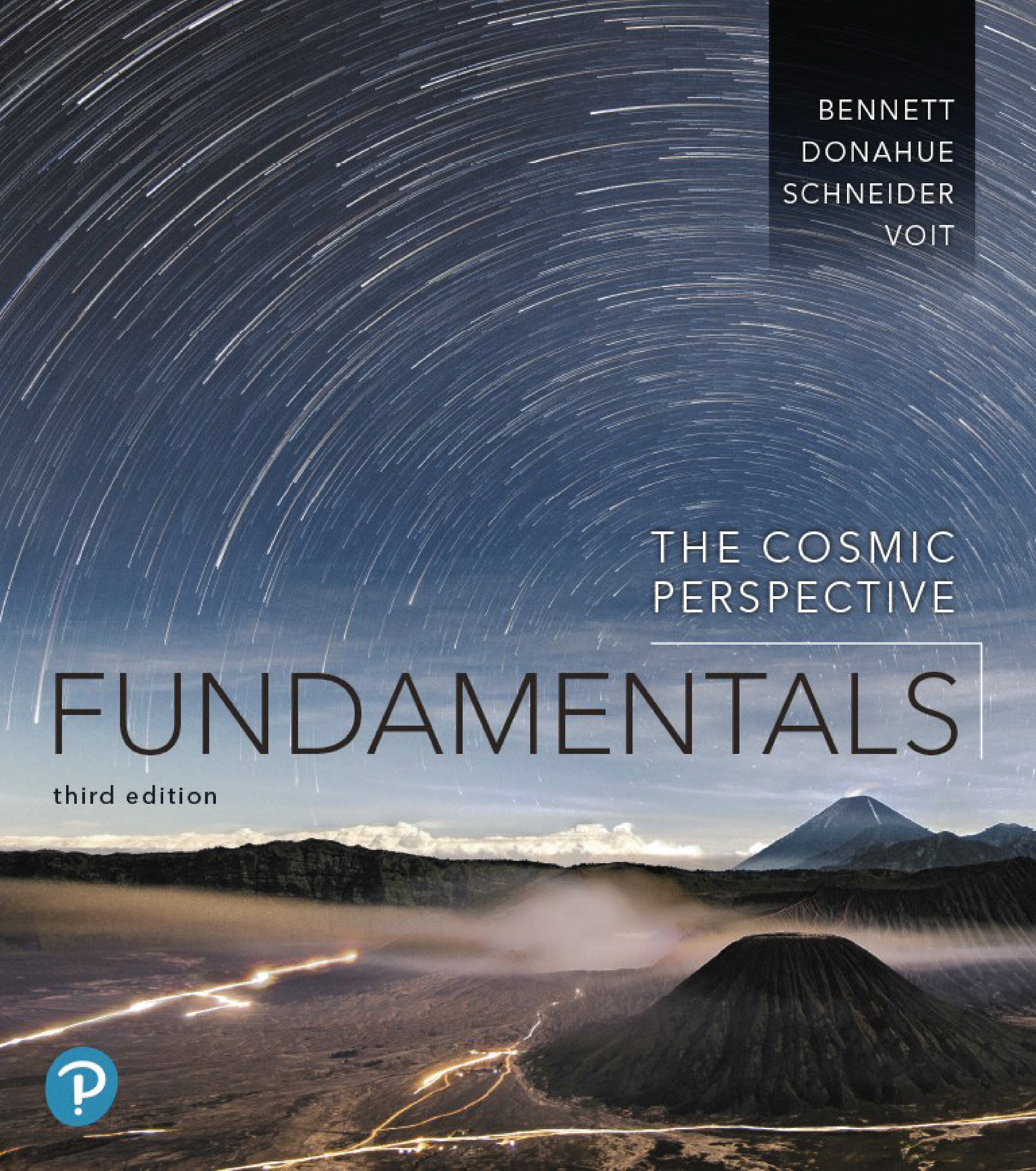


BENNETT
DONAHUE
SCHNEIDER
VOIT

THE COSMIC PERSPECTIVE
FUNDAMENTALS

third edition

THE COSMIC PERSPECTIVE
FUNDAMENTALS

third edition

JEFFREY BENNETT
University of Colorado at Boulder

MEGAN DONAHUE
Michigan State University

NICHOLAS SCHNEIDER
University of Colorado at Boulder

MARK VOIT
Michigan State University

Pearson

Director Physical Science Portfolio: Jeanne Zalesky
Physics & Astronomy Portfolio Analyst: Ian Desrosiers
Content Producer: Mary Tindle
Managing Producer: Kristen Flathman
Product Portfolio Editorial Assistant: Frances Lai
Rich Media Content Producer: Ali Candlin
Full-Service Vendor: Lifland et al., Bookmakers
Copyeditor: Lifland et al., Bookmakers
Compositor: SPi Global
Design Manager: Jerilyn Bockorick
Interior and Cover Designer: Alisha Webber
Illustrators: Rolin Graphics; Troutt Visuals
Rights & Permissions Project Manager: Ben Ferrini
Rights & Permissions Management: Matthew Perry
Photo Researcher: Matthew Perry
Manufacturing Buyer: Stacey Weinberger
Director of Field Marketing: Tim Galligan
Director of Product Marketing: Allison Rona
Field Marketing Manager: Yez Alayan
Product Marketing Manager: Elizabeth Bell

Cover Photo Credit: Rawin Cheasagul/Getty Images

Library of Congress Cataloguing-in-Publication data is on file with the publisher.

ISBN 10: 0-134-98850-7;
ISBN 13: 978-0-134-98850-4 (Student edition)

Pearson

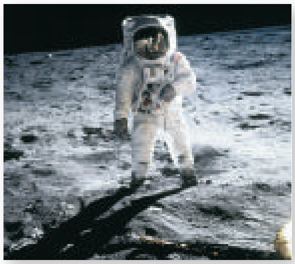
www.pearson.com

Dedication

TO ALL WHO HAVE EVER WONDERED about the mysteries of the universe. We hope this book will answer some of your questions—and that it will also raise new questions in your mind that will keep you curious and interested in the ongoing human adventure of astronomy.

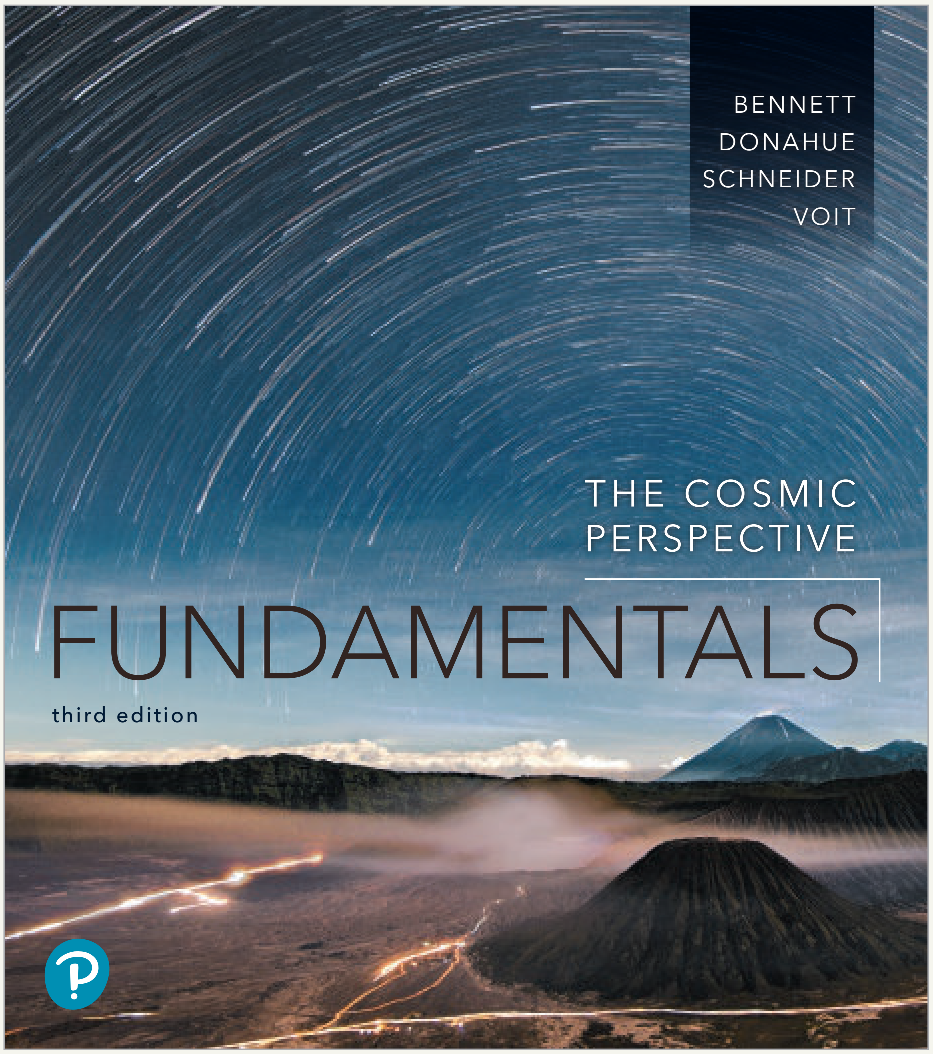
And, especially, to Michaela, Emily, Sebastian, Grant, Nathan, Brooke, and Angela. The study of the universe begins at birth, and we hope that you will grow up in a world with far less poverty, hatred, and war so that all people will have the opportunity to contemplate the mysteries of the universe into which they are born. ✴

Brief Contents



Explore Modern Astronomy and Its Connections to Our Lives

The Cosmic Perspective Fundamentals **provides a brief, engaging, and up-to-date introduction to astronomy for anyone who is curious about the universe. As respected teachers and active researchers, the authors present astronomy using a coherent narrative and a thematic approach that engages students immediately and guides them through connecting ideas. The Third Edition has been fully updated with the latest scientific discoveries, including detection of gravitational waves, results from recent planetary missions, and new insights into extrasolar planets. Mastering Astronomy includes a wealth of author-created resources for students to use before, during, and after class.**



Pearson

A Clear Framework Makes Learning Targeted and Expectations Clear for Students . . .

Each chapter begins with an opening page that includes a brief overview of the chapter content and a clear set of **Learning Goals** associated with the chapter. Each Learning Goal is phrased as a question to engage students as they read. Each section is written to address the **Learning Goal questions** from the chapter-opening page.

For more than four centuries after the Copernican revolution taught us that Earth is just one member of our Sun's planetary system, the study of planetary systems remained limited to our own. Then, less than three decades ago, a new scientific revolution began with the first discoveries of planets around other stars. The image above, from the Large Binocular Telescope, shows infrared light from four planets (marked b, c, d, e) orbiting the star HR 8799; light from the star itself (center) was mostly blocked out during the exposure, as indicated by the solid red circle. The discovery that planetary systems are common around other stars has profound implications, making it seem more likely that we might someday find life elsewhere, perhaps even intelligent life. It also allows us to learn more about the general nature of planets and how they form, giving us deeper insights into our cosmic origins. In this chapter, we'll explore the exciting new science of other planetary systems.

LEARNING GOALS

7.1 Detecting Planets Around Other Stars
- How do we detect planets around other stars?
- What properties of extrasolar planets can we measure?

7.2 Characteristics of Extrasolar Planets
- How do extrasolar planets compare with planets in our solar system?
- Are Earth-like planets common?

THE PROCESS OF SCIENCE IN ACTION

7.3 Extrasolar Planets and the Nebular Theory
- Do we need to modify our theory of solar system formation?

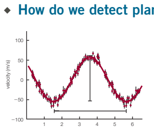
P. 113

Each chapter concludes with a **visual summary** that provides a concise review of the answers to the Learning Goal questions. The summary is followed by a 12-question **Quick Quiz** and a set of **short-answer, essay, and quantitative questions**.

summary of key concepts

7.1 Detecting Planets Around Other Stars

- **How do we detect planets around other stars?**



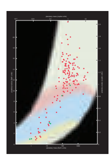
We can look for a planet's gravitational effect on its star through the **astrometric method**, which looks for small shifts in stellar position, or the **Doppler method**, which looks for the back-and-forth motion of stars revealed by Doppler shifts. For the small fraction of planetary systems with orbits aligned edge-on to Earth, we can search for **transits**, in which a planet blocks a little of its star's light as it passes in front of it.

- **What properties of extrasolar planets can we measure?**

All detection methods allow us to determine a planet's orbital period and distance from its star. The astrometric and Doppler methods can provide masses (or minimum masses), while the transit method can provide sizes. In cases where transit and Doppler methods are used together, we can determine average density. In some cases, transits (and eclipses) can provide other data, including limited data about atmospheric composition and temperature.

7.2 Characteristics of Extrasolar Planets

- **How do extrasolar planets compare with planets in our solar system?**



The known extrasolar planets have a much wider range of properties than the planets in our solar system. Many orbit much closer to their stars and with more eccentric orbital paths; even some jovian planets, called **hot Jupiters**, are found close to their stars. We also find properties indicating planetary types such as "water worlds" that do not fall neatly into the traditional terrestrial and jovian categories.

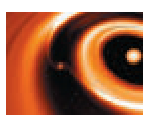
- **Are Earth-like planets common?**

Current data indicate that planetary systems are very common, and that Earth-size planets are also common. We do not yet have enough data to know whether such planets have Earth-like orbits, but we should learn the answer as more data are collected.

THE PROCESS OF SCIENCE IN ACTION

7.3 Extrasolar Planets and the Nebular Theory

- **Do we need to modify our theory of solar system formation?**



Our basic theory of solar system formation seems to be sound, but we have had to modify it to allow for planetary migration and a wider range of planetary types than we find in our solar system. Many mysteries remain, but they are unlikely to require major change to the nebular theory of solar system formation.

P. 126

. . . with Emphasis on the Process of Science

tools of science Spectroscopy

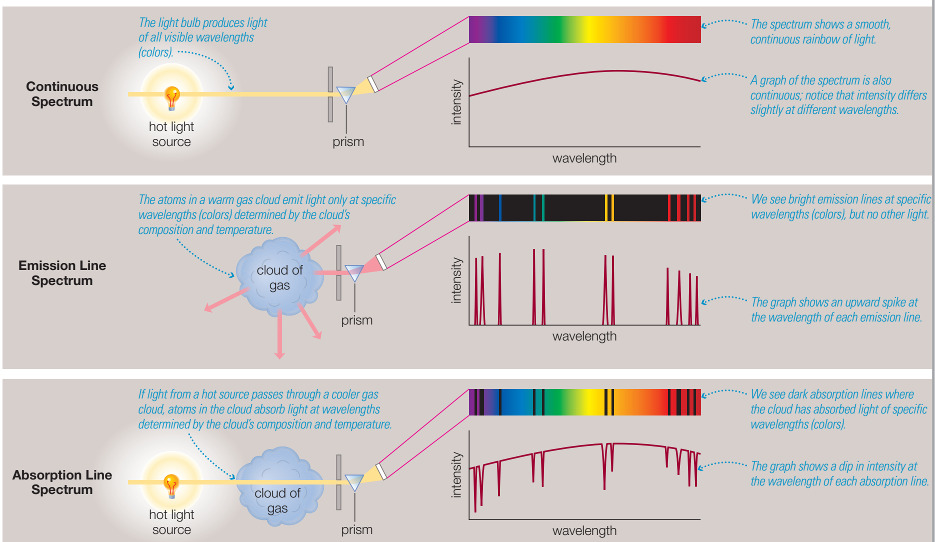
Three Types of Spectra

Spectroscopy is the study of light that has been spread out into a spectrum by a device such as a prism. The figure shows the three basic kinds of spectra that we observe: (1) a **continuous spectrum** contains light that is smoothly spread across a broad range of wavelengths; (2) an **emission line spectrum** has bright lines on a dark background; and (3) an **absorption line spectrum** has dark lines on a continuous background.

Spectra provide a wealth of information about the objects we study. We previously discussed how a *thermal radiation* spectrum—which is one type of continuous spectrum—tells us an object's surface temperature (see Tools of Science, page 79) and how *Doppler shifts* in the wavelengths of spectral lines tell us the speed of an object toward or away from us (see Tools of Science, page 117). We learn even more from the spectral lines themselves.

The laws of quantum mechanics (see Tools of Science, page 152) dictate that each different kind of atom, ion, or molecule produces spectral lines at a unique set of wavelengths—in essence, its "chemical fingerprint." We can therefore determine the composition of a distant object by identifying and comparing all the different "fingerprints" in its spectrum. It does not matter whether the lines are absorption lines or emission lines; the wavelengths of the lines are what tell us an object's composition.

We can put these ideas together to illustrate how the spectrum of a star like the Sun reveals its composition. The hot Sun emits thermal radiation, much like the hot light bulb in the figure, producing a continuous spectrum. The low-density, uppermost layers of the Sun act like a cloud of gas that the continuous spectrum must pass through on its way to Earth. Atoms in these layers absorb light at specific wavelengths, producing an absorption line spectrum. The wavelengths of those lines tell us the kinds of atoms that are present in the Sun, and a more detailed analysis tells us the relative proportions of those elements.

