. Mercury would lose its new atmosphere for exactly the same reasons it lost whatever it originally outgassed, and whatever is generated nowadays by bombardment: its low gravity makes it hard to hold on to an atmosphere, and its closeness to the sun makes thermal escape rapid.

15. If Venus rotated faster, it would have (1) more erosion from faster winds, (2) circulation patterns like Earth's, and (3) a magnetic field (probably) that could keep the solar wind at a greater distance, so (4) atmospheric escape through nonthermal processes would probably be reduced.

16. In the daytime, the warmer air over land rises and draws air from the sea to replace it. This leads to winds from sea to shore. At night, the air over the sea is warmer, so the circulation is reversed. The circulation pattern resembles Hadley circulation, with the warmer region (sea or shore) corresponding to Earth's equatorial region.

17. Answers will depend on the student's choice of processes. For the example given (bombardment as a source process): Bombardment is important only on planets for which other processes are unimportant, so it mainly occurs on small planets for which outgassing is negligible. It can be more important for planets closer to the Sun, where the solar wind is stronger. Bombardment might depend on the planet's composition or rotation rate, but this is beyond the scope of this text.

18. a. The bottle contracts. Microscopically, the molecules inside are slowed as the air cools. They collide with the walls less frequently and with less force. Molecules striking the bottle wall from the inside are no longer balancing those striking from the outside, so the bottle contracts.

b. The accumulation of frost is condensation, and the disappearance of ice cubes is sublimation. Whether either of these occurs in your home depends on your local humidity and the operation of your freezer. These processes are important on Mars at the polar caps.

19. a. Following the method of Mathematical Insight 11.1 and assuming an reflectivity of 0.15, we find the "no greenhouse" temperature of the planet around 51 Pegasi:

$$T = 280\text{ K} \times \sqrt[4]{\frac{(1-\text{reflectivity})}{d^2}} = 280\text{ K} \times \sqrt[4]{\frac{(1-0.15)}{0.051^2}} = 1190\text{ K}$$

This is far warmer than the Earth's temperature of under 300 K.

b. With a very high reflectivity of 0.8, the "no greenhouse" temperature of the planet around 51 Pegasi is:

$$T = 280\text{ K} \times \sqrt[4]{\frac{(1-\text{reflectivity})}{d^2}} = 280\text{ K} \times \sqrt[4]{\frac{(1-0.8)}{0.051^2}} = 830\text{ K}$$

This is still significantly warmer than the Earth's temperature of under 300 K.

c. Even in the reflective atmosphere case, the planet is probably too hot to be habitable.

20. a. In the formula for escape velocity from Chapter 5, we must plug in a radius that is 200 km above the surface of Venus. Because Venus has a radius of 6,050 km, we need to use a distance of 6,250 km in the formula. We find that the escape velocity from Venus's exosphere is:

$$v_{\text{escape}} = \sqrt{\frac{2GM}{r}} = \sqrt{\frac{2 \times \left(6.67 \times 10^{-11} \ \frac{\text{m}^3}{\text{kg} \times \text{s}^2}\right) \times \left(4.87 \times 10^{24} \ \text{kg}\right)}{6.25 \times 10^6 \ \text{m}}} = 10,200 \ \frac{\text{m}}{\text{s}} = 10.2 \ \frac{\text{km}}{\text{s}}$$

b. Following the method of Mathematical Insight 11.2, we find the following thermal speeds for hydrogen and deuterium:

$$\text{hydrogen:} \quad v_{\text{thermal}} = \sqrt{\frac{2kT}{m}} = \sqrt{\frac{2 \times \left(1.38 \times 10^{-23} \ \frac{\text{joule}}{\text{K}}\right) \times \left(350 \ \text{K}\right)}{1.67 \times 10^{-27} \ \text{kg}}} = 2400 \ \frac{\text{m}}{\text{s}} = 2.4 \ \frac{\text{km}}{\text{s}}$$

$$\text{deuterium:} \quad v_{\text{thermal}} = \sqrt{\frac{2kT}{m}} = \sqrt{\frac{2 \times \left(1.38 \times 10^{-23} \ \frac{\text{joule}}{\text{K}}\right) \times \left(350 \ \text{K}\right)}{2 \times 1.67 \times 10^{-27} \ \text{kg}}} = 1700 \ \frac{\text{m}}{\text{s}} = 1.7 \ \frac{\text{km}}{\text{s}}$$

c. Deuterium is a bit slower than hydrogen, making it less likely to undergo thermal escape. Because hydrogen preferentially escapes a bit faster than deuterium, the deuterium left behind will become enriched on Venus relative to hydrogen.

Chapter 12. Jovian Planet Systems

This chapter covers the four jovian planets, their satellites, and their rings. It is possible to cover this broad subject range in a single chapter because we emphasize the general properties of these objects, highlighting their differences in cases where these differences have meaningful interpretations. The chapter begins with a reminder of just how different jovian planets are from terrestrial planets. The subsequent sections cover jovian interiors, atmospheres, magnetospheres, satellites, and rings.

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

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

Like the other chapters of Part III, this chapter has been completely rewritten for this edition in order to make it simpler and clearer to students. Nevertheless, the major content of the chapter has remained intact, though it should be easier for you to teach from and for students to follow. Note the following specific changes:

- Jargon reduction: we no longer emphasize the terms *zones* and *belts* for Jupiter's atmosphere, instead just focusing on the fact that we see alternating bands of color and what causes them.
- The multi-part photo montages of the previous edition have also been split up to allow for a clearer layout and to present content in more "bite-size" chunks.

Teaching Notes (By Section)

Section 12.1 The Jovian Worlds: A Different Kind of Planet

The section opens with a discussion of how we learned that the jovian planets were so different from Earth and reminds students of those differences. A few slides will help drive this home. Many students fail to appreciate how fundamentally different the jovian planets are, still trying to imagine craters and a rocky surface below the clouds.

Section 12.2 Jovian Planet Interiors

As we did in explaining geological processes, we turn first to the interiors of the planets. The subsection "Inside Jupiter" is intended to help build intuition with respect to this non-intuitive phenomenon before moving on to interior comparisons.

Section 12.3 Jovian Planet Atmospheres

This section on atmospheres builds directly on the concepts covered in Chapter 11 on terrestrial planet atmospheres. As in the previous section, we begin with the case of Jupiter before moving on to a comparative study of the jovian atmospheres. If you are short on time, you may wish to gloss over the details in this section so you can move on to the jovian moons and rings.

- We suggest emphasizing that the same atmospheric processes govern structure and circulation on both terrestrial and jovian planets.
- Many students are interested in the colors of the jovian planets, which are discussed in this section.
- Students might wonder whether jovian planets undergo atmospheric evolution through the same processes discussed in Chapter 11. The short answer is no (because nothing can escape their strong gravity), but the question can make for a useful discussion.

Section 12.4 Jovian Planet Magnetospheres

This short section discusses jovian planet magnetospheres; it may be skipped if time limitations are a factor. However, the relationship between interiors, magnetic fields, and charged particles is a recurring theme throughout the book.

Section 12.5 A Wealth of Worlds: Satellites of Ice and Rock

This section covers the diverse subject of icy satellites. It opens with some new physical ideas necessary to an understanding of the behavior and geology of the satellites: tidal heating and ice geology. Then the major satellites are discussed from the jovian system outward. We do not cover all satellites, sticking instead to the most important or most curious. In many cases the geology of the satellites is not understood, and we do not consider it worthwhile to memorize facts for which there is no explanation. In addition to exploring the most interesting cases of Io, Europa, Titan, Miranda, and Triton, students should mainly carry away the idea that even frigid, icy bodies undergo a surprising amount of geological activity.

Section 12.6 Jovian Planet Rings

This section covers planetary rings. The two key points to emphasize are (1) how rings work, including tidal forces and orbital resonances, and (2) origin of the rings.

- The rings are very compelling visually, and a slide show may provide additional motivation for students to learn these concepts.
- Resonances are a recurrent theme in the outer solar system and will come up again in Chapter 13.

Answers/Discussion Points for Think About It Questions

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

Section 12.1

- If you could track only cloud features (and their reappearance from day to day), you wouldn't get a very precise measurement of Earth's day. Clouds at different latitudes move at different speeds and in different directions.

Section 12.2

- This question asks students to think about the nature of planets and gravity. If Saturn were a solid object with a density less than that of water, then it would float. But it is not solid, and the presence of a downward gravity would cause Saturn to spread out over the ocean like a popped water balloon. At that point, dense materials would sink and gases would rise upward into the atmosphere of the gigantic planet.

Section 12.3

- Jupiter has plenty of explosives but no free oxygen with which to burn them.

Section 12.5

- Like all bodies in the solar system, Titan should have been heavily cratered when the solar system was young. So the question is whether the craters have been erased. In Titan's case, the most likely erasure process would be erosion, especially if there is rain of liquid ethane. The *Cassini* mission will answer this fascinating question in 2004.

Section 12.6

- Ring particles at the inner edge travel faster, just as planets closest to the Sun travel faster.

Solutions to End-of-Chapter Problems (Chapter 12)

1. Saturn's core is pockmarked with impact craters and dotted with volcanoes erupting basaltic lava. *This is not a possible discovery. The core lies below tens of thousands of kilometers of dense gas and even metallic hydrogen. No impactors reach that depth, and the conditions at the core are so extreme that nothing resembling familiar basaltic volcanism could occur.*
2. Neptune's deep blue color is not due to methane, as previously thought, but instead is due to its surface being covered with an ocean of liquid water. *This is not plausible. Neptune does have a great deal of water, but temperatures at the visible surface would be far too cold for it to be liquid.*
3. A jovian planet in another star system has a moon as big as Mars. *This is plausible. We know of no reason why larger satellites could not exist around extrasolar planets. After all, some of them are much larger than Jupiter.*
4. An extrasolar planet is discovered that is made primarily of hydrogen and helium. It has approximately the same mass as Jupiter but the same size as Neptune. *This is unlikely. A Jupiter-mass planet might be larger if it were hotter, but we know of no means to make such a planet much smaller than Jupiter's size.*
5. A new small moon is discovered to be orbiting Jupiter. It is smaller than any of Jupiter's other moons and orbits slightly farther than any of the other moons, but it has several large, active volcanoes. *This is not plausible. Tidal forces are too weak on objects so far away, and they are not forced into elliptical orbits by resonances. It would also be too small to have volcanoes from radioactive heating.*
6. A new moon is discovered to be orbiting Neptune. The moon orbits in Neptune's equatorial plane and in the same direction that Neptune rotates, but it is made almost entirely of metals

such as iron and nickel. *This is not plausible. Solid objects at those distances are largely icy and rocky. While some asteroids have metallic composition, they would not be captured by Neptune.*