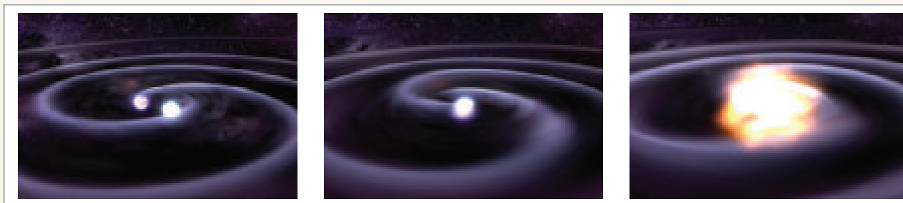


Examples of conditions under which we see the three basic types of spectra.

P. 132

Tools of Science boxes introduce key tools when they are first needed with the subject matter.

The final section of each chapter focuses on a topic that illustrates **the Process of Science in Action.**



The ripples represent gravitational waves carrying energy away from the system. *The loss of orbital energy means the orbit must decay . . .* *. . . until the two objects ultimately merge, producing a particularly strong pulse of gravitational waves.*

▲ **FIGURE 10.16**
This sequence uses a rubber sheet analogy to illustrate the gravitational waves produced by a binary system with two neutron stars. The gravitational waves carry away orbital energy, causing the orbit to decay until the two neutron stars collide and merge together. The time required for this sequence to play out (from left to right) would typically be a few tens of millions of years.

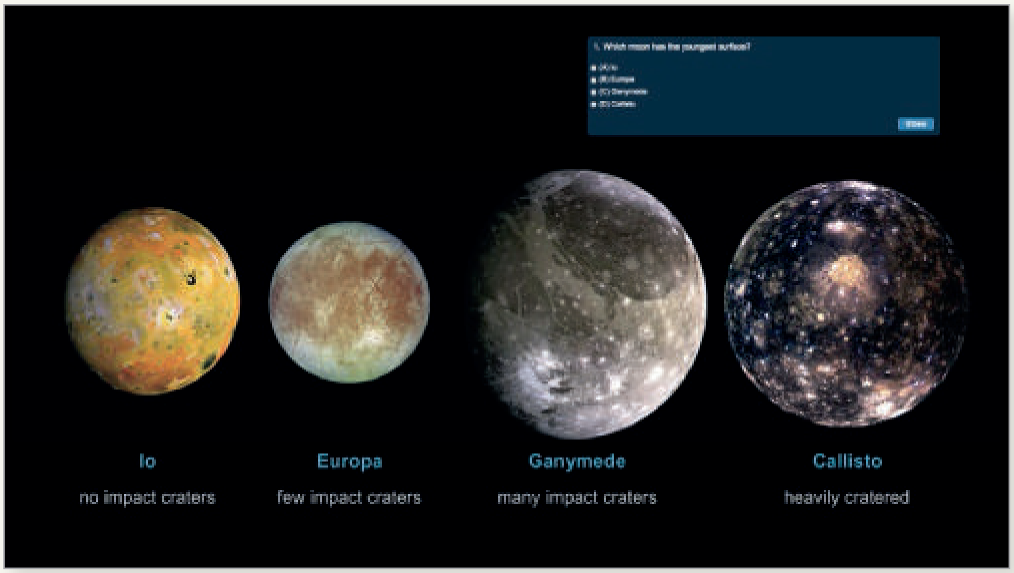
THE PROCESS OF SCIENCE IN ACTION

10.3 Gravitational Waves

Einstein's general theory of relativity makes many predictions that have been tested and verified, including the effects of gravity on time discussed in the previous section. Another important prediction is the existence of what we call *gravitational waves*. Einstein himself doubted that we would ever detect such waves, but we have, and how we detect them is this chapter's case study in the process of science in action. As you will see, gravitational-wave detectors have given astronomers an entirely new way to observe the universe.

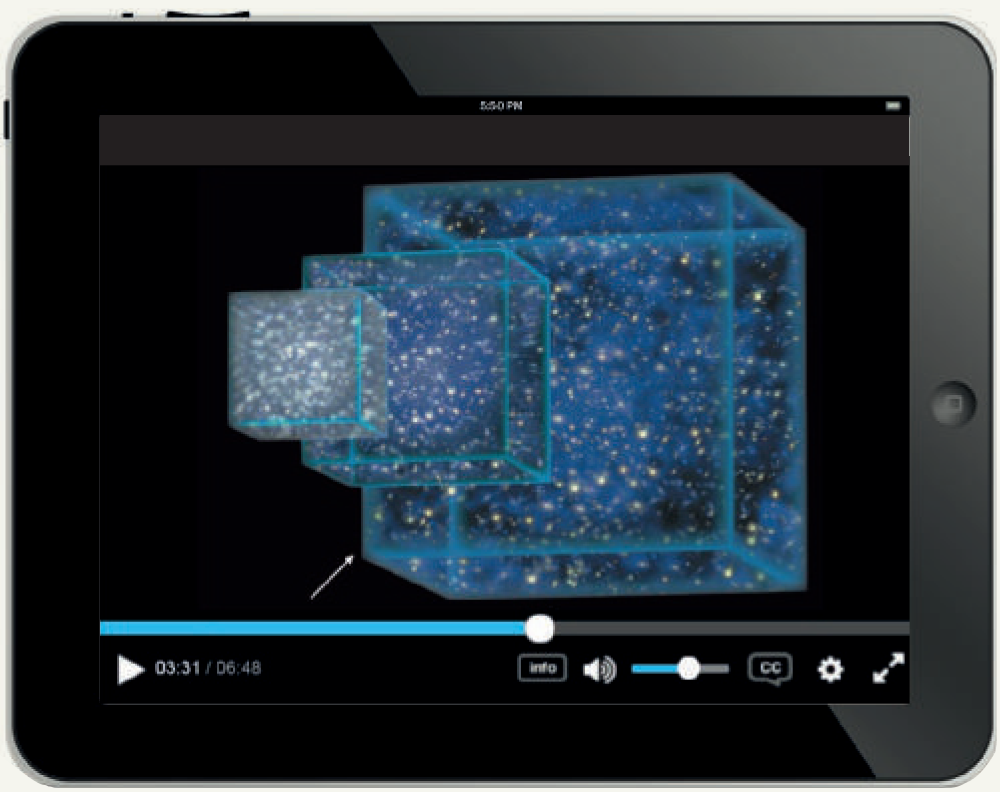
P. 178

Mastering Astronomy's Study Area Helps Students Come Prepared to Class . . .

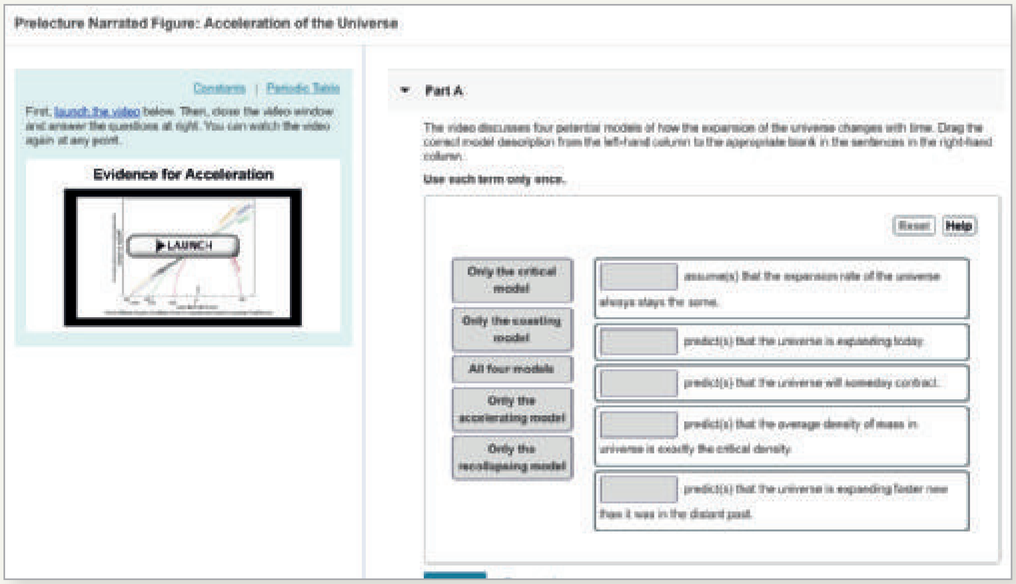


The Study Area features a Quick Quiz for each chapter, many videos and interactive figures, a set of self-guided tutorials covering key concepts, a media workbook, World Wide Telescope tours, and much more — PLUS access to a full etext of *The Cosmic Perspective Fundamentals*.

NEW! Dozens of new videos about key concepts and figures in the text, all written and most narrated by the authors to ensure consistency of terminology and pedagogy. Most videos include embedded pause-and-predict questions that allow students to check their understanding as they watch. Students can use these videos to help prepare for lectures, while instructors will find the same videos with assignable tutorials in the instructor-accessible Item Library.

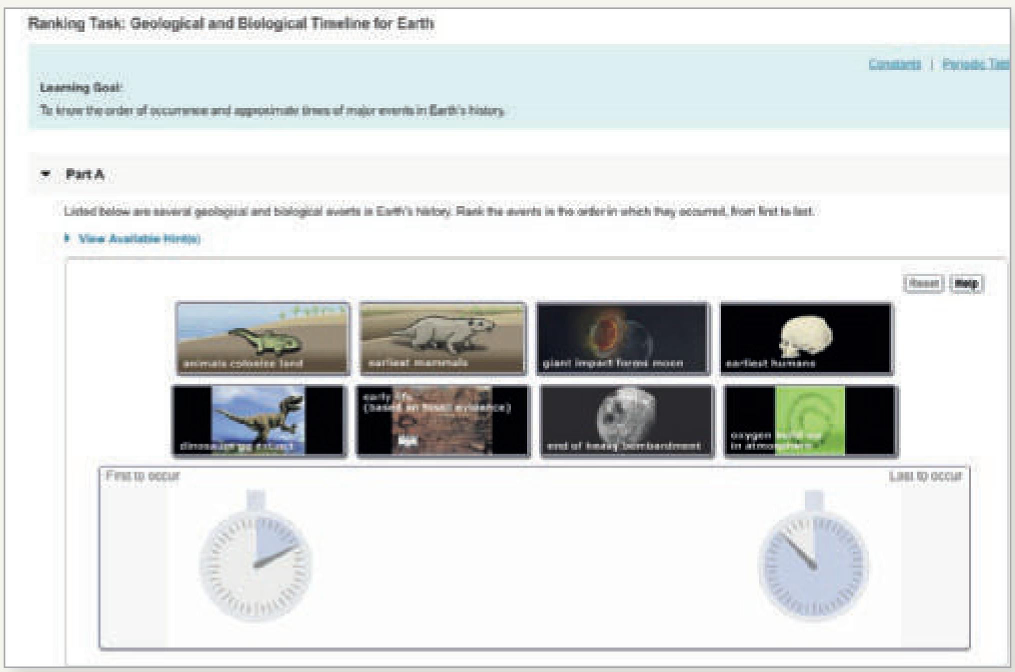


. . . While Instructors Can Access a Large Library of Homework and Test Questions



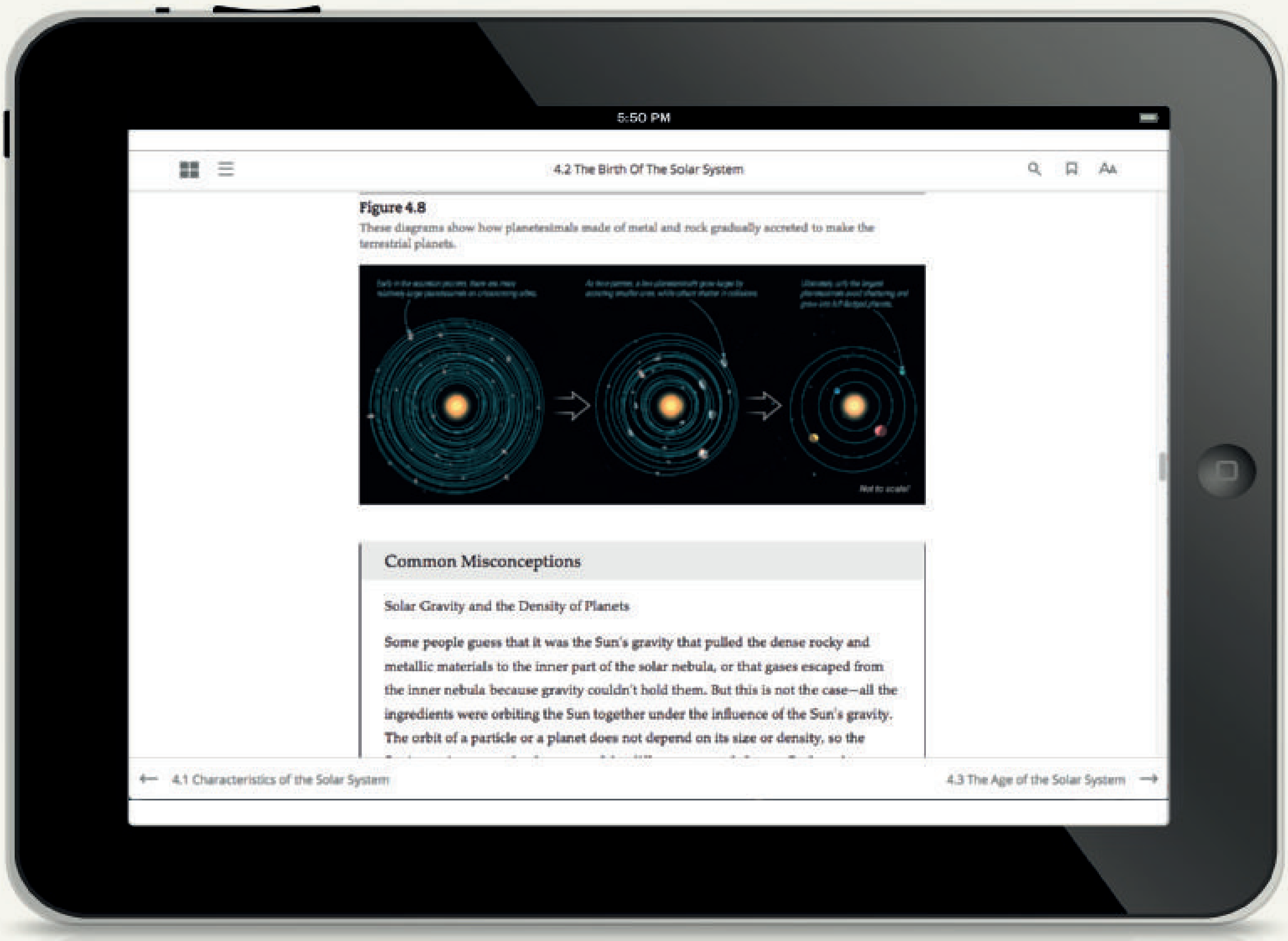
The Item Library consists of more than 250 assignable tutorials—all written or co-written by the textbook authors—including new tutorials based on all of the videos and interactive figures as well as updated tutorials on key concepts, process of science, vocabulary, and much more.

Many of the **assignable tutorials** use ranking or sorting tasks, which research shows to be particularly effective in building conceptual understanding. **The Item Library** also includes all end-of-chapter exercises from the book and a large test bank.