7. An icy, medium-size moon is discovered to be orbiting a jovian planet in a star system that is only a few hundred million years old. The moon shows evidence of active tectonics. *Apart from the difficulty of observing moons around extrasolar planets, there is nothing unusual about tectonic activity on medium-size icy satellites.*

8. A jovian planet is discovered in a star system that is much older than our solar system. The planet has no moons at all, but it has a system of rings as spectacular as the rings of Saturn. *This is not plausible. With no moons of any size, there would be no source of ring particles.*

9–13. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

14. If the Jupiter-forming nebula had come together with no rotation ...
    - All the material would have fallen into Jupiter, leaving nothing to make satellites.
    - With no satellites, no rings will form.
    - If Jupiter didn't rotate, its weather patterns wouldn't be smeared into belts and zones.
    - If Jupiter didn't rotate, it wouldn't have a magnetic field.
    - If Jupiter didn't rotate, it would be spherical instead of "squashed."

15. Its dark appearance in the infrared indicates that the Great Red Spot is cooler and therefore higher than neighboring clouds.

16. a. The gravitational attraction of Saturn on Mimas is less than that of Jupiter on Amalthea; therefore, Saturn's mass must be less than Jupiter's.

    b. If Saturn is less massive but almost as large as Jupiter, its density must be lower.

17. Without ingredients besides hydrogen and helium, the jovian planets would all be gray in color, and there would be no clouds or precipitation.

18. Consult the latest *Sky and Telescope* magazine (or many websites) for tabulations of the location of the jovian satellites. Good observers may be able to record the orbital resonances between the three inner satellites.

19. Answers will vary.

20. a. First, we convert a loss rate of a ton of sulfur dioxide per second into units of kilograms per year:

$$1000\,\frac{\text{kg}}{\text{s}} \times \frac{3600\ \text{s}}{1\ \text{hr}} \times \frac{24\ \text{hr}}{1\ \text{day}} \times \frac{365\ \text{day}}{1\ \text{yr}} = 3.15 \times 10^{10}\,\frac{\text{kg}}{\text{yr}}$$

Over 4.5 billion years, the total mass loss is then:

$$\text{mass lost} = 3.15 \times 10^{10}\,\frac{\text{kg}}{\text{yr}} \times 4.5 \times 10^{9}\ \text{yr} = 1.4 \times 10^{20}\ \text{kg}$$

Thus, the fraction of Io's mass lost in 4.5 billion years is:

$$\text{fraction of mass lost} = \frac{\text{mass lost}}{\text{mass}} = \frac{1.4 \times 10^{20}\ \text{kg}}{893 \times 10^{20}\ \text{kg}} = 0.0016 = 0.16\%$$

Note that this is a fairly insignificant overall mass loss.

b. If sulfur dioxide is 1% of Io's mass, then the current total mass of sulfur dioxide is:

$$1\% \times 893 \times 10^{20}\,\text{kg} = 8.93 \times 10^{20}\,\text{kg}$$

Given the mass loss rate from part (a), Io would run out of sulfur dioxide in a time of:

$$\text{time to run out} = \frac{\text{mass available}}{\text{mass loss rate}} = \frac{8.93 \times 10^{20}\,\text{kg}}{3.15 \times 10^{10}\,\text{kg/yr}} = 2.8 \times 10^{10}\,\text{yr} = 28\text{ billion yr}$$

Thus, Io will not run out of sulfur dioxide for quite some time.

21. With one collision every 5 hours, the total number of collisions suffered by a ring particle is given by the following equation:

$$\#\ \text{collisions} = \text{collision rate} \times \text{time} = \frac{1\text{ collision}}{5\text{ hours}} \times \text{time}$$

A time of 4.5 billion years is equivalent to:

$$\text{time} = 4.5 \times 10^{9}\,\text{yr} \times \frac{365\text{ day}}{1\text{ yr}} \times \frac{24\text{ hr}}{1\text{ day}} = 3.94 \times 10^{13}\,\text{hr}$$

Thus, the total number of collisions suffered by a ring particle in 4.5 billion years would be:

$$\#\ \text{collisions} = \frac{1\text{ collision}}{5\text{ hr}} \times 3.94 \times 10^{13}\,\text{hr} = 7.8 \times 10^{12}\,\text{collisions} \approx 8\text{ trillion collisions}$$

Chapter 13. Remnants of Rock and Ice: Asteroids, Comets, and Pluto

Small bodies in the solar system are important for two reasons: what they tell us about the formation of the solar system, and what small bodies can do to planets if they collide. This chapter connects these two subjects with an understanding of how comets and asteroids have been nudged by the jovian planets ever since formation. While our understanding of asteroids has improved steadily in recent years, the study of comets has undergone a major breakthrough in the discovery of Kuiper-belt objects. This discovery has helped put Pluto in context as the largest free-roaming Kuiper-belt object.