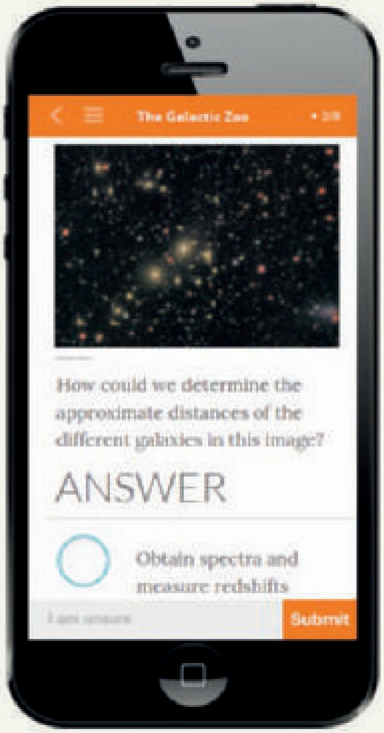


Reach Every Student with Pearson eText

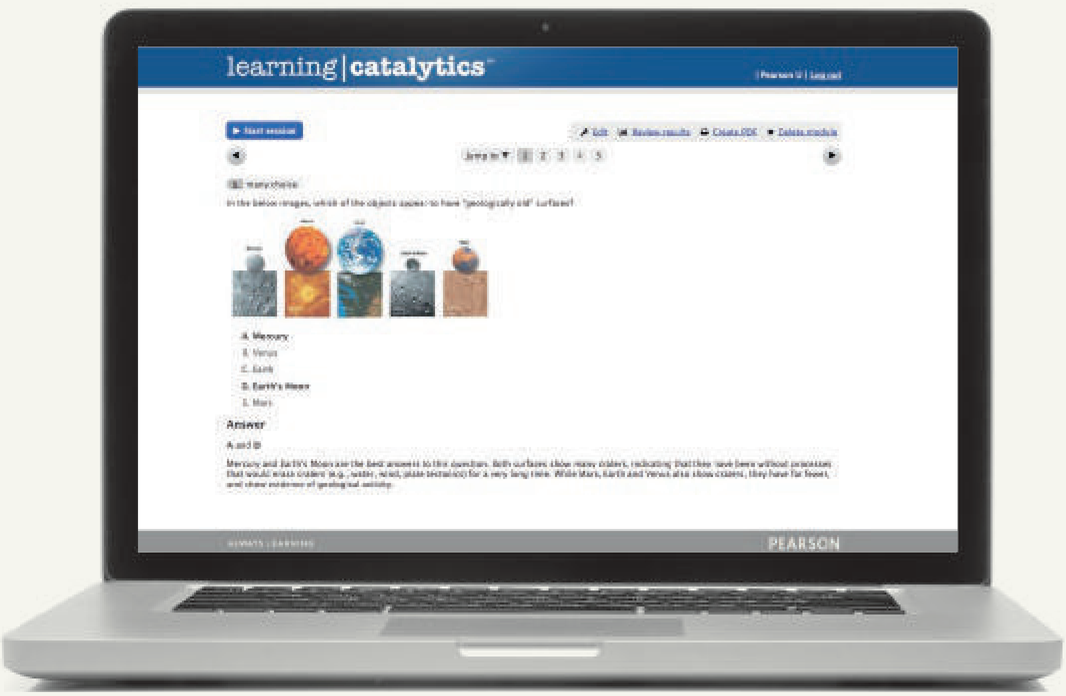
Pearson eText, optimized for mobile, seamlessly integrates videos and other rich media with the text and gives students access to their textbook anytime, anywhere.



Engage Students Before and During Class with Dynamic Study Modules and Learning Catalytics



NEW! Dynamic Study Modules in Mastering Astronomy help students study effectively—and at their own pace—by keeping them motivated and engaged. The assignable modules rely on the latest research in cognitive science, using methods—such as adaptivity, gamification, and intermittent rewards—to stimulate learning and improve retention.



With **Learning Catalytics**, you'll hear from every student when it matters most. You pose a variety of questions that help students recall ideas, apply concepts, and develop critical-thinking skills. Your students respond using their own smartphones, tablets, or laptops. You can monitor responses with real-time analytics and find out what your students do—and don't—understand. Then you can adjust your teaching accordingly, and even facilitate peer-to-peer learning, helping students stay motivated and engaged.

This page intentionally left blank

Detailed Contents

We humans have gazed into the sky for countless generations. We have wondered how our lives are connected to the Sun, Moon, planets, and stars that adorn the heavens. Today, through the science of astronomy, we know that these connections go far deeper than our ancestors ever imagined. This book focuses on the story of modern astronomy and the new perspective—*the cosmic perspective*—that astronomy gives us on ourselves and our planet.

Who Is This Book For?

The Cosmic Perspective Fundamentals is designed to support one-term college courses in introductory astronomy—particularly those in which instructors couple the text with Mastering™ Astronomy to create an active or collaborative learning environment. No prior background in astronomy or physics is assumed, making *The Cosmic Perspective Fundamentals* suitable for both high school courses and college courses for nonscience majors. *The Cosmic Perspective Fundamentals* differs from our more comprehensive texts (*The Cosmic Perspective* and *The Essential Cosmic Perspective*) in covering a smaller set of topics and therefore being much shorter in length, but it is built upon the same "big picture" approach to astronomy and uses the same pedagogical principles.

New to This Edition

Many new discoveries have been made in astronomy during the four years since publication of the second edition of *The Cosmic Perspective Fundamentals,* leading to many changes in this third edition. Indeed, the changes are too many to list here, but those who used the second edition will notice significant updates to almost every chapter in the book, primarily as a result of the many new astronomical discoveries that have occurred in recent years, including results from missions such as *New Horizons*, *Rosetta*, *Dawn*, *Curiosity*, *MAVEN*, *Cassini*, *Juno*, and more; the first direct detections of gravitational waves; and major advances in our understanding of extrasolar planets.

Topical Selection

A briefer, focused text must necessarily cover fewer topics. We have carefully selected those topics using the following four criteria:

- ***Importance.*** We surveyed a large number of professors to identify the topics considered of greatest importance in a college-level astronomy course, in order to ensure that the most fundamental concepts are covered in this text. Most astronomy courses begin with topics such as the scale of the universe, seasons, and phases of the Moon and then progress to study of the planets, stars, galaxies, and cosmology. Our selected topics have been organized in a similar fashion. The fifteen chapters are designed so that they can be covered in a typical semester at a rate of approximately one chapter per week.
- ***Active learning.*** Educational research has shown that students learn scientific concepts best by actively solving conceptual problems, both individually and in collaboration with other students. We have emphasized topics that are well suited to active learning, and each chapter includes **Think About It** critical thinking questions for in-class discussion and **See It for Yourself** hands-on activities to further promote active learning. These in-text features are reinforced by a variety of active learning resources on the Mastering Astronomy website.
- ***Engagement.*** Most students in a college astronomy course are there to satisfy a general education requirement, but the subject is sufficiently interesting that it should be possible to choose topics that students will find highly engaging—and that they will therefore be willing to work hard to learn.
- ***Process of science.*** We believe that the primary purpose of a general education requirement in science is to ensure that students learn about science itself. Throughout the book, we have chosen topics that illustrate important aspects of the process of science, and each chapter concludes with a section called **The Process of Science in Action,** which presents a case study of how the process of science has helped (or is currently helping) to provide greater insight into key topics in astronomy.

Book Structure

To facilitate student learning, we have created a simple pedagogical structure used in each of the book's fifteen chapters:

- Each chapter begins with an opening page that includes a brief overview of the chapter content and a clear set of **Learning Goals** associated with the chapter. Each Learning Goal is phrased as a question to engage students as they read.
- Each chapter consists of three sections. The first two sections focus on the key topics of the chapter; the third section builds on the ideas from the first two sections, but focuses on **The Process of Science in Action.**
- Each section is written to address the Learning Goal questions from the chapter-opening page.
- Each chapter concludes with a **visual summary** that provides a concise review of the answers to the Learning Goal questions.
- The summary is followed by a 12-question **Quick Quiz** and a set of **short-answer, essay, and quantitative questions.**

Additional features of the book include the following:

- **Tools of Science** boxes, which present a brief overview of key tools that astronomers use, including theories, equations, observational techniques, and technology. Each chapter includes one Tools of Science box related to the chapter content.

- **Common Misconceptions** boxes, which address popularly held but incorrect ideas about topics in the text
- **Annotated Figures and Photos**, which act like the voice of an instructor, walking students through the key ideas presented in complex figures, photos, and graphs
- **Cosmic Context Figures**, which combine text and illustrations into accessible and coherent two-page visual summaries that will help improve student understanding of essential topics

Mastering Astronomy—A New Paradigm in Astronomy Teaching

What is the single most important factor in student success in astronomy? Both research and common sense reveal the same answer: *study time*. No matter how good the teacher or how good the textbook, students learn only when they spend adequate time studying. Unfortunately, limitations on resources for grading have prevented most instructors from assigning much homework despite its obvious benefits to student learning. And limitations on help and office hours have made it difficult for students to make sure they use self-study time effectively. That, in a nutshell, is why we created Mastering Astronomy. For students, it provides personalized learning designed to coach them *individually*—responding to their errors with specific, targeted feedback and providing optional hints for those who need additional guidance. For professors, Mastering Astronomy provides the unprecedented ability to automatically monitor and record students' step-by-step work and evaluate the effectiveness of assignments and exams.

All students registered for Mastering Astronomy receive full access to the Study Area. Key resources available in the Study Area include the following:

- A large set of prelecture videos, narrated figures, and interactive figures that will help students understand key concepts from the textbook
- A set of self-study tools, including a Quick Quiz for each chapter and interactive self-guided tutorials that go into depth on topics that some students find particularly challenging
- A downloadable set of group activities
- Additional videos covering basic math skills, as well as selected videos of the authors speaking to the public
- And much more, including a media workbook, Starry Night activities, World Wide Telescope tours, and even access to a full etext of *The Cosmic Perspective Fundamentals*

Instructors have access to many additional resources, including a large Item Library featuring more than 250 assignable tutorials, organized by chapter, that include guidance for understanding key concepts, assessments based on the large set of prelecture videos, ranking tasks, sorting tasks, and more. There is also a set of Math Review tutorials to help students who need work on topics including scientific notation, working with units, metric units, and problem-solving skills.

Finally, please note that nearly all the content available at the Mastering Astronomy site for *The Cosmic Perspective Fundamentals* has been written or co-written by the textbook authors. This means that you can count on consistency between the textbook and web resources, with both emphasizing the same concepts and using the same terminology and the same pedagogical approaches. This type of consistency ensures that students will be able to study in the most efficient way possible.

Acknowledgments

A textbook may carry author names, but it is the result of hard work by a long list of committed individuals, as well as many reviewers. We could not possibly list everyone who has helped, but we would especially like to thank our editorial team at Pearson, our production team at Lifland et al., and the more than 100 professors who have reviewed our texts in depth, providing valuable feedback; a list of these professors can be found in *The Cosmic Perspective*, ninth edition.

Jeff Bennett
Megan Donahue
Nick Schneider
Mark Voit

Jeffrey Bennett, a recipient of the American Institute of Physics Science Communication Award, holds a B.A. in biophysics (UC San Diego) and an M.S. and Ph.D. in astrophysics (University of Colorado). He specializes in science and math education and has taught at every level from preschool through graduate school. Career highlights include serving 2 years as a visiting senior scientist at NASA headquarters, where he developed programs to build stronger links between research and education, proposing and helping to develop the Voyage scale model solar system on the National Mall (Washington, DC) and developing the free app *Totality by Big Kid Science* to help people learn about total solar eclipses. He is the lead author of textbooks in astronomy, astrobiology, mathematics, and statistics and of critically acclaimed books for the public including *Beyond UFOs* (Princeton University Press), *Math for Life* (Big Kid Science), *What Is Relativity?* (Columbia University Press), *On Teaching Science* (Big Kid Science), and *A Global Warming Primer* (Big Kid Science). He is also the author of six science picture books for children, titled *Max Goes to the Moon*, *Max Goes to Mars, Max Goes to Jupiter, Max Goes to the Space Station*, *The Wizard Who Saved the World*, and *I, Humanity*; all six have been launched to the International Space Station and read aloud by astronauts for NASA's Story Time From Space program. His personal website is www.jeffreybennett.com.

Megan Donahue is a full professor in the Department of Physics and Astronomy at Michigan State University (MSU), a Fellow of the American Physical Society and of the American Association for the Advancement of Science, and President of the American Astronomical Society (2018–2020). Her research focuses on using x-ray, UV, infrared, and visible light to study galaxies and clusters of galaxies: their contents—dark matter, hot gas, galaxies, active galactic nuclei—and what they reveal about the contents of the universe and how galaxies form and evolve. She grew up on a farm in Nebraska and received an S.B. in physics from MIT, where she began her research career as an x-ray astronomer. She has a Ph.D. in astrophysics from the University of Colorado. Her Ph.D. thesis on theory and optical observations of intergalactic and intracluster gas won the 1993 Robert Trumpler Award from the Astronomical Society for the Pacific for an outstanding astrophysics doctoral dissertation in North America. She continued postdoctoral research as a Carnegie Fellow at Carnegie Observatories in Pasadena, California, and later as an STScI Institute Fellow at Space Telescope. Megan was a staff astronomer at the Space Telescope Science Institute until 2003, when she joined the MSU faculty. She is also actively involved in advising national and international astronomical facilities and NASA, including planning future NASA missions. Megan is married to Mark Voit, and they collaborate on many projects, including this textbook, over 70 peer-reviewed astrophysics papers, and the nurturing of their children, Michaela, Sebastian, and Angela. Megan has run three full marathons, including Boston. These days she runs trails with friends, orienteers, and plays piano and bass guitar for fun and no profit.

Nicholas Schneider is a full professor in the Department of Astrophysical and Planetary Sciences at the University of Colorado and a researcher in the Laboratory for Atmospheric and Space Physics. He received his B.A. in physics and astronomy from Dartmouth College in 1979 and his Ph.D. in planetary science from the University of Arizona in 1988. His research interests include planetary atmospheres and planetary astronomy. One research focus is the odd case of Jupiter's moon Io. Another is the mystery of Mars's lost atmosphere, which he is helping to answer by leading the Imaging UV Spectrograph team on NASA's *MAVEN* mission now orbiting Mars. Nick enjoys teaching at all levels and is active in efforts to improve undergraduate astronomy education. Over his career he has received the National Science Foundation's Presidential Young Investigator Award, the Boulder Faculty Assembly's Teaching Excellence Award, and NASA's Exceptional Scientific Achievement Medal. Off the job, Nick enjoys exploring the outdoors with his family and figuring out how things work.

Mark Voit is a full professor in the Department of Physics and Astronomy and Associate Dean for Undergraduate Studies at Michigan State University. He earned his A.B. in astrophysical sciences at Princeton University and his Ph.D. in astrophysics at the University of Colorado in 1990. He continued his studies at the California Institute of Technology, where he was a research fellow in theoretical astrophysics, and then moved on to Johns Hopkins University as a Hubble Fellow. Before going to Michigan State, Mark worked in the Office of Public Outreach at the Space Telescope, where he developed museum exhibitions about the Hubble Space Telescope and helped design NASA's award-winning HubbleSite. His research interests range from interstellar processes in our own galaxy to the clustering of galaxies in the early universe, and he is a Fellow of the American Association for the Advancement of Science. He is married to coauthor Megan Donahue and cooks terrific meals for her and their three children. Mark likes getting outdoors whenever possible and particularly enjoys running, mountain biking, canoeing, orienteering, and adventure racing. He is also author of the popular book *Hubble Space Telescope: New Views of the Universe*.

How to Succeed in Your Astronomy Course

If Your Course Is	Times for Reading the Assigned Text (per week)	Times for Homework Assignments (per week)	Times for Review and Test Preparation (average per week)	Total Study Time (per week)
3 credits	2 to 4 hours	2 to 3 hours	2 hours	6 to 9 hours
4 credits	3 to 5 hours	2 to 4 hours	3 hours	8 to 12 hours
5 credits	3 to 5 hours	3 to 6 hours	4 hours	10 to 15 hours

The Key to Success: Study Time

The single most important key to success in any college course is to spend enough time studying. A general rule of thumb for college classes is that you should expect to study about 2 to 3 hours per week *outside* of class for each unit of credit. For example, based on this rule of thumb, a student taking 15 credit hours should expect to spend 30 to 45 hours each week studying outside of class. Combined with time in class, this works out to a total of 45 to 60 hours spent on academic work—not much more than the time a typical job requires, and you get to choose your own hours. Of course, if you are working or have family obligations while you attend school, you will need to budget your time carefully.

The table above gives rough guidelines for how you might divide your study time. If you find that you are spending fewer hours than these guidelines suggest, you can probably improve your grade by studying longer. If you are spending more hours than these guidelines suggest, you may be studying inefficiently; in that case, you should talk to your instructor about how to study more effectively.

Using This Book

Each chapter in this book is designed to make it easy for you to study effectively and efficiently. To get the most out of each chapter, you might wish to use the following study plan.

- A textbook is not a novel, and you'll learn best by reading the elements of this text in the following order:
  1. Start by reading the Learning Goals and the introductory paragraph at the beginning of the chapter so that you'll know what you are trying to learn.
  2. Get an overview of key concepts by studying the illustrations and their captions and annotations. The illustrations highlight most major concepts, so this "illustrations first" strategy gives you an opportunity to survey the concepts before you read about them in depth. You will find the two-page Cosmic Context figures especially useful.
  3. Read the chapter narrative, trying the Think About It questions and the See It for Yourself activities as you go along, but save the boxed features (Common Misconceptions, Tools of Science) to read later. As you read, make notes on the pages to remind yourself of ideas you'll want to review later. Take notes as you read, but avoid using a highlight pen (or a highlighting tool if you are using an e-book), which makes it too easy to highlight mindlessly.
  4. After reading the chapter once, go back through and read the boxed features.
  5. Review the Summary of Key Concepts, ideally by trying to answer the Learning Goal questions for yourself before reading the given answers.
- After completing the reading as outlined above, test your understanding with the end-of-chapter exercises. A good way to begin is to make sure you can answer all of the Quick Quiz questions; if you don't know an answer, look back through the chapter until you figure it out.
- Further build your understanding by making use of the videos, quizzes, and other resources available at Mastering Astronomy. These resources have been developed specifically to help you learn the most important ideas in your course, and they have been extensively tested to make sure they are effective. They really do work, and the only way you'll gain their benefits is by going to the website and using them.

General Strategies for Studying

- Budget your time effectively. Studying 1 or 2 hours each day is more effective, and far less painful, than studying all night before homework is due or before exams. *Note*: Research shows that it can be helpful to create a "personal contract" for your study time (or for any other personal commitment), in which you specify rewards you'll give yourself for success and penalties you'll assess for failings.
- Engage your brain. Learning is an active process, not a passive experience. Whether you are reading, listening to a lecture, or working on assignments, always make sure that your mind is actively engaged. If you find your mind drifting or find yourself falling asleep, make a conscious effort to revive yourself, or take a break if necessary.
- Don't miss class, and come prepared. Listening to lectures and participating in class activities and discussions is much more effective than reading someone else's notes or watching a video later. Active participation will help you retain what you are learning. Also, be sure to complete any assigned reading *before* the class in which it will be discussed. This is crucial, since class lectures and discussions are designed to reinforce key ideas from the reading.

- Take advantage of resources offered by your professor, whether it be email, office hours, review sessions, online chats, or other opportunities to talk to and get to know your professor. Most professors will go out of their way to help you learn in any way that they can.
- Start your homework early. The more time you allow yourself, the easier it is to get help if you need it. If a concept gives you trouble, do additional reading or studying beyond what has been assigned. And if you still have trouble, ask for help: You surely can find friends, peers, or teachers who will be glad to help you learn.
- Working together with friends can be valuable in helping you understand difficult concepts. However, be sure that you learn *with* your friends and do not become dependent on them.
- Don't try to multitask. Research shows that human beings simply are not good at multitasking: When we attempt it, we do more poorly at all of the individual tasks. And in case you think you are an exception, research has also shown that those people who believe they are best at multitasking are often the worst! So when it is time to study, turn off your electronic devices, find a quiet spot, and concentrate on your work. (If you *must* use a device to study, as with an e-book or online homework, turn off email, text, and other alerts so that they will not interrupt your concentration; some apps will do this for you.)

Preparing for Exams

- Rework problems and other assignments; try additional questions, including the online quizzes available at Mastering Astronomy, to be sure you understand the concepts. Study your performance on assignments, quizzes, or exams from earlier in the term.
- Study your notes from classes, and reread relevant sections in your textbook. Pay attention to what your instructor expects you to know for an exam.
- Study individually *before* joining a study group with friends. Study groups are effective only if every individual comes prepared to contribute.
- Don't stay up too late before an exam. Don't eat a big meal within an hour of the exam (thinking is more difficult when blood is being diverted to the digestive system).
- Try to relax before and during the exam. If you have studied effectively, you are capable of doing well. Staying relaxed will help you think clearly.

Presenting Homework and Writing Assignments

All work that you turn in should be of *collegiate quality:* neat and easy to read, well organized, and demonstrating mastery of the subject matter. Future employers and teachers will expect this quality of work. Moreover, although submitting homework of collegiate quality requires "extra" effort, it serves two important purposes directly related to learning:

1. The effort you expend in clearly explaining your work solidifies your learning. Writing (or typing) triggers different areas of your brain than reading, listening, or speaking. As a result, writing something down will reinforce your learning of a concept, even when you think you already understand it.
2. By making your work clear and self-contained (that is, making it a document that you can read without referring to the questions in the text), you will have a much more useful study guide when you review for a quiz or exam.

The following guidelines will help ensure that your assignments meet the standards of collegiate quality:

- Always use proper grammar, proper sentence and paragraph structure, and proper spelling. Do not use texting shorthand, and don't become over-reliant on spell checkers, which may miss "too two three mistakes, to."
- All answers and other writing should be fully self-contained. A good test is to imagine that a friend is reading your work and to ask yourself whether the friend would understand exactly what you are trying to say. It is also helpful to read your work out loud to yourself, making sure that it sounds clear and coherent.
- In problems that require calculation:
    1. Be sure to *show your work* clearly so that both you and your instructor can follow the process you used to obtain an answer. Also, use standard mathematical symbols, rather than "calculator-ese." For example, show multiplication with the $\times$ symbol (not with an asterisk), and write 10^5, not 10^5 or 10E5.
    2. *Word problems should have word answers*. That is, after you have completed any necessary calculations, make sure that any problem stated in words is answered with one or more *complete sentences* that describe the point of the problem and the meaning of your solution.
    3. *Units are crucial*. If your answer has units, be sure they are stated clearly. For example, if you are asked to calculate a distance, be sure you state whether your answer is in miles, kilometers, or some other distance unit.
    4. Express your word answers in a way that would be *meaningful* to most people. For example, most people would find it more meaningful if you expressed a result of 720 hours as 1 month. Similarly, if a precise calculation yields an answer of 9,745,600 years, it may be more meaningfully expressed in words as "nearly 10 million years."
- Include illustrations whenever they help explain your answer, and make sure your illustrations are neat and clear. For example, if you graph by hand, use a ruler to make straight lines. If you use software to make illustrations, be careful not to make them overly cluttered with unnecessary features.
- If you study with friends, be sure that you turn in your own work stated in your own words—you should avoid anything that might give even the *appearance* of possible academic dishonesty.

This page intentionally left blank

A Modern View of the Universe

1

This Hubble Space Telescope photo shows a piece of the sky so small that you could block your view of it with a grain of sand held at arm's length. Yet the photo shows an almost unimaginable expanse of both space and time: Nearly every object within it is a galaxy containing billions of stars, most likely orbited by planets, and some of the smaller smudges are galaxies so far away that their light has taken more than 12 billion years to reach us. A major goal of this book is to help you understand what you see in this photograph. We'll begin with a brief survey of our modern, scientific view of the universe.

LEARNING GOALS

1.1 The Scale of the Universe
- What is our place in the universe?
- How big is the universe?

1.2 The History of the Universe
- How did we come to be?
- How do our lifetimes compare to the age of the universe?

THE PROCESS OF SCIENCE IN ACTION

1.3 Defining Planets
- What is a planet?

1.1 The Scale of the Universe

For most of human history, our ancestors imagined Earth to be stationary at the center of a relatively small universe. This idea made sense at a time when understanding was built upon everyday experience. After all, we cannot feel the constant motion of Earth as it rotates on its axis and orbits the Sun, and if you observe the sky you'll see that the Sun, Moon, planets, and stars all appear to revolve around us each day. Nevertheless, we now know that Earth is a planet orbiting a rather average star in a rather typical galaxy, and that our universe is filled with far greater wonders than our ancestors ever imagined.

◆ What is our place in the universe?

Before we can discuss the universe and its great wonders, we first need to develop a general sense of our place within it. We can do this by thinking about what we might call our "cosmic address," illustrated in Figure 1.1.

Our Cosmic Address Earth is a *planet* in our **solar system**, which consists of the Sun, the planets and their moons, and countless smaller objects that include rocky *asteroids* and icy *comets*. Keep in mind that our Sun is a *star*, just like the stars we see in our night sky.

Our solar system belongs to the huge, disk-shaped collection of stars called the **Milky Way Galaxy**. A **galaxy** is a great island of stars in space, all held together by gravity and orbiting a common center. The Milky Way is a relatively large galaxy, containing more than 100 billion stars, and we think that most of these stars are orbited by planets. Our solar system is located a little over halfway from the galactic center to the edge of the galactic disk.

Billions of other galaxies are scattered throughout space. Some galaxies are fairly isolated, but most are found in groups. Our Milky Way, for example, is one of the two largest among more than 50 galaxies (most relatively small) in the **Local Group**. Groups of galaxies with many more large members are often called **galaxy clusters**.

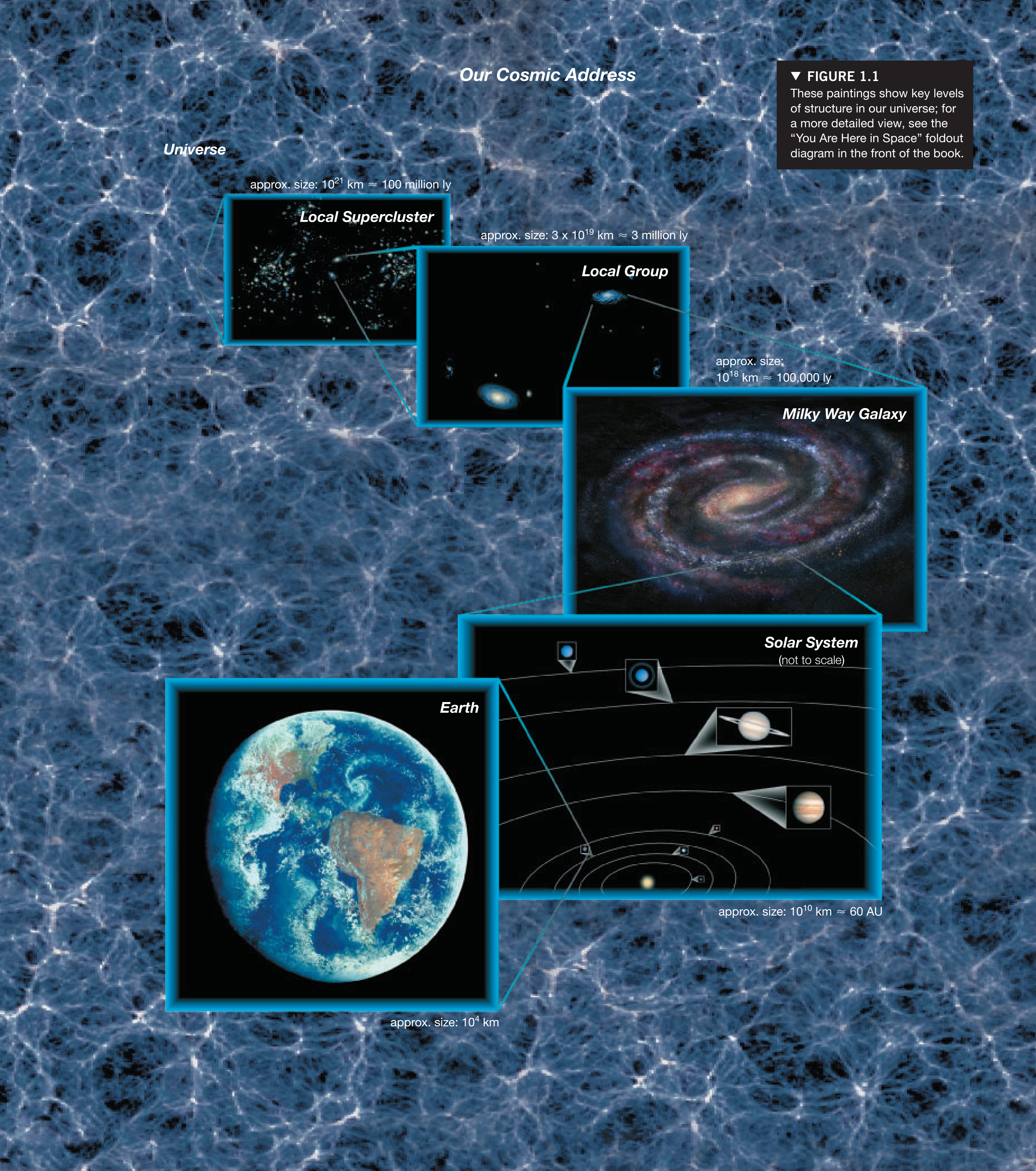
On a very large scale, galaxies and galaxy clusters appear to be arranged in giant chains and sheets with huge voids between them; the background of Figure 1.1 represents this large-scale structure. The regions in which galaxies and galaxy clusters are most tightly packed are called **superclusters**, which are essentially clusters of galaxy clusters. Our Local Group is located in the outskirts of the Local Supercluster (also called *Laniakea*, Hawaiian for "immense heaven").

think about it Some people think that our tiny physical size in the vast universe makes us insignificant. Others think that our ability to learn about the wonders of the universe gives us significance despite our small size. What do *you* think?

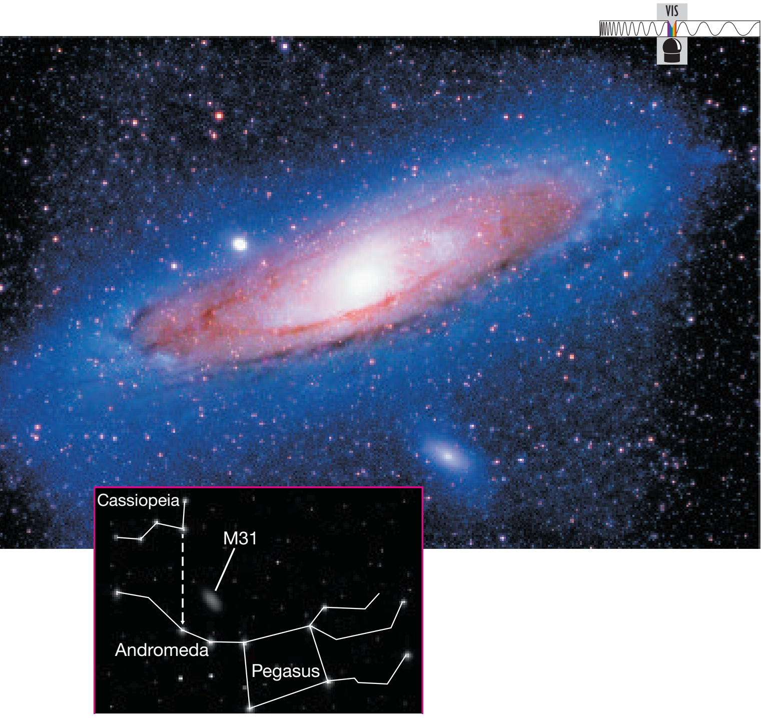
Together, all these structures make up our **universe**. In other words, the universe is the sum total of all matter and energy, encompassing the superclusters and voids and everything within them.

Astronomical Distance Measurements The labels in Figure 1.1 give approximate sizes for the various structures in kilometers (recall that 1 kilometer ≈ 0.6 mile), but many distances in astronomy are so large that kilometers are not the most convenient unit. Instead, we often use two other units:

- One **astronomical unit (AU)** is Earth's average distance from the Sun, which is about 150 million kilometers (93 million miles). We commonly describe distances within our solar system in AU.



▼ **FIGURE 1.1**
These paintings show key levels of structure in our universe; for a more detailed view, see the "You Are Here in Space" foldout diagram in the front of the book.



▲ **FIGURE 1.2**
The Andromeda Galaxy (also known as M31). When we look at this galaxy, we see light that traveled through space for 2.5 million years. The inset shows the galaxy's location in the constellation Andromeda.

- One **light-year (ly)** is the *distance* that light can travel in 1 year, which is about 10 trillion kilometers (see Tools of Science, page 10). We generally use light-years to describe the distances of stars and galaxies.

Looking Back in Time Light-years are a unit of distance, but they are related to the time it takes light to travel through space. Consider Sirius, the brightest star in the night sky, which is located about 8 light-years away. Because it takes light 8 years to travel this distance, we see Sirius not as it is today, but rather as it was 8 years ago. The star Betelgeuse, a bright red star in the constellation Orion, is about 600 light-years away, which means we see it as it was about 600 years ago. If Betelgeuse exploded in the past 600 years or so (a possibility we'll discuss in Chapter 9), we would not yet know it, because the light from the explosion would not yet have reached us.

The general idea that light takes time to travel through space leads to a remarkable fact: **The farther away we look in distance, the further back we look in time**. The effect is dramatic for large distances. The Andromeda Galaxy (Figure 1.2) is about 2.5 million light-years away, which means we see it as it looked about 2.5 million years ago. We see more distant galaxies as they were even further in the past.

It's also amazing to realize that any "snapshot" of a distant galaxy is a picture of both space and time. For example, because the Andromeda Galaxy is about 100,000 light-years in diameter, the light we see from the far side of the galaxy must have left on its journey to us some 100,000 years before the light from the near side. Figure 1.2 therefore shows different parts of the galaxy spread over a time period of 100,000 years. When we study the universe, it is impossible to separate space and time.

see it for yourself The glow from the central region of the Andromeda Galaxy is faintly visible to the naked eye and easy to see with binoculars. Use a star chart to find it in the night sky, and remember that you are seeing light that spent 2.5 million years in space before reaching your eyes. If students on a planet in the Andromeda Galaxy were looking at the Milky Way right now, what would they see? Could they know that we exist here on Earth?

The Observable Universe As we'll discuss in Section 1.2, the measured age of the universe is about 14 billion years. This fact, combined with the fact that looking deep into space means looking far back in time, places a limit on the portion of the universe that we can see, even in principle.

Figure 1.3 shows the idea. If we look at a galaxy that is 7 billion light-years away, we see it as it looked 7 billion years ago*—which means we see it as it was when the universe was half its current age. If we look at a galaxy that is 12 billion light-years away (like the most distant ones in the Hubble Space Telescope photo on page 1), we see it as it was 12 billion years ago, when the universe was only 2 billion years old. And if we tried to look beyond 14 billion light-years, we'd be looking to a time more than 14 billion years ago—which is before the universe existed and therefore means that there is nothing to see. This distance of 14 billion light-years therefore marks the boundary (or *horizon*) of our **observable universe**—the portion of the entire universe that we can potentially observe. Note that this fact does not put any limit on the size of the *entire* universe, which may be far larger than our observable universe. We simply have no hope of seeing or studying anything beyond the bounds of our observable universe.