The topic of "Cosmic Collisions" offers a real opportunity to demonstrate the relevance of astronomy to our existence. Recent Hollywood movies try to make this point through the possible threat of an impact, but the deeper connection goes back to the role that impacts have played in biological evolution and our very presence on the planet.

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

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

Like the other chapters of Part III, this chapter has been completely rewritten for this edition in order to make it simpler and clearer to students. Nevertheless, the major content of the chapter has remained intact, though it should be easier for you to teach from and for students to follow. Note in particular that we have tried to reduce redundancy about asteroids and comets with earlier chapters (8 and 9). For example, we now simply review the fact that these objects come in three main groups (asteroid belt, Kuiper belt, Oort cloud) in the beginning of the chapter.

Teaching Notes (By Section)

Section 13.1 Remnants from Birth

This section reminds students of the motivation for studying the small objects and introduces the minimum number of new terms needed for the chapter.

- Note that we do not use the term *meteoroid*, and we use the term *comet* to include all icy objects, whether or not they happen to have tails. Students therefore do not need to learn Kuiper-belt objects as separate from comets.
- We also do not classify comets using an arbitrary period cutoff (long-period vs. short-period), instead classifying them by their place of origin (Oort cloud vs. Kuiper belt). The two kinds of classification are basically the same, but the latter is more physically motivated.

Section 13.2 Asteroids

After an overview of asteroid properties, this section explains how orbital resonances are responsible for both the existence of asteroids and their occasional collisions with planets.

Section 13.3 Meteorites

Students are usually amazed to learn that meteorites are pieces of asteroids and that asteroids may themselves be pieces of shattered planets. This section emphasizes the relationship between rocks that you can hold, the processes that brought them to Earth, and what we can learn about the asteroids themselves.

- Learning about meteorites can be all the more effective if you have samples to view or to hold. Meteorite dealers can be found easily on the Web or in popular astronomical magazines. One well-established dealer is Robert Haag, PO Box 27527, Tucson, AZ 85726, 520-882-8804. Etched iron meteorites are particularly impressive: Their visual appeal and high density immediately attract students. The inescapable story they tell (from the core of a shattered "mini-planet") challenges a lot of preconceived notions about the permanence of celestial bodies. Meteorites are normally sold by the gram, with common varieties currently priced around $1 a gram for small specimens.

Section 13.4 Comets

This section covers the appearance and origin of comets. Because most students have little idea what they're actually seeing when they look at a comet, we cover this topic first. Emphasize how small the nucleus is and how large and insubstantial the tails are. The different effects of the Sun on atoms, dust, and large grains in the tail make a useful sequence and set the scene for shooting stars later in the chapter.

- Some students may remember seeing comets Hyakutake and Hale–Bopp but probably did not understand their significance at the time. Nonetheless, reminding them of these comets may make a good common starting point for this section.
- When discussing the origin of comets, emphasize the parallels with asteroids: Jovian planets keep both kinds of objects from forming a single large object, jovian planets nudge their orbits through resonances, and both kinds of objects can collide with planets. The explanation for their different composition (ice vs. rock) should be very familiar to students by now.
- Some students may have a hard time believing that the Oort cloud is populated by comets ejected from much closer in, believing instead that they must have formed in place, at huge distances from the Sun. You should point out that densities in a solar nebula the size of the Oort cloud would have been much too low for material to accrete into comets. You should also point to the discussion of gravitational encounters in Chapter 5.

Section 13.5 Pluto: Lone Dog, or Part of a Pack?

This section focuses on Pluto and the question of whether it is a true planet or merely a large Kuiper-belt comet. This is a good opportunity for class discussion, because there are many defensible viewpoints.

Section 13.6 Cosmic Collisions: Small Bodies Versus the Planets

The discussion of cosmic collisions proceeds from the irrefutable (Shoemaker–Levy 9 impact on Jupiter, meteor showers) to the controversial (death of the dinosaurs, threats to civilization). These are just the two ends of the continuum shown in the final figure of the chapter. This is a great opportunity to show the connections between astronomy, geology, biology, and sociology.

- The question of how to deal with asteroid threats makes an excellent discussion topic—again with many defensible viewpoints and no right answer.
- Showing clips from popular movies such as *Deep Impact* and *Armageddon* would make an excellent starting point for a discussion on science fact versus science fiction concerning the asteroid impact threat.

Answers/Discussion Points for Think About It Questions

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

Section 13.1

- Disaster literally means "bad star," and reflects the ancient belief that stars influence our lives. An asterisk looks like a star. A meteoric career is one in which the person rapidly shoots to stardom, and then burns out quickly. Knowing that meteor means "a thing in the air," you'll realize the term meteorology refers to the study of air or atmosphere.