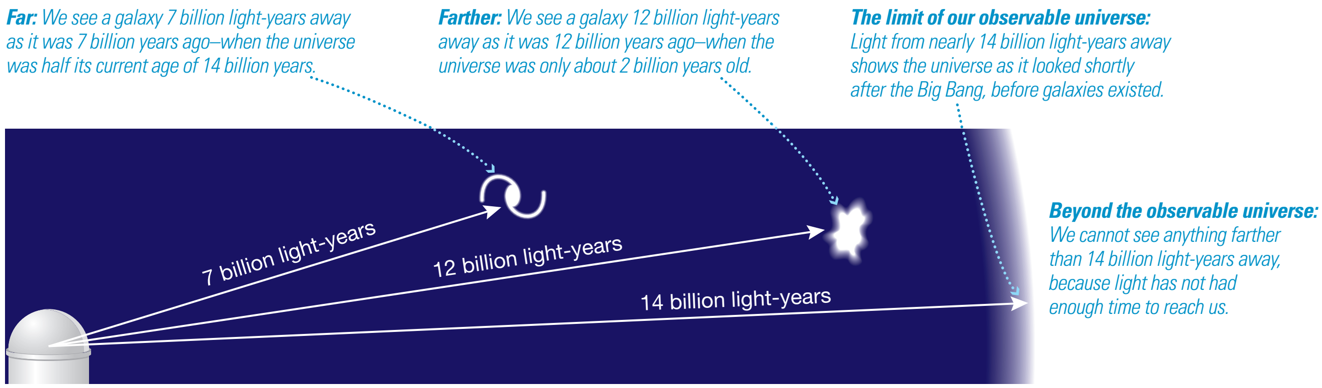
common misconceptions

The Meaning of a Light-Year

Maybe you've heard people say things like "It will take me light-years to finish this homework!" But that statement doesn't make sense, because light-years are a unit of *distance*, not time. If you are unsure whether the term *light-year* is being used correctly, try testing the statement by using the fact that 1 light-year is about 10 trillion kilometers, or 6 trillion miles. The statement then becomes "It will take me 6 trillion miles to finish this homework," which clearly does not make sense.

---

*As we'll discuss in Chapter 12, distances to faraway galaxies in an expanding universe can be described in more than one way; distances like those given here are based on the time it has taken a galaxy's light to reach us (called the *lookback time*).



▲ **FIGURE 1.3**

The farther away we look in space, the further back we look in time. The age of the universe therefore puts a limit on the size of the *observable* universe—the portion of the entire universe that we could observe in principle.

basic astronomical objects, units, and motions

This box summarizes key definitions used throughout this book.

Basic Astronomical Objects

star A large, glowing ball of gas that generates heat and light through nuclear fusion in its core. Our Sun is a star.

planet A moderately large object that orbits a star and shines primarily by reflecting light from its star. According to the current definition, an object can be considered a planet only if it (1) orbits a star, (2) is large enough for its own gravity to make it round, and (3) has cleared most other objects from its orbital path. An object that meets the first two criteria but not the third, like Pluto, is designated a **dwarf planet**.

moon (or **satellite**) An object that orbits a planet. The term *satellite* is also used more generally to refer to any object orbiting another object.

asteroid A relatively small and rocky object that orbits a star.

comet A relatively small and ice-rich object that orbits a star.

small solar system body An asteroid, comet, or other object that orbits a star but is too small to qualify as a planet or dwarf planet.

Collections of Astronomical Objects

solar system The Sun and all the material that orbits it, including the planets, dwarf planets, and small solar system bodies. Although the term *solar system* technically refers only to our own star system (*solar* means "of the Sun"), it is often applied to other star systems as well.

star system A star (sometimes more than one star) and any planets and other materials that orbit it.

galaxy A great island of stars in space, all held together by gravity and orbiting a common center, with a total mass equivalent to millions, billions, or even trillions of stars.

cluster of galaxies (or **group of galaxies**) A collection of galaxies bound together by gravity. Small collections (up to a few dozen galaxies) are generally called *groups*, while larger collections are called *clusters*.

supercluster A gigantic region of space where many individual galaxies and many groups and clusters of galaxies are packed more closely together than elsewhere in the universe.

universe (or **cosmos**) The sum total of all matter and energy—that is, all galaxies and everything between them.

observable universe The portion of the entire universe that can be seen from Earth, at least in principle. The observable universe is probably only a tiny portion of the entire universe.

Astronomical Distance Units

astronomical unit (AU) The average distance between Earth and the Sun, which is about 150 million kilometers. More technically, 1 AU is the length of the semimajor axis of Earth's orbit.

light-year (ly) The distance that light can travel in 1 year, which is about 9.46 trillion kilometers.

Terms Relating to Motion

rotation The spinning of an object around its axis. For example, Earth rotates once each day around its axis, which is an imaginary line connecting the North and South Poles.

orbit (or **revolution**) The orbital motion of one object around another due to gravity. For example, Earth orbits around the Sun once each year.

expansion (of the universe) The increase in the average distance between galaxies as time progresses.

▲ **FIGURE 1.4**
This photo shows the pedestals housing the Sun (the gold sphere on the nearest pedestal) and the inner planets in the Voyage scale model solar system (Washington, D.C.). The model planets are encased in the sidewalk-facing disks visible at about eye level on the planet pedestals. To the left is the National Air and Space Museum.

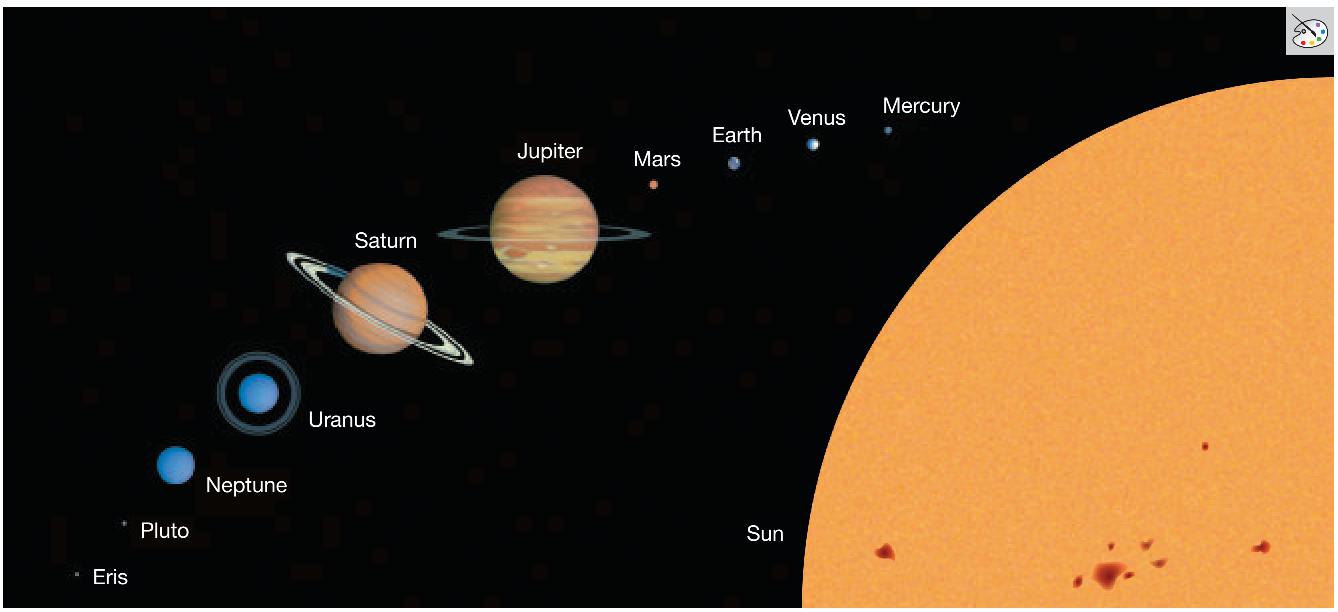
◆ How big is the universe?

Figure 1.1 put numbers on the sizes of different structures in the universe, but these numbers have little meaning for most people—after all, they are literally astronomical. Let's try to put these numbers into perspective.

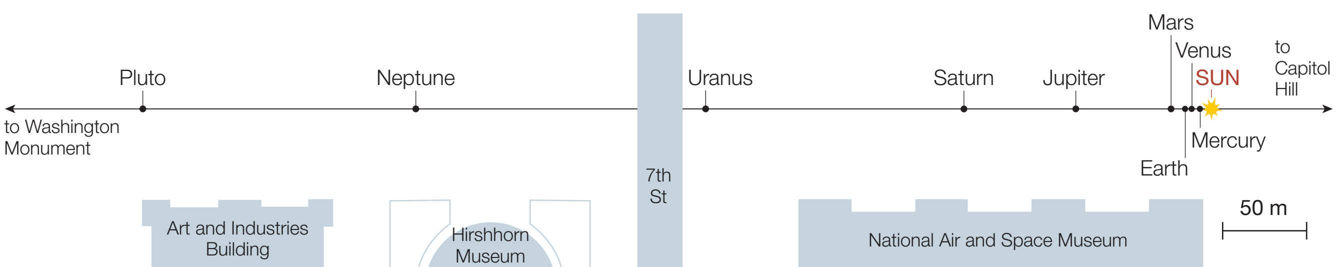
The Scale of the Solar System One of the best ways to develop perspective on cosmic sizes and distances is to imagine our solar system shrunk down to a scale that would allow you to walk through it. The Voyage scale model solar system (Figure 1.4) makes such a walk possible by showing sizes and distances in the solar system at *one ten-billionth* of their actual values.

Figure 1.5a shows the Sun and planets at their actual sizes (but not distances) on the Voyage scale: The model Sun is about the size of a large grapefruit, Jupiter is about the size of a marble, and Earth is about the size of the ball point in a pen. You can immediately see some key facts about our solar system. For example, the Sun is far larger than any of the planets; in mass, the Sun outweighs all the planets combined by a factor of nearly 1000. The planets also vary considerably in size: The storm on Jupiter known as the Great Red Spot (visible near Jupiter's lower left in the painting) could swallow up the entire Earth.

The scale of the solar system is even more remarkable when you combine the sizes shown in Figure 1.5a with the distances illustrated by the map of the Voyage model in Figure 1.5b. For example, the ball-point-sized Earth is located



a The scaled sizes (but not distances) of the Sun, the planets, and the two largest known dwarf planets.



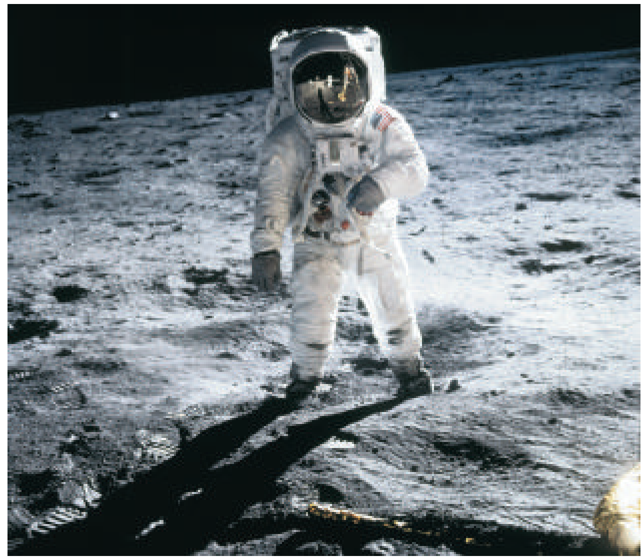
b Locations of major objects in the Voyage model (Washington, D.C.).

▲ **FIGURE 1.5**
The Voyage scale model represents sizes and distances in the solar system at one *ten-billionth* of their actual values. Planets are lined up in the model, but in reality each planet orbits the Sun independently and a perfect alignment never occurs.

about 15 meters (16.5 yards) from the grapefruit-sized Sun, which means you can picture Earth's orbit as a circle of radius 15 meters around a grapefruit.

Perhaps the most striking feature of our solar system when we view it to scale is its emptiness. The Voyage model shows the planets along a straight path, so we'd need to draw each planet's orbit around the model Sun to show the full extent of our planetary system. Fitting all these orbits would require an area measuring more than a kilometer on a side—an area equivalent to more than 300 football fields arranged in a grid. Spread over this large area, only the grapefruit-size Sun, the planets, and a few moons would be big enough to see. The rest of the area would look virtually empty (that's why we call it *space*!).

Seeing our solar system to scale also helps put space exploration into perspective. The Moon, the only other world on which humans have ever stepped (Figure 1.6), lies only about 4 centimeters ($1\frac{1}{2}$ inches) from Earth in the Voyage model. On this scale, the palm of your hand can cover the entire region of the universe in which humans have so far traveled. The trip to Mars is more than 150 times as far as the trip to the Moon, even when Mars is on the same side of its orbit as Earth. And while you can walk from Earth to Pluto in just a few minutes on the Voyage scale, the *New Horizons* spacecraft, which flew past Pluto in 2015, took more than 9 years to make the real journey, despite traveling at a speed nearly 100 times that of a commercial jet.



▲ **FIGURE 1.6**
This famous photograph from the first Moon landing (*Apollo 11* in July 1969) shows astronaut Buzz Aldrin, with Neil Armstrong reflected in his visor. Armstrong was the first to step onto the Moon's surface, saying, "That's one small step for a man, one giant leap for mankind." (When asked why this photo became so iconic, Aldrin replied, "Location, location, location!")

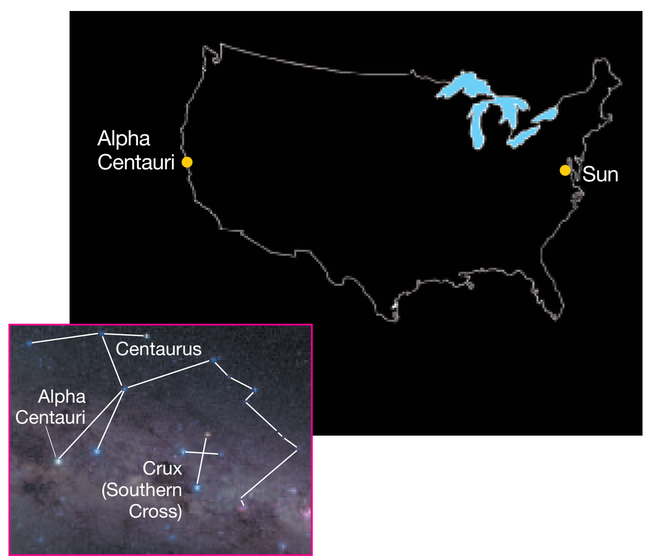
Distance to Stars If you visit the Voyage model in Washington, D.C., you need to walk only about 600 meters to go from the Sun to Pluto. How much farther would you have to walk to reach the next star on this scale?

Amazingly, you would need to walk to California. If this answer seems hard to believe, you can check it for yourself. A light-year is about 10 trillion kilometers, which becomes 1000 kilometers on the 1-to-10-billion scale (because 10 trillion ÷ 10 billion = 1000). The nearest star system to our own, a three-star system called Alpha Centauri (Figure 1.7), is about 4.4 light-years away. That distance is about 4400 kilometers (2700 miles) on the 1-to-10-billion scale, roughly equivalent to the distance across the United States.

The tremendous distances to the stars give us some perspective on the technological challenge of astronomy. For example, because the largest star of the Alpha Centauri system is roughly the same size and brightness as our Sun, viewing it in the night sky is somewhat like being in Washington, D.C., and seeing a very bright grapefruit in San Francisco (neglecting the problems introduced by the curvature of the Earth). It may seem remarkable that we can see this star at all, but the blackness of the night sky allows the naked eye to see it as a faint dot of light. It looks much brighter through powerful telescopes, but we still cannot see features of the star's surface.

Now, consider the difficulty of detecting *planets* orbiting nearby stars, which is equivalent to looking from Washington, D.C., and trying to find ball points or marbles orbiting grapefruits in California or beyond. When you consider this challenge, it is all the more amazing to realize that we now have technology capable of finding such planets [Section 7.1].

The vast distances to the stars also offer a sobering lesson about interstellar travel. Although science fiction shows like *Star Trek* and *Star Wars* make such travel look easy, the reality is far different. Consider the *Voyager 2* spacecraft. Launched in 1977, *Voyager 2* flew by Jupiter in 1979, Saturn in 1981, Uranus in 1986, and Neptune in 1989. It is now bound for the stars at a speed of close to 50,000 kilometers per hour—about 100 times as fast as a speeding bullet. But even at this speed, *Voyager 2* would take about 100,000 years to reach Alpha Centauri if it were headed in that direction (which it's not). Convenient interstellar travel remains well beyond our present technology.



▲ **FIGURE 1.7**
On the same 1-to-10-billion scale on which you can walk from the Sun to Pluto in just a few minutes, you'd need to cross the United States to reach Alpha Centauri, the nearest other star system. The inset shows the location and appearance of Alpha Centauri among the constellations.