Section 13.2

- The gaps are visible in the distribution of semimajor axes—the *average* distance from the Sun. But asteroids travel on elliptical orbits, meaning they rarely lie at exactly their orbital distance. Although there may be very few asteroids with semimajor axes of 2.5 AU, for example, many asteroids of other semimajor axes will cross the distance of 2.5 AU on their elliptical orbits.
- By studying the asteroid's orbit, you could learn whether it was close or distant. But, by measuring its brightness at infrared and visible wavelengths at the same time, you could determine whether it was highly reflective or large.

Section 13.5

- The definition of a planet makes an excellent classroom discussion, not just in developing the definition but also in evaluating the value of definitions. Encourage students to offer specific criteria (orbiting the Sun but not another planet, roughly spherical, larger than a certain size, etc.), and then see how many objects fit the definition. The test cases of Pluto, Charon, Ceres, and Triton may lead to answers other than "nine planets." Close with a discussion of whether the definition is useful or just a matter of semantics.

Section 13.6

- Phaethon appears to be an extinct comet—one with all its ices used up or buried deep below a crust.
- This is really two questions: how big an impact would wipe out civilization (though not necessarily humans), and how often would such an impact occur? Nobody knows exactly how "robust" civilization would be to a catastrophe of this nature. Would civilization collapse if agriculture were wiped out for a few years? Or is civilization so resilient it could withstand even

a mass extinction that doomed lifeforms incapable of working together to overcome hardship? In the pessimistic view, civilization might fall in the panic after a 1-km impactor, striking every million years, on average. In the optimistic view, we could survive even the 10-km impactors arriving every ~hundred million years.

Solutions to End-of-Chapter Problems (Chapter 13)

1. A small asteroid that orbits within the asteroid belt has an active volcano. *Surprising! Even the largest asteroids are too small to be geologically active now.*
2. Scientists discover a meteorite that, based on radiometric dating, is 7.9 billion years old. *Surprising! This would be older than our solar system, so it would be possible only if the meteorite originated in a different (and older) star system.*
3. An object that resembles a comet in size and composition is discovered to be orbiting in the inner solar system. *This is reasonable. Many comets from the outer solar system have their orbits altered so they become locked in the inner solar system. But exposed ices would be used up in a few years, so the object might not last long or might become covered in a protective layer of dust.*
4. Studies of a large object in the Kuiper belt reveal that it is made almost entirely of rocky (as opposed to icy) material. *This would be surprising. Objects forming that far out should contain mostly ices. We know of no way for a large asteroid to be flung into a Kuiper-belt orbit.*
5. Astronomers discover a previously unknown comet that will produce a spectacular display in Earth's skies about 2 years from now. *This would not be surprising at all. We wish it happened more.*
6. A mission to Pluto finds that it has lakes of liquid water on its surface. *Surprising. Water would be frozen at Pluto's temperature, and we know of no extra heat sources.*
7. Geologists discover a crater from a 5-km object that impacted the Earth more than 100 million years ago. *This would not be surprising. A slightly larger impact 65 million years ago is thought to have caused a mass extinction.*
8. Archaeologists learn that the fall of ancient Rome was caused in large part by an asteroid impact in southern Africa. *This would be surprising. An impact large enough to affect Roman civilization all the way from South Africa would have caused more widespread devastation and should have been noted in many historical and geological records.*

9–12. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

13. Students should list five effects from the list below. They will have to use their own judgement in evaluating which are superficial and which and profound.
    - The asteroids might have accreted into a single planet between Mars and Jupiter.
    - Comet orbits would not be nudged, so comets would not collide as frequently with Earth.
    - From the previous two ideas, Earth would not have been as heavily impacted.
    - Earth would not have received as many volatiles from the outer solar system.
    - Saturn's rings would not be broken into rings and gaps.
    - The asteroid belt would not have gaps.
    - Kuiper-belt objects would not clump into orbital groups.
    - Pluto and other Kuiper-belt objects would not be prevented from colliding with Neptune.
    - Io, Europa, and Ganymede would not be geologically active.
14. The factual story goes as follows, though students are encouraged to add more creative touches: At first the iron atom floated in space in the molecular cloud. The cloud collapsed

into the solar nebula. As the nebula cooled, iron atoms collected together and condensed into metallic flakes. As the nebula cooled further, rocky flakes formed, and then planetesimals formed by accreting the rocky and metallic flakes. A planetesimal grew into an asteroid large enough to melt, and the iron flowed to the core (differentiation). The asteroid collided with another asteroid, shattering it into pieces. A metallic piece was blasted away (and probably nudged by Jupiter) and collided with the Earth.

15. Because Barkley emits a higher proportion of thermal emission (infrared) than reflected light (visible), it must be warmer than Jordan. This means it must be darker (in order to be warmed by the Sun). Because Barkley has a lower reflectivity than Jordan, it must be larger in order to appear as bright. Jordan would make a better candidate for mining metal, and Barkley a better candidate for carbon-rich material.

16. a. The comet's volume is:

$$V = \frac{4}{3} \times \pi \times \left(\text{radius}\right)^3 = \frac{4}{3} \times \pi \times \left(1000 \text{ m}\right)^3 = \frac{4}{3} \times \pi \times 10^9 \text{ m}^3 = 4.2 \times 10^9 \text{ m}^3$$

so its mass (given in the problem) is:

$$m = V \times \text{density} = \left(4.2 \times 10^9 \text{ m}^3\right) \times 1000 \frac{\text{kg}}{\text{m}^3} = 4.2 \times 10^{12} \text{ kg}$$

Therefore, its kinetic energy is

$$KE = \frac{1}{2} mv^2 = \frac{1}{2} \times \left(4.2 \times 10^{12} \text{ kg}\right) \times \left(3 \times 10^4 \ \frac{\text{m}}{\text{s}}\right)^2 = 1.9 \times 10^{21} \text{ joule}$$

b. Converting this kinetic energy to units of megatons, we find that it is equivalent to:

$$\frac{1.9 \times 10^{21} \text{ joule}}{4.2 \times 10^{15} \ \frac{\text{joule}}{\text{megaton}}} = 450{,}000 \text{ megatons}$$

Clearly, such an impact could be devastating, though not enough to cause a mass extinction.

17. Following the hint in the problem, we calculate the probability of impact by assuming a giant dartboard in which the bull's-eye is the area of the Earth's disk and the total dartboard area has a radius of 3 million km:

$$\begin{aligned}
\text{Probability} &\approx \frac{\text{area of bullseye}}{\text{area of dartboard}} \\
&= \frac{\text{area of Earth's disk}}{\text{area of target}} \\
&= \frac{\pi \times (6371 \text{ km})^2}{\pi \times (3{,}000{,}000 \text{ km})^2} \\
&= 4.5 \times 10^{-6} \ \text{(or about 4.5 chances in a million)}
\end{aligned}$$

Given that Toutatis was bound to come within 3 million kilometers of the Earth, the probability of a collision is still quite small. Nevertheless, the probability of nearly 5 in a million is greater than the probability of winning big in a lottery. The question of whether this probability should count as a "near miss" is a matter of opinion.

18. Following the method of Mathematical Insight 11.1, we find the "no greenhouse" temperature of a comet with reflectivity 0.03 at 50,000 AU to be:

$$T = 280\text{ K} \times \sqrt[4]{\frac{(1-\text{reflectivity})}{d^2}} = 280\text{ K} \times \sqrt[4]{\frac{(1-0.03)}{50,000^2}} = 1.24\text{ K}$$

At 3 AU, the "no greenhouse" temperature of this comet is:

$$T = 280\text{ K} \times \sqrt[4]{\frac{(1-\text{reflectivity})}{d^2}} = 280\text{ K} \times \sqrt[4]{\frac{(1-0.03)}{3^2}} = 160\text{ K}$$

At 1 AU, the "no greenhouse" temperature of this comet is:

$$T = 280\text{ K} \times \sqrt[4]{\frac{(1-\text{reflectivity})}{d^2}} = 280\text{ K} \times \sqrt[4]{\frac{(1-0.03)}{1^2}} = 278\text{ K}$$

Given that water sublimes at about 150 K, the temperature is high enough whenever the comet is within about 3 AU of the Sun, meaning that the comet should form a tail when it is in this region of the solar system (assuming it has enough volatiles remaining to form a tail).

19. Observing project. Answers will vary.
20. Students should find that only a small amount of dark material is necessary in order to turn a snowball dark.

Chapter 14. Planet Earth: Seen in a New Light

Up to this point in Part III, we have focused on those aspects of Earth that make it similar to other worlds. In particular, in Chapters 10 and 11, we used Earth to help show the general principles of geology and atmospheres that apply to all planets. But we have not yet covered the many ways in which Earth is unique among the known worlds. Thus, the point of this chapter is for students to take what they have learned earlier and use it to help them see Earth in a new light—that is, with insights and appreciation that they could not have gained without first learning about planets in general.

- A common question: What if I'm running out of time to cover this chapter at the end of the semester? Our answer: Students usually want to cover this material, since it brings everything that they have studied to bear on their home planet. If you are short on time and can cover only selected sections, we have found that the favorite topics of students are those in the last two sections: life on Earth (Section 14.5) and the lessons we have learned from other worlds about global warming, ozone depletion, and mass extinctions (Section 14.6).
- If you are not running out of time and your course does not include the material in Parts IV–VI (stars, galaxies, cosmology), we suggest that you still cover Chapter 24 on life beyond Earth. With this chapter as background, you can go right into Chapter 24 quite easily.

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

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

Like the other chapters of Part III, this chapter has been completely rewritten for this edition in order to make it simpler and clearer to students. Note the following content changes:

- The first section (14.1) now lists explicitly the major ways that Earth differs from other worlds in our solar system. The rest of the chapter then focuses only on these differences.