The Size of the Milky Way Galaxy We must change our scale to visualize the galaxy, because very few stars would even fit on Earth with the 1-to-10-billion

▲ **FIGURE 1.8**
This painting shows the Milky Way Galaxy on a scale where its diameter is the length of a football field. On this scale, stars are microscopic and the distance between our solar system and Alpha Centauri is only 4.4 millimeters. There are so many stars in our galaxy that it would take thousands of years just to count them out loud.

▲ **FIGURE 1.9**
The number of stars in the observable universe is comparable to the number of grains of dry sand on all the beaches on Earth.

scale we used to visualize the solar system. Let's therefore reduce our scale by another factor of 1 billion (making it a scale of 1 to 10^{19}).

On this new scale, each light-year becomes 1 millimeter, and the 100,000-light-year diameter of the Milky Way Galaxy becomes 100 meters, or about the length of a football field. Visualize a football field with a scale model of our galaxy centered over midfield (Figure 1.8). Our entire solar system is a microscopic dot located around the 20-yard line. The 4.4-light-year separation between our solar system and Alpha Centauri becomes just 4.4 millimeters on this scale—smaller than the width of your little finger. If you stood at the position of our solar system in this model, millions of star systems would lie within reach of your arms.

Another way to put the galaxy into perspective is to consider its number of stars—more than 100 billion. Imagine that tonight you are having difficulty falling asleep (perhaps because you are contemplating the scale of the universe). Instead of counting sheep, you decide to count stars. If you are able to count about one star each second, how long would it take you to count 100 billion stars in the Milky Way? Clearly, the answer is 100 billion (10^{11}) seconds, but how long is that? Amazingly, 100 billion seconds is more than 3000 years. (You can confirm this by dividing 100 billion by the number of seconds in 1 year.) You would need thousands of years just to *count* the stars in the Milky Way Galaxy, and this assumes you never take a break—no sleeping, no eating, and absolutely no dying!

The Observable Universe As incredible as the scale of our galaxy may seem, the Milky Way is only one of more than 100 billion large galaxies in the observable universe. Just as it would take thousands of years to count the stars in the Milky Way, it would take thousands of years to count all these galaxies.

Think for a moment about the total number of stars in all these galaxies. If we assume 100 billion galaxies and 100 billion stars per galaxy, the total number of stars in the observable universe is roughly 100 billion × 100 billion, or 10,000,000,000,000,000,000,000 (10^{22}). How big is this number? Visit a beach. Run your hands through the fine-grained sand. Imagine counting each tiny grain of sand as it slips through your fingers. Then imagine counting every grain of sand on the beach and continuing to count *every* grain of dry sand on *every* beach on Earth. If you could actually complete this task, you would find that the number of grains of sand was comparable to the number of stars in the observable universe (Figure 1.9).

think about it Contemplate the incredible numbers of stars in our galaxy and in the universe, and the fact that each star is a potential sun for a system of planets. How does this perspective affect your thoughts about the possibilities for finding life—or intelligent life—beyond Earth? Explain.

1.2 The History of the Universe

Our universe is vast not only in space, but also in time. In this section, we will briefly discuss the history of the universe as we understand it today.

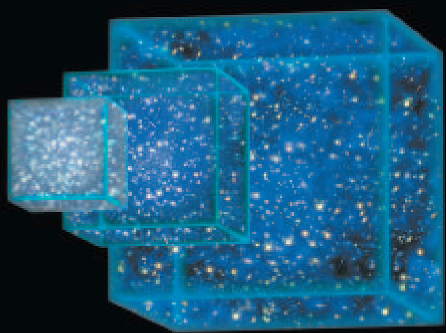
◆ How did we come to be?

Figure 1.10 summarizes the history of the universe according to modern science. Let's start at the upper left of the figure, and discuss the key events and what they mean.

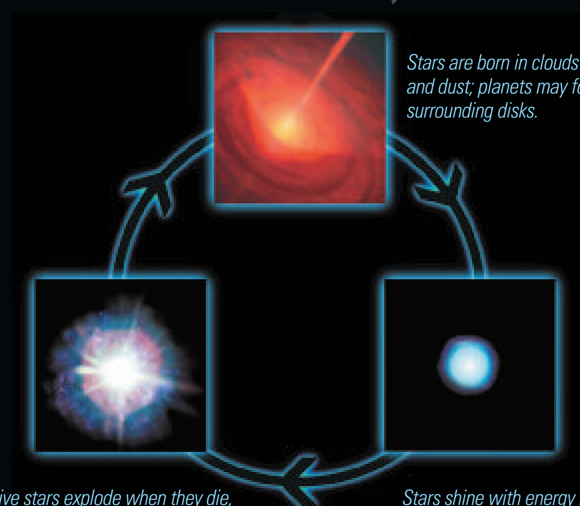
Our Cosmic Origins

▼ **FIGURE 1.10**

Birth of the Universe: The expansion of the universe began with the hot and dense Big Bang. The cubes show how one region of the universe has expanded with time. The universe continues to expand, but on smaller scales gravity has pulled matter together to make galaxies.



Galaxies as Cosmic Recycling Plants: The early universe contained only two chemical elements: hydrogen and helium. All other elements were made by stars and recycled from one stellar generation to the next within galaxies like our Milky Way.



Life Cycles of Stars: Many generations of stars have lived and died in the Milky Way.

Earth and Life: By the time our solar system was born, $4\frac{1}{2}$ billion years ago, about 2% of the original hydrogen and helium had been converted into heavier elements. We are therefore "star stuff," because we and our planet are made from elements manufactured in stars that lived and died long ago.

common misconceptions

Confusing Very Different Things

Most people are familiar with the terms *solar system* and *galaxy*, but few realize how incredibly different they are. Our solar system is a single star system, while our galaxy is a collection of more than 100 billion star systems—so many that it would take thousands of years just to count them. Moreover, if you look at the sizes in Figure 1.1, you'll see that our galaxy is about 100 million times larger in diameter than our solar system. So be careful; numerically speaking, mixing up *solar system* and *galaxy* is a gigantic mistake!

The Big Bang, Expansion, and the Age of the Universe Telescopic observations of distant galaxies show that the entire universe is *expanding*, meaning that average distances between galaxies are increasing with time. This fact implies that galaxies must have been closer together in the past, and if we go back far enough, we must reach the point at which the expansion began. We call this beginning the **Big Bang**, and scientists use the observed rate of expansion to calculate that it occurred about 14 billion years ago. The three cubes in the upper left corner of Figure 1.10 represent the expansion of a small piece of the entire universe through time.

The universe as a whole has continued to expand ever since the Big Bang, but on smaller scales the force of gravity has drawn matter together. Structures such as galaxies and galaxy clusters occupy regions where gravity has won out against the overall expansion. That is, while the universe as a whole continues to expand, individual galaxies and galaxy clusters (and objects within them such as stars and planets) do *not* expand. This idea is also illustrated by the three cubes in Figure 1.10. Notice that as the cube as a whole grew larger, the matter within it clumped into galaxies and galaxy clusters. Most galaxies, including our own Milky Way, formed within a few billion years after the Big Bang.

tools of science — Doing the Math

Mathematics is one of the most important tools of science, because it allows scientists to make precise, numerical predictions that can be tested through observations or experiments. These types of tests make it possible for us to gain confidence in scientific ideas. That is why the development of science and mathematics has often gone hand in hand. For example, Sir Isaac Newton developed the mathematics of calculus so that he could do the calculations necessary to test his theory of gravity, and Einstein used new mathematical ideas to work out the details of his general theory of relativity. Fortunately, you don't have to be a Newton or an Einstein to benefit from mathematics in science. Calculations using only multiplication and division can still provide important insights into scientific ideas. Let's look at a few examples.

EXAMPLE 1: How far is a light-year?

Solution: A light-year (ly) is the distance that light can travel in one year; recall that light travels at the *speed of light*, which is 300,000 km/s. Just as we can find the distance that a car travels in 2 hours by multiplying the car's speed by 2 hours, we can find a light-year by multiplying the speed of light by 1 year. Because we are given the speed of light in kilometers per second, we must carry out the multiplication while converting 1 year into seconds (see Appendix C for a review of unit conversions). The result is

$$
\begin{aligned}
1\text{ ly} &= \left(300{,}000\,\frac{\text{km}}{\text{s}}\right) \times (1\text{ yr}) \\
&= \left(300{,}000\,\frac{\text{km}}{\cancel{\text{s}}}\right) \times \left(1\,\cancel{\text{yr}} \times 365\,\frac{\cancel{\text{day}}}{\cancel{\text{yr}}} \times 24\,\frac{\cancel{\text{hr}}}{\cancel{\text{day}}} \times 60\,\frac{\cancel{\text{min}}}{\cancel{\text{hr}}} \times 60\,\frac{\cancel{\text{s}}}{\cancel{\text{min}}}\right) \\
&= 9{,}460{,}000{,}000{,}000\text{ km}
\end{aligned}
$$

That is, 1 light-year is equivalent to 9.46 trillion kilometers, which is easier to remember as almost 10 trillion kilometers.

EXAMPLE 2: How big is the Sun on the 1-to-10-billion scale?

Solution: The Sun's actual radius is 695,000 km, which we express in scientific notation as 6.95×10^5 km. (See Appendix C to review powers of 10 and scientific notation.) To find the Sun's radius on the 1-to-10-billion scale, we divide its actual radius by 10 billion, or 10^{10}:

$$
\begin{aligned}
\text{scaled radius} &= \frac{\text{actual radius}}{10^{10}} \\
&= \frac{6.95 \times 10^5\text{ km}}{10^{10}} \\
&= 6.95 \times 10^{(5-10)}\text{ km} \\
&= 6.95 \times 10^{-5}\text{ km}
\end{aligned}
$$

This answer is easier to interpret if we convert it to centimeters, which we can do by recalling that there are 1000 ($= 10^3$) meters in a kilometer and 100 ($= 10^2$) centimeters in a meter:

$$
6.95 \times 10^{-5}\,\cancel{\text{km}} \times \frac{10^3\,\cancel{\text{m}}}{1\,\cancel{\text{km}}} \times \frac{10^2\text{ cm}}{1\,\cancel{\text{m}}} = 6.95\text{ cm}
$$

On the 1-to-10-billion scale, the Sun is just under 7 centimeters in radius, or 14 centimeters in diameter.

EXAMPLE 3: How fast is Earth orbiting the Sun?

Solution: Earth completes one orbit in 1 year, so we can find its average orbital speed by dividing the circumference of its orbit by 1 year. Earth's orbit is nearly circular with a radius of 1 AU ($= 1.5 \times 10^8$ km); the circumference of a circle is given by the formula $2\pi \times$ radius. If we want the speed to come out in units of km/hr, we divide this circumference by 1 year converted to hours, as follows:

$$
\begin{aligned}
\text{orbital speed} &= \frac{\text{orbital circumference}}{1\text{ yr}} \\
&= \frac{2 \times \pi \times (1.5 \times 10^8\text{ km})}{1\,\cancel{\text{yr}} \times \dfrac{365\,\cancel{\text{day}}}{\cancel{\text{yr}}} \times \dfrac{24\text{ hr}}{\cancel{\text{day}}}} \\
&\approx 107{,}000\text{ km/hr}
\end{aligned}
$$

Earth's average speed as it orbits the Sun is more than 100,000 km/hr.

Stellar Lives and Galactic Recycling Within galaxies like the Milky Way, gravity drives the collapse of clouds of gas and dust to form stars and planets. Stars are not living organisms, but they nonetheless go through "life cycles." A star is born when gravity compresses the material in a cloud to the point at which the center becomes dense enough and hot enough to generate energy by **nuclear fusion**, the process in which lightweight atomic nuclei smash together and stick (or fuse) to make heavier nuclei. The star "lives" as long as it can shine with energy from fusion, and "dies" when it exhausts its usable fuel.

In its final death throes, a star blows much of its content back out into space. The most massive stars die in titanic explosions called *supernovae*. The returned matter mixes with other matter floating between the stars in the galaxy, eventually becoming part of new clouds of gas and dust from which new generations of stars can be born. Galaxies therefore function as cosmic recycling plants, recycling material expelled from dying stars into new generations of stars and planets. This cycle is illustrated in the lower right of Figure 1.10. Our own solar system is a product of many generations of such recycling.

Star Stuff The recycling of stellar material is connected to our existence in an even deeper way. By studying stars of different ages, we have learned that the early universe contained only the simplest chemical elements: hydrogen and helium (and a trace of lithium). We and Earth are made primarily of other elements, such as carbon, nitrogen, oxygen, and iron. Where did these other elements come from? Evidence shows that they were manufactured by stars, some through the nuclear fusion that makes stars shine and most others through nuclear reactions accompanying the explosions that end stellar lives.

By the time our solar system formed, about $4\frac{1}{2}$ billion years ago, earlier generations of stars had already converted up to 2% of our galaxy's original hydrogen and helium into heavier elements. Therefore, the cloud that gave birth to our solar system was made of roughly 98% hydrogen and helium and 2% other elements. This 2% may sound small, but it was more than enough to make the small rocky planets of our solar system, including Earth. On Earth, some of these elements became the raw ingredients of life, which ultimately blossomed into the great diversity of life on Earth today.

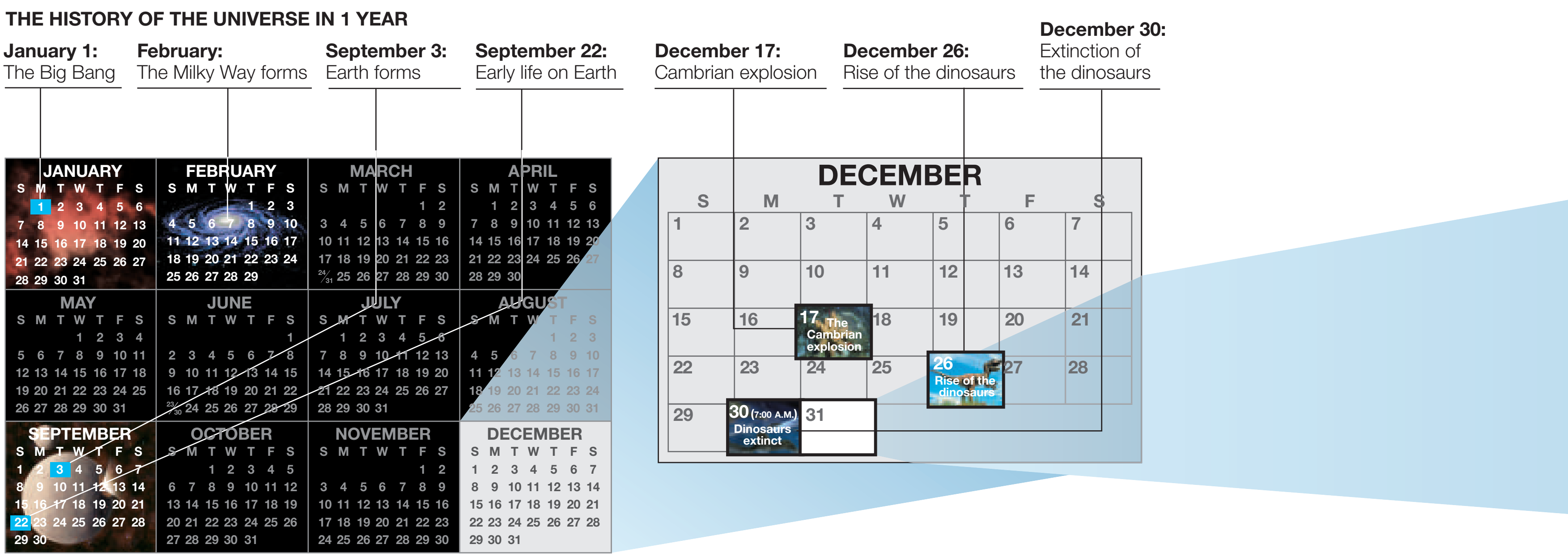
In summary, most of the material from which we and our planet are made was created inside stars that lived and died before the birth of our Sun. As astronomer Carl Sagan (1934–1996) said, we are "star stuff."

◆ How do our lifetimes compare to the age of the universe?

We can put the 14-billion-year age of the universe into perspective by imagining this time compressed into a single year, so each month represents a little more than 1 billion years. On this *cosmic calendar*, the Big Bang occurs at the first instant of January 1 and the present is the stroke of midnight on December 31 (Figure 1.11).

On this time scale, the Milky Way Galaxy probably formed in February. Many generations of stars lived and died in the subsequent cosmic months, enriching the galaxy with the "star stuff" from which we and our planet are made.

Our solar system and our planet did not form until early September on this scale, or $4\frac{1}{2}$ billion years ago in real time. By late September, life on Earth was flourishing. However, for most of Earth's history, living organisms remained relatively primitive and microscopic. On the scale of the cosmic calendar, recognizable animals became prominent only in mid-December. Early dinosaurs appeared on the day after Christmas. Then, in a cosmic instant, the dinosaurs disappeared forever—probably because of the impact of an asteroid or a comet [Section 6.3]. In real time the death of the dinosaurs occurred some 65 million years ago, but on the cosmic calendar it was only yesterday. With the dinosaurs gone, small furry mammals



▲ **FIGURE 1.11**
The cosmic calendar compresses the 14-billion-year history of the universe into 1 year, so that each month represents a little more than 1 billion years. (Adapted from the cosmic calendar created by Carl Sagan. For a more detailed version, see the "You Are Here in Time" foldout diagram in the front of the book.)

inherited Earth. Some 60 million years later, or at around 9 P.M. on December 31 of the cosmic calendar, early hominids (human ancestors) began to walk upright.