- In the second edition, the section on Earth's unique geology included a summary of all four geological processes on Earth. With our revision, this material has now been covered in Chapter 10. Here, we focus only on plate tectonics, since that is the key unique feature of Earth's geology.
- Similarly, we have focused discussion on the unique features of Earth's atmosphere—namely on its composition, which includes its very low carbon dioxide abundance but high oxygen and ozone abundances.
- We have significantly expanded discussion of the carbon dioxide cycle (formerly referred to as the carbonate–silicate cycle) and of long-term climate change, including snowball Earth episodes.
- We no longer discuss the runaway greenhouse effect on Venus in this chapter, since that is now discussed in Chapter 11.
- The section on life in the solar system is no longer in this chapter, and this material is instead covered in the new Chapter 24.

Teaching Notes (By Section)

Section 14.1 How Is Earth Different?

This section gives an overview of how we will use what we've learned about planets in general to explore the unique features of Earth.

- The key to this chapter is understanding what makes Earth unique, so pay close attention to the bulleted list of five major ways in which Earth is unique that appears at the end of this section.

Section 14.2 Our Unique Geology

This section focuses on plate tectonics and its role on Earth.

- Regarding Wegener and continental drift: People who want to claim that science lacks objectivity often point to the decades-long rejection of Wegener's idea of continental drift. However, we believe this is instead a good example of how science is supposed to work. Wegener proposed a specific mechanism for his idea of continental drift: that continents "plow through" the crust due to gravity and tidal forces. It was quickly realized by other scientists that this mechanism made no sense. Thus, while it is true that scientists often ridiculed Wegener's idea, it was his nonsensical mechanism that led to the ridicule. Once a viable mechanism was identified, it did not take long at all before a consensus emerged that continents really do get rearranged with time. Note that, today, geologists generally avoid the term "continental drift" because of its implication that it means continents plow through the crust, rather than being carried along with the movements of the plates.

Section 14.3 Our Unique Atmosphere and Oceans

The discussion of Earth's atmosphere is focused on four major questions regarding how our atmosphere differs from those of Venus and Mars. At first, the differences may look insurmountably large, but the section explains them one by one and even shows how they are logical consequences of one another.

- Note that, in some sense, the answers in this section are still superficial: they depend on taking climate stability and the presence of life as givens. Thus, this section sets the stage for the discussion of those deeper issues in the next two sections.

Section 14.4 Climate Regulation and the Carbon Dioxide Cycle

This section discusses how Earth keeps a fairly stable climate through the carbon dioxide cycle, and what happens when the process temporarily breaks down in snowball Earth episodes.

- We introduce the valuable concept of feedback loops to explain climate stability; you may wish to emphasize this concept further or do a demonstration with audio feedback.
- Snowball Earth is an active topic of research, so watch for new findings on this interesting issue.
- The issue of whether Earth is "lucky" to have plate tectonics is very important to the question of life in the universe (especially intelligent life). It makes an interesting topic of discussion in class.

Section 14.5 Life on Earth

This section follows the scientific study of life in chronological order from its unseen origin to the present. The goal is more than just biological history: Students learn how planetary processes affected the origin and evolution of life and also how life has altered the planet—particularly the atmosphere.

- Be aware that the origin of life is a controversial and in some cases emotional topic. Students will approach it from a wide variety of viewpoints—religious, cultural, scientific, and so on. It is not necessary or advisable to challenge those beliefs in order to teach this topic. You will have to make clear that the sequence of events described here is a theory supported by observation, much as Chapter 9 presents a theory and supporting observations for the formation of the solar system. Much less "data" is available for the origin of life, of course, but the theory presented is the best one that can be formed using scientific principles.
- You may particularly wish to emphasize that the scientific view presented here need not contradict personal religious beliefs. For example, the theory does not require or exclude the existence of a Creator; the scientific theory may be nothing more than the description of how the Creator created. Be sensitive to the possibility that student opinions on the matter may differ significantly from your own and from other students'.
- You may also wish to remind students of the distinction made in Chapter 3 between science and nonscience. Since religious beliefs, including creationism, generally do not try to claim scientific support, science can say little about their validity. In fact, it is quite possible for students to learn and appreciate the scientific theory of evolution without necessarily believing that it actually happened.

Section 14.6 Our Future Survival: Lessons from Other Worlds

Here we bring home the three biggest lessons for Earth that we have learned at least in part by studying the solar system: global warming, ozone depletion, and mass extinctions. These are three of the hottest topics in Earth science, and students are well prepared at this point to examine some of the controversies and subtleties.

Answers/Discussion Points for Think About It Questions

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

Section 14.1

- Major cities are generally located in coastal regions, and therefore could flood with even a relatively small rise in sea level. Note that the rise need not even be as high as the elevation of the cities—even a rise of a few centimeters could send storm surges much further inland in many cities.

Section 14.2

- One seafloor plate is subducting under another near Indonesia. Volcanism has created the Indonesian islands, which are slowly merging together. Millions of years from now, they may form a new continent or become part of Australia (if they get "scraped off" the ocean floor as subduction carries the underlying seafloor crust downward, leaving the island attached to Australia).
- Earthquakes are common in these areas because they are near plate boundaries, where plates interact with one another and can therefore slip in ways that cause earthquakes.
- This question will require students to investigate some local geology. You may wish to do this for your school locality, and discuss notable geological formations in class.