Perhaps the most astonishing thing about the cosmic calendar is that the entire history of human civilization falls into just the last half-minute. The ancient Egyptians built the pyramids only about 11 seconds ago on this scale. About 1 second ago, Kepler and Galileo proved that Earth orbits the Sun rather than vice versa. The average college student was born about 0.05 second ago, around 11:59:59.95 P.M. on the cosmic calendar. On the scale of cosmic time, the human species is the youngest of infants, and a human lifetime is a mere blink of an eye.

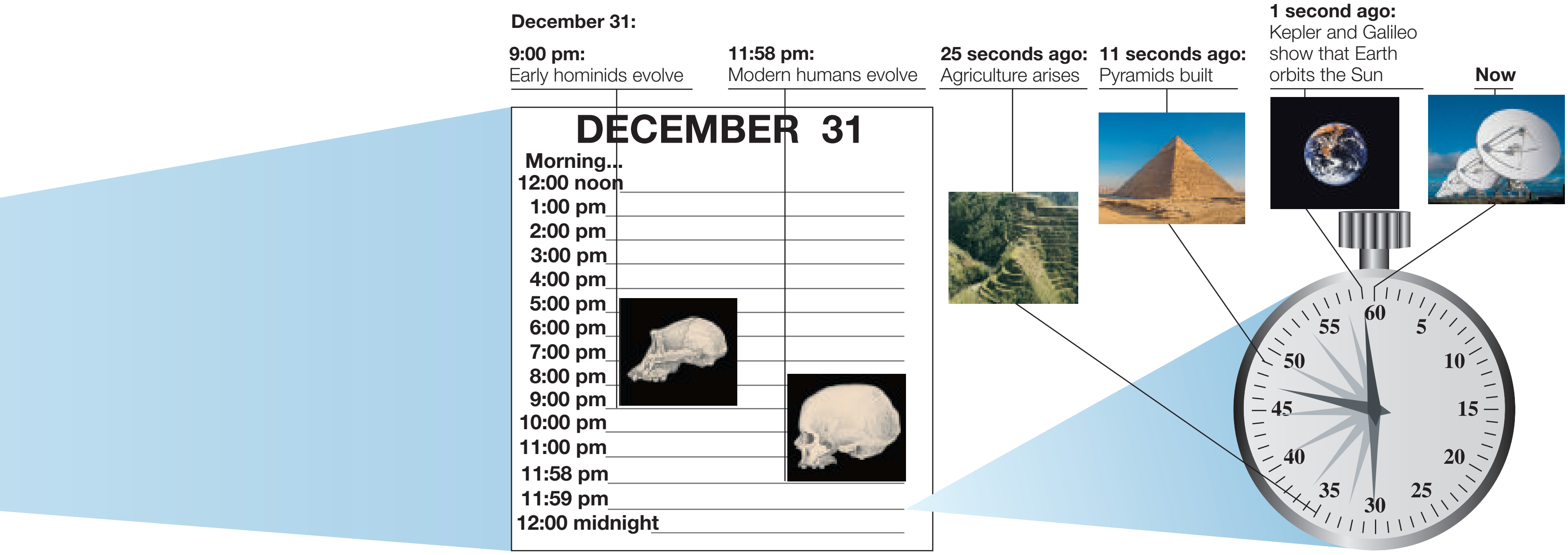
think about it Study the more detailed cosmic calendar found on the foldout in the front of this book. How does an understanding of the scale of time affect your view of human civilization? Explain.

THE PROCESS OF SCIENCE IN ACTION

1.3 Defining Planets

One of the goals of this book is to help you learn more about science in general as you study the science of astronomy. We will therefore conclude each chapter with a case study that illustrates the process of science in action. Here, we look at the process of scientific classification, focusing on the challenge of defining the seemingly simple term *planet*.

Science begins with observations of the world around us, and after observing we often try to classify the objects we find. Scientific classification helps us organize our thinking and provides a common language for discussion. In this chapter, we have already classified objects into categories such as planets, stars, and galaxies. The box on page 5 provides basic definitions for these categories but does not explain *how* we came to classify objects in this way. The story behind the definition of *planet* provides an excellent example of how scientists classify objects and how scientific classification must adapt to new discoveries.



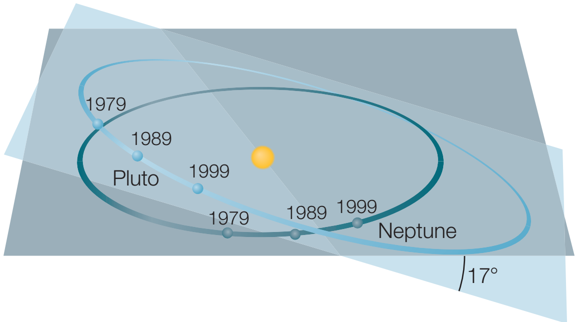
◆ What is a planet?

The difference between a star and a planet is not obvious from a casual glance at the night sky. In fact, the term *star* historically applied to almost any shining object in the night sky, including the planets and even the brief flashes of light known as "shooting stars" (or *meteors*), which we now know to be caused by comet dust entering Earth's atmosphere. To the naked eye, the difference between stars and planets becomes clear only if you observe the sky over a period of many days or weeks: Stars remain fixed in the patterns of the constellations, while planets appear to move slowly among the constellations of stars [Section 2.3].

Planets as Wanderers The word *planet* comes from the Greek for "wanderer," and in ancient times it applied to all objects that appear to move, or wander, among the constellations. The Sun and the Moon were counted as planets, because they move steadily through the constellations. Earth did *not* count as a planet, since it is not something we see in the sky and it was presumed to be stationary at the center of the universe. Ancient observers therefore recognized seven objects as planets: the Sun, the Moon, and the five planets that are easily visible to the naked eye (Mercury, Venus, Mars, Jupiter, and Saturn). The special status of these seven objects is still enshrined in the names of the seven days of the week. In English, only Sunday, "Moonday," and "Saturnday" are obvious, but if you know a romance language like Spanish you'll be able to figure out the rest: Tuesday is Mars day (martes), Wednesday is Mercury day (miércoles), Thursday is Jupiter day (jueves), and Friday is Venus day (viernes).

This original definition of *planet* began to change about 400 years ago, when we learned that Earth is *not* the center of the universe but rather an object that orbits the Sun. The term *planet* then came to mean any object that orbits the Sun, which added Earth to the list of planets and removed the Sun and Moon (because the Moon orbits Earth). This definition successfully accommodated the planets Uranus and Neptune after their discoveries in 1781 and 1846, respectively, and it can also be easily adapted for planets around other stars.

A weakness of this definition became apparent as scientists began to discover asteroids, starting with the discovery of Ceres in 1801. Ceres was initially hailed



▲ **FIGURE 1.12**
Pluto's orbit is significantly elongated and tilted with respect to those of the other planets. Pluto even comes closer than Neptune to the Sun for 20 years in each 248-year orbit, as was the case between 1979 and 1999. There's no danger of a collision, however, because Neptune completes exactly three orbits for every two of Pluto's orbits.

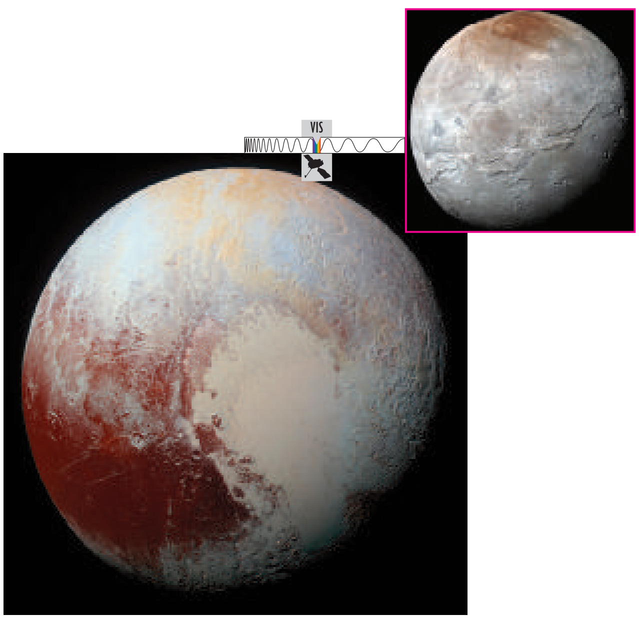
as a new "planet," but as the number of known asteroids grew—and as we realized that asteroids were all much smaller than the traditional planets—scientists decided that these relatively small worlds should count only as "minor planets." Today we refer to "minor planets" as asteroids or comets, depending on their composition, though larger ones, such as Ceres, also qualify as *dwarf planets*.

The Case of Pluto The most recent change in the definition of *planet* comes from the story of Pluto. Pluto was quickly given planetary status upon its discovery in 1930, partly because astronomers were actively searching for a planet but also because they initially overestimated its mass. Still, it was clear from the start that Pluto was a misfit among the known planets. Its 248-year orbit around the Sun is more elongated in shape than that of any other planet. Its orbit is also significantly tilted relative to the orbits of the other planets (Figure 1.12). It became even more of a misfit after astronomers pinned down its mass and composition: Pluto is only about $\frac{1}{25}$ as massive as Mercury, smallest of the first eight planets, and its ice-rich composition is more similar to that of a comet than to that of any of the other planets.

Pluto's low mass, unusual orbit, and comet-like composition eventually began to cause controversy over its status as a planet. Scientists had known since the 1950s that many of the comets that we see in the inner solar system come from the same region of the solar system in which Pluto orbits (called the *Kuiper belt* **[Section 4.1]**). By the 1990s, advancing telescope technology had made it possible for astronomers to discover vast numbers of objects orbiting within the Kuiper belt, including some that were not much smaller than Pluto. Then, in 2005, astronomer Mike Brown announced the discovery of Eris, which is slightly more massive than Pluto. This discovery forced astronomers to consider the question of whether Eris and other objects similar in size to Pluto should count as planets.

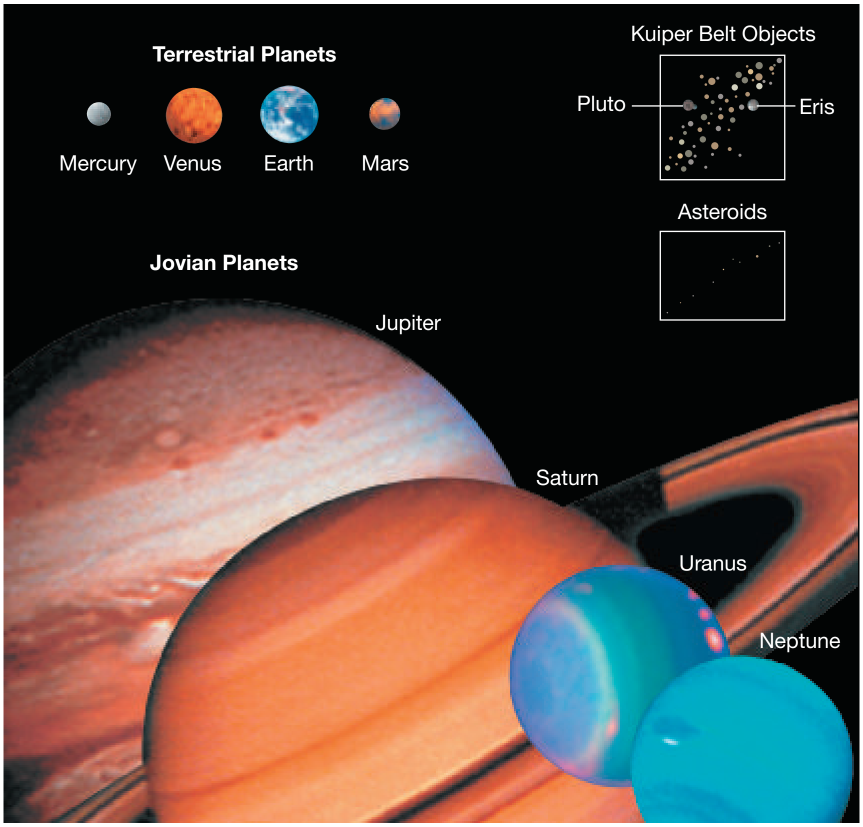
Decisions on astronomical names and definitions are officially made by the International Astronomical Union (IAU), which is made up of astronomers from nations around the world. Members of the IAU considered numerous possible definitions of the term *planet*. One proposed definition would have applied the term to any object large enough for its own gravity to make it round. Proponents of this definition argued that it would make planetary status depend only on an object's intrinsic characteristics (as opposed to also including orbital properties), and that roundness is a good indicator of whether an object is large enough to have had any "planet-like" geological activity during its history; this latter idea was confirmed by the dramatic images of Pluto and its moon Charon obtained by the *New Horizons* spacecraft during its 2015 flyby (Figure 1.13). Those arguing against this definition pointed out that, in addition to significantly raising the official number of planets in our solar system, it would also have meant counting numerous large moons — including Earth's Moon — as planets.

The definition that ultimately won out (in an IAU vote held in 2006) focused on both size and orbits, defining a planet as an object that (1) orbits a star (but is not itself a star),* (2) is massive enough for its own gravity to make it round, and (3) dominates its orbital region. This definition leaves out moons because they orbit planets rather than stars, and it leaves out Pluto and Eris because, although they orbit the Sun and are round, they share their orbital region with many similarly sized objects.



▲ **FIGURE 1.13**
Pluto and its largest moon, Charon (shown to scale), as seen by the *New Horizons* spacecraft during its 2015 flyby of them. As we'll discuss further in Chapter 6, the visible surface features offer clear evidence that both worlds have had interesting geological histories, and Pluto may have ongoing geological activity.

*The officially adopted definition refers only to objects orbiting *our Sun*, but astronomers have generally applied the definition in a way that also allows us to refer to "planets" orbiting other stars.



▲ **FIGURE 1.14**
Relative sizes of various objects in the solar system. Notice that the eight planets divide clearly into two groups, known as the *jovian planets* (Jupiter, Saturn, Uranus, and Neptune) and the *terrestrial planets* (Mercury, Venus, Earth, and Mars). Pluto and Eris clearly belong to a group of much smaller but more numerous objects.

Future Challenges The adopted definition of *planet* still stirs some controversy, but it works well in dividing the objects of our solar system by size: Figure 1.14 shows that the eight planets clearly divide into two groups, while Pluto and Eris clearly belong to a different group. Nevertheless, the current definition is likely to face future challenges, including one that may arise fairly soon. Over the past few years, astronomers have discovered that many small objects in the outer solar system appear to be following an orbital pattern suggesting that they are being tugged on by the gravity of an undiscovered object at least several times as massive as Earth. As this book goes to press, astronomers are actively searching for such an object, which has been called "planet nine." But note that, if it really exists, this object would likely be sharing the same general region of the solar system with many other ice-rich objects, which would mean it would not count as a planet under the current definition, despite its large size. And even if this object turns out not to exist in our solar system, we will probably find similar objects in other solar systems, forcing us once again to reconsider the definition of a planet.

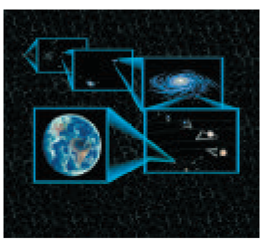
Perhaps the most important scientific idea to take away from this debate is that nature need not obey the classification systems we propose. Whether we call an object like Pluto a planet, a dwarf planet, or a large comet may affect the way we think about it, but it does not change what it actually is or our scientific interest in it. A key part of science is learning to adapt our own notions of organization to the underlying reality of nature. As we discover new things, we must sometimes change our definitions.

think about it How would *you* define "planet," and why? Defend your choice.

summary of key concepts

1.1 The Scale of the Universe

◆ What is our place in the universe?



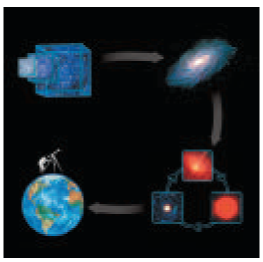
Earth is a planet orbiting the Sun. Our Sun is one of more than 100 billion stars in the **Milky Way Galaxy**. Our galaxy is one of more than 70 galaxies in the **Local Group**. The Local Group is one small part of the **Local Supercluster**, which is one small part of the **universe**.

◆ How big is the universe?

On a 1-to-10-billion scale, the Sun is the size of a grapefruit, Earth is a ball point about 15 meters away, and the nearest stars are thousands of kilometers away. Our galaxy has so many stars that it would take thousands of years just to count them out loud. The **observable universe** contains more than 100 billion galaxies, and the total number of stars is comparable to the number of grains of dry sand on all the beaches on Earth.

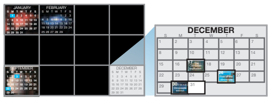
1.2 The History of the Universe

◆ How did we come to be?