Section 14.3

- Oxygen would eventually be used up in chemical reactions with the surface, and animals could not survive. This process might take millions of years.

Section 14.4

- Lots of possible answers for everyday examples of feedback. For most students, the easiest examples to cite will be "people" ones: e.g., positive or negative reinforcement of behaviors.
- Not in less than 400,000 years. On the time scales that matter to people, the CO_2 cycle will not help us at all.
- Without plate tectonics, carbonates would still form on the seafloor, but they would not be recycled into the mantle, so less CO_2 would be outgassed. This kind of outgassing is the only way out of "snowball Earth." Thus, without plate tectonics, Earth could not recover from a snowball phase.

Section 14.5

- Europa (and some other jovian moons) could have subsurface oceans, and internal heat could potentially lead to eruptions on the ocean bottom like those of black smokers. Mars could have underground "hot springs" near sources of volcanic heat. Even if these structures really exist on these worlds, it's no guarantee that life arose there. Nevertheless, if life arose here under such conditions, it at least offers a reason to make it worthwhile to search for possible life on these other worlds.
- This is of course a subjective question, but should at least get students to consider the views of other people. Viable answers might include, e.g., the idea of an "unseen" hand guiding the entire process, the idea that the process was able to unfold only because a Creator had set up the laws of nature in such a way as to allow it, or views of God that don't involve a direct hand in the origin of life.
- Defining life is a difficult but thought-provoking topic, a good choice for class discussion. You may wish to incorporate the test cases in discussion question 18 at the end of the chapter.
- The "pace of change" question is also best answered in classroom discussion.

Section 14.6

- What to do about burning fossil fuels? Again, this question involves another value judgment for which there is no correct answer.
- Identifying personal impacts on the ozone hole involves a value judgment; this topic is another candidate for discussion.

Solutions to End-of-Chapter Problems (Chapter 14)

1. A fossil of an organism that died more than 300 million years ago, found in the crust near a mid-ocean ridge. *This would not be possible, because (1) fossils form in sedimentary rocks, not lava; (2) the crust close to mid-ocean ridges is much younger than 300 million years.*

2. Evidence that fish once swam in a region that is now high on a mountaintop. *This is reasonable: Plate tectonics has forced low-lying regions upward in many places around the world.*
3. A "lost continent" on which humans had a great city just a few thousand years ago, but which now resides deep underground near a subduction zone. *This is not plausible. Plates move only a few centimeters per year, so a continent could not be subducted in a few thousand years.*
4. A planet in another solar system that has no life but has an atmosphere nearly identical to Earth's. *This would be very hard to explain, since oxygen is not stable in our atmosphere without continuous resupply by living things.*
5. A planet in another solar system that has an ozone layer but no ordinary oxygen (O_2) in its atmosphere. *This is implausible. Ozone is very reactive and is continuously derived from* O_2.
6. Evidence that the early Earth had more carbon dioxide in its atmosphere than the Earth does today. *This is not only reasonable but probable. Feedback processes may have maintained pleasant temperatures back then through a higher* CO_2 *abundance to counteract the fainter sunlight.*
7. Discovery of life on Mars that also uses DNA as its genetic molecule and that uses a genetic code very similar to that used by life on Earth. *Some scientists would consider this surprising, and others would not. It would mean that life somehow traveled from one planet to the other or that both were "seeded" from the outside.*
8. Evidence of photosynthesis occurring on a planet in another solar system that lies outside the solar system's habitable zone. *Assuming that the photosynthetic life needs liquid water, this discovery would be plausible on a planet beyond its star's habitable zone if another heat source (such as tidal heating) kept water from freezing. If the planet is within the inner edge of its star's habitable zone, airborne photosynthetic life might exist.*

9–11. These questions all ask students to briefly restate and explain ideas taken directly from the reading. The key in grading these questions is to make sure that students demonstrate that they *understand* the concepts about which they are writing.

12. Sample solution: If Earth had been closer to the Sun, the warmer temperatures might have forced more water vapor into the atmosphere. This would have increased the greenhouse effect, leading to further warming, evaporation of the oceans, and possible escape of all the water to space (as with Venus). Without liquid water on the surface, life as we know it would not have arisen on Earth.
13. The population would be 12 billion in 40 years, and 24 billion in 80 years. Responses as to whether this will occur will vary; students may either cite the untapped potentials to feed new population or point to the many constraints on further growth. In fact, the rate of population growth slowed during the 1990s, and most demographers predict that population will stop growing during the twenty-first century. (However, it is not clear whether it will stop growing because people choose to have smaller families or because natural processes will cause an increase in the death rate.)
14. Higher temperatures increase the formation rate of carbonate rocks, reducing atmospheric CO_2 and the greenhouse effect. This is an example of negative feedback—a stabilizing effect.
15. The presence of abundant ozone would probably be an indication of abundant "regular" oxygen (O_2). These highly-reactive gases are only present in our atmosphere due to biology—photosynthetic life, and we would interpret their presence in significant amounts as indications of life. The discovery would not bear on the question of simple vs. more advanced life—unless we watched it disappear!
16. Essay question. Very interesting to grade!