The universe began in the **Big Bang** and has been expanding ever since, except in localized regions where gravity has caused matter to collapse into galaxies and stars. The Big Bang essentially produced only two chemical elements: hydrogen and helium. The rest have been produced by stars and recycled within galaxies from one generation of stars to the next, which is why we are "star stuff."

◆ **How do our lifetimes compare to the age of the universe?**

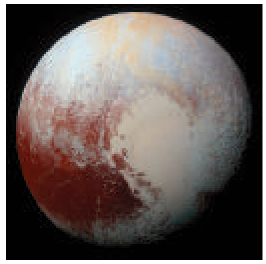


On a cosmic calendar that compresses the history of the universe into 1 year, human civilization is just a few seconds old, and a human lifetime lasts only a fraction of a second.

THE PROCESS OF SCIENCE IN ACTION

1.3 Defining Planets

◆ **What is a planet?**



The definition of the term *planet* has changed over time. It originally referred to objects that wandered among the constellations, but now applies to Earth and seven other objects in our solar system, while Pluto, Eris, and similar objects are classified as *dwarf planets*. The definition may yet change again, showing how scientific classification must adapt to new discoveries.

Investigations

For instructor-assigned homework and other learning materials, go to www.MasteringAstronomy.com.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning.

1. Which of the following correctly lists our "cosmic address" from smallest to largest? (a) Earth, solar system, Milky Way Galaxy, Local Group, Local Supercluster, universe (b) Earth, solar system, Local Group, Local Supercluster, Milky Way Galaxy, universe (c) Earth, Milky Way Galaxy, solar system, Local Group, Local Supercluster, universe
2. An *astronomical unit* is (a) any planet's average distance from the Sun. (b) Earth's average distance from the Sun. (c) any large astronomical distance.
3. A *light-year* is (a) about 10 trillion kilometers. (b) the time it takes light to reach the nearest star. (c) the time it takes light to travel around the Sun.
4. The star Betelgeuse is about 600 light-years away. If it explodes tonight, (a) we'll know because it will be brighter than the full Moon. (b) we'll know because debris from the explosion will rain down on us from space. (c) we won't know about it until about 600 years from now.
5. Could we see a galaxy that is 50 billion light-years away? (a) Yes, if we had a big enough telescope. (b) No, because it would be beyond the bounds of our observable universe. (c) No, because a galaxy could not possibly be that far away.
6. If we represent the solar system on a scale that allows us to walk from the Sun to Pluto in a few minutes, then (a) the planets are the size of basketballs and the nearest stars are a few miles away. (b) the planets are marble size or smaller and the nearest stars are thousands of miles away. (c) the planets are microscopic and the stars are millions of miles away.
7. The number of stars in the Milky Way Galaxy is roughly (a) 100,000. (b) 100 million. (c) 100 billion.
8. When we say the universe is *expanding*, we mean that (a) everything in the universe is growing in size. (b) the average distance between galaxies is growing with time. (c) the universe is getting older.
9. The *Big Bang* is the name astronomers give to (a) the explosion that occurs when a star dies. (b) the largest explosion ever observed. (c) the birth of the universe.
10. We are "star stuff" in the sense that (a) we are made of elements that were produced in stars. (b) our bodies have the same chemical composition as stars. (c) we are born, live, and die, just like stars.
11. The age of our solar system is about (a) $\frac{1}{3}$ of the age of the universe. (b) $\frac{3}{4}$ of the age of the universe. (c) the same as the age of the universe.
12. The event that triggered the change in Pluto's status from planet to dwarf planet was the discovery that (a) it is smaller than the planet Mercury. (b) it has a comet-like composition of ice and rock. (c) it is not the most massive object in its region of the solar system.

Short-Answer/Essay Questions

Explain all answers clearly, using complete sentences and proper essay structure if needed. An asterisk (*) designates a quantitative problem, for which you should show all your work.

13. *Our Cosmic Origins.* Write one to three paragraphs summarizing why we could not be here if the universe did not contain both stars and galaxies.
14. *Alien Technology.* Some people believe that Earth is regularly visited by aliens who travel here from other star systems. For this to be true, how much more advanced than our own technology would the alien space travel technology have to be? Write one to two paragraphs to give a sense of the technological difference. (*Hint:* The ideas of scale in this chapter can help you contrast the distance the aliens would have to travel with the distances we currently are capable of traveling.)
15. *Looking for Evidence.* In this first chapter, we have discussed the scientific story of the universe but have not yet discussed most of the evidence that backs it up. Choose one idea from this chapter—such as the idea that there are billions of galaxies, that the universe was born in the Big Bang, or that we are "star stuff"—and briefly discuss the type of evidence you would like to see before accepting the idea. (*Hint:* It's okay to look ahead in the book to see the evidence presented in later chapters.)
16. *The Value of Classification.* Section 1.3 discussed difficulties that can arise with attempts to define scientific classifications precisely, such as those that occur with the term *planet*. Make a bullet list of pros and cons (at least three of each) of having classification schemes. Then write a one-paragraph summary stating your opinion of the value (or lack of value) of scientific classification.
17. *The Cosmic Perspective.* Write a one-page essay describing how the ideas presented in this chapter affect your perspectives on your own life and on human civilization.

*18. *Light-Minute.* Just as a light-year is the distance that light can travel in 1 year, a light-minute is the distance that light can travel in 1 minute. What is a light-minute in kilometers?

*19. *Sunlight.* Use the speed of light and the Earth–Sun distance of 1 AU to calculate how long it takes light to travel from the Sun to Earth.

*20. *Cosmic Calendar.* The cosmic calendar condenses the 14-billion-year history of the universe into 1 year. How long does 1 second represent on the cosmic calendar?

*21. *Saturn vs. the Milky Way.* Photos of Saturn with its rings can look so similar to photos of galaxies that children often think they are similar objects, but of course galaxies are far larger. About how many times larger in diameter is the Milky Way Galaxy than Saturn's rings? (*Data:* Saturn's rings are 270,000 km in diameter; the Milky Way is 100,000 light-years in diameter.)

*22. *Galactic Rotation.* Our solar system is located about 27,000 light-years from the galactic center and orbits the center once every 230 million years. How fast are we traveling around the galaxy, in km/hr?

Understanding the Sky

2

This time-exposure photo, taken at Arches National Park in Utah, shows how the entire sky seems to circle daily around a point above Earth's North Pole (or South Pole, for the Southern Hemisphere). Stars far to the north, like those visible within the arch, complete their entire circles above the northern horizon. Other stars—along with the Sun, Moon, and planets—follow circles that cross the horizon, which is why they rise in the east and set in the west each day. This daily circling of the sky explains why most of our ancestors assumed that the universe revolved around Earth. Today, we know that it is actually Earth's daily rotation that makes the sky appear to turn. How did we learn this fact? Through careful study of other, more subtle patterns of change in the sky, including the patterns we will study in this chapter.

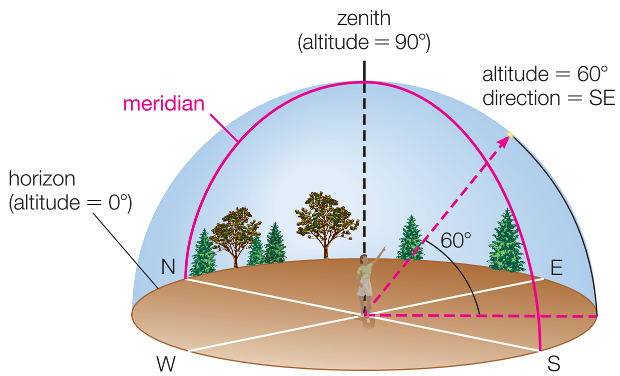
LEARNING GOALS

2.1 Understanding the Seasons
- What causes the seasons?
- Why do the constellations we see depend on the time of year?

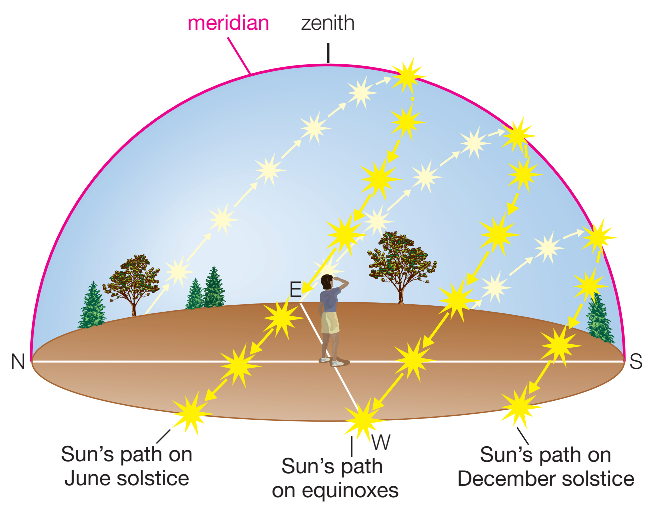
2.2 Understanding the Moon
- Why do we see phases of the Moon?
- What causes eclipses?

THE PROCESS OF SCIENCE IN ACTION

2.3 The Puzzle of Planetary Motion
- Why did the ancient Greeks reject the real explanation for planetary motion?



▲ **FIGURE 2.1**
From any place on Earth, the local sky looks like a dome (hemisphere). This diagram shows key reference points in the local sky. It also shows how we can describe any position in the local sky by its altitude and direction.



▲ **FIGURE 2.2**
This diagram shows the Sun's path in different seasons for a Northern Hemisphere location (latitude 40°N). The precise paths are different for other latitudes.

Discovering the Universe for Yourself

2.1 Understanding the Seasons

We're all familiar with seasonal changes, such as longer and warmer days in summer and shorter and cooler days in winter. But *why* do the seasons occur? We'll explore the answer in this section.

◆ What causes the seasons?

Seasons are a result of the way the tilt of Earth's axis causes sunlight to fall differently on Earth at different times of year. To understand exactly how this works, we'll first look at how Earth's rotation produces the apparent daily path of the Sun through the sky, then examine how Earth's axis tilt and orbit cause this path to change over the course of each year.

The Sun's Daily Path The general pattern of the Sun's daily path through the sky is fairly simple: Unless you live within the Arctic or Antarctic circle, the Sun always rises somewhere in the east, reaches its highest point around noon, then sets somewhere in the west. Ancient people assumed that the Sun actually circled Earth each day, but we now know that its daily motion arises from Earth's rotation. Just as the world seems to circle around you if you spin in place, the Sun seems to go around us on our rotating planet. However, while the general pattern is always the same, the Sun's precise path through the sky varies with the seasons.

To describe the Sun's daily path more clearly, we need to define a few key reference points in the sky (Figure 2.1). The boundary between Earth and sky defines the **horizon**. The point directly overhead is the **zenith**. The **meridian** is an imaginary half-circle stretching from the horizon due south, through the zenith, to the horizon due north. We can pinpoint the position of any object in the sky by stating its *direction* along the horizon (sometimes expressed as *azimuth*) and its *altitude* above the horizon.

Figure 2.2 shows how the Sun's daily path differs at different times of year for a typical Northern Hemisphere location. Notice that the Sun's path is long and high in summer, with the Sun rising well north of due east and setting well north of due west. In winter, the Sun's path is short and low, as it rises well south of due east and sets well south of due west. Notice also that the Sun *never* passes directly overhead at this latitude. The Sun can reach the zenith only for locations within the *tropics,* meaning locations on Earth that are between latitudes of $23\frac{1}{2}$°N and $23\frac{1}{2}$°S.

The Reason for Seasons

The Reason for Seasons The causes of these seasonal changes in the Sun's path are summarized in the four steps of Figure 2.3 (pp. 20–21). Step 1 illustrates how Earth's rotation axis is tilted with respect to its orbit. Notice that the axis remains pointed in the same direction in space (toward the North Star, Polaris) throughout the year. As a result, the orientation of the axis *relative to the Sun* changes over the course of each orbit: The Northern Hemisphere is tipped toward the Sun in June and away from the Sun in December, while the reverse is true for the Southern Hemisphere. That is why the two hemispheres experience opposite seasons.

Step 2 shows Earth in June, when the axis tilt causes sunlight to strike the Northern Hemisphere at a steeper angle and the Southern Hemisphere at a shallower angle. The steeper sunlight angle makes it summer in the Northern Hemisphere, for two reasons. First, as shown in the zoom-out, the steeper angle means more concentrated sunlight, which tends to make it warmer. Second, if you visualize what happens as Earth rotates each day, you'll see that the steeper angle also means the Sun follows a longer and higher path through the sky (the path shown for June in Figure 2.2), giving the Northern Hemisphere more hours of daylight during which it is warmed by the Sun. The opposite is true for the Southern Hemisphere at this time: The shallower sunlight angle makes it winter there, because sunlight is less concentrated and the Sun follows a shorter, lower path through the sky.

The sunlight angle gradually changes as Earth orbits the Sun. At the opposite side of Earth's orbit, Step 4 shows that it has become winter for the Northern Hemisphere and summer for the Southern Hemisphere. In between these two extremes, Step 3 shows that both hemispheres are illuminated equally in March and September. It is therefore spring for the hemisphere that is on the way from winter to summer, and fall for the hemisphere on the way from summer to winter.

The key point is this: Seasons occur because of the combination of Earth's axis tilt and its orbit around the Sun. If Earth did not have an axis tilt, we would not have seasons.

think about it Jupiter has an axis tilt of about 3°, small enough to be insignificant. Saturn has an axis tilt of about 27°, slightly greater than that of Earth. Both planets have nearly circular orbits around the Sun. Do you expect Jupiter to have seasons? Do you expect Saturn to have seasons? Explain.

Solstices and Equinoxes

To help us mark the changing seasons, we define four special moments in the year, each of which corresponds to one of the four special positions in Earth's orbit shown in Figure 2.3.

- The **June solstice**, called the *summer solstice* in the Northern Hemisphere, occurs around June 21 and is the moment when the Northern Hemisphere is tipped most directly toward the Sun and receives the most direct sunlight.
- The **December solstice**, called the *winter solstice* in the Northern Hemisphere, occurs around December 21 and is the moment when the Northern Hemisphere receives the least direct sunlight.
- The **March equinox**, called the *spring* (or *vernal*) *equinox* in the Northern Hemisphere, occurs around March 21 and is the moment when the Northern Hemisphere goes from being tipped slightly away from the Sun to being tipped slightly toward the Sun.
- The **September equinox**, called the *fall* (or *autumnal*) *equinox* in the Northern Hemisphere, occurs around September 22 and is the moment when the Northern Hemisphere first starts to be tipped away from the Sun.

The exact dates and times of the solstices and equinoxes can vary by up to a couple days from the dates given above, depending on where we are in the leap year cycle. Leap years add a day—February 29—to the calendar every fourth year, except century years that are *not* divisible by 400. (So the years 1700, 1800, and 1900 were not leap years, but the year 2000 was.) Leap days keep the calendar aligned with the seasons by making the average length of the calendar year match the true length of the year, which is very close to $365\frac{1}{4}$ days.

First Days of Seasons

We usually say that each equinox or solstice marks the first day of a season. For example, the day of the June solstice is usually called the "first day of summer" in the Northern Hemisphere. Notice, however, that the Northern Hemisphere has its *maximum* tilt toward the Sun at this time. You might then wonder why we consider the summer solstice to be the beginning rather than the midpoint of summer.

The choice is somewhat arbitrary, but it makes sense in at least two ways. First, it was much easier for ancient people to identify the days on which the Sun reached extreme positions in the sky—such as when it reached its highest point

common misconceptions

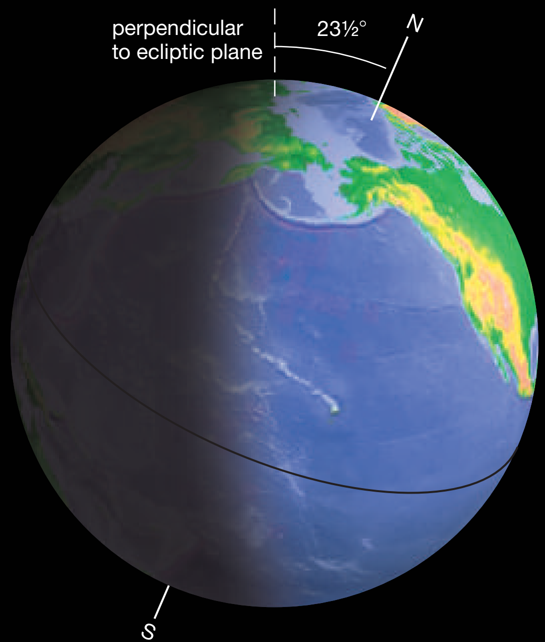
The Cause of Seasons

Many people guess that seasons are caused by variations in Earth's distance from the Sun. But if this were true, the whole Earth would have summer or winter at the same time, and it doesn't: The seasons are opposite in the Northern and Southern Hemispheres. In fact, Earth's slightly varying orbital distance has virtually no effect on the weather. The real cause of seasons is Earth's axis tilt, which causes the two hemispheres to take turns being tipped toward the Sun over the course of each year.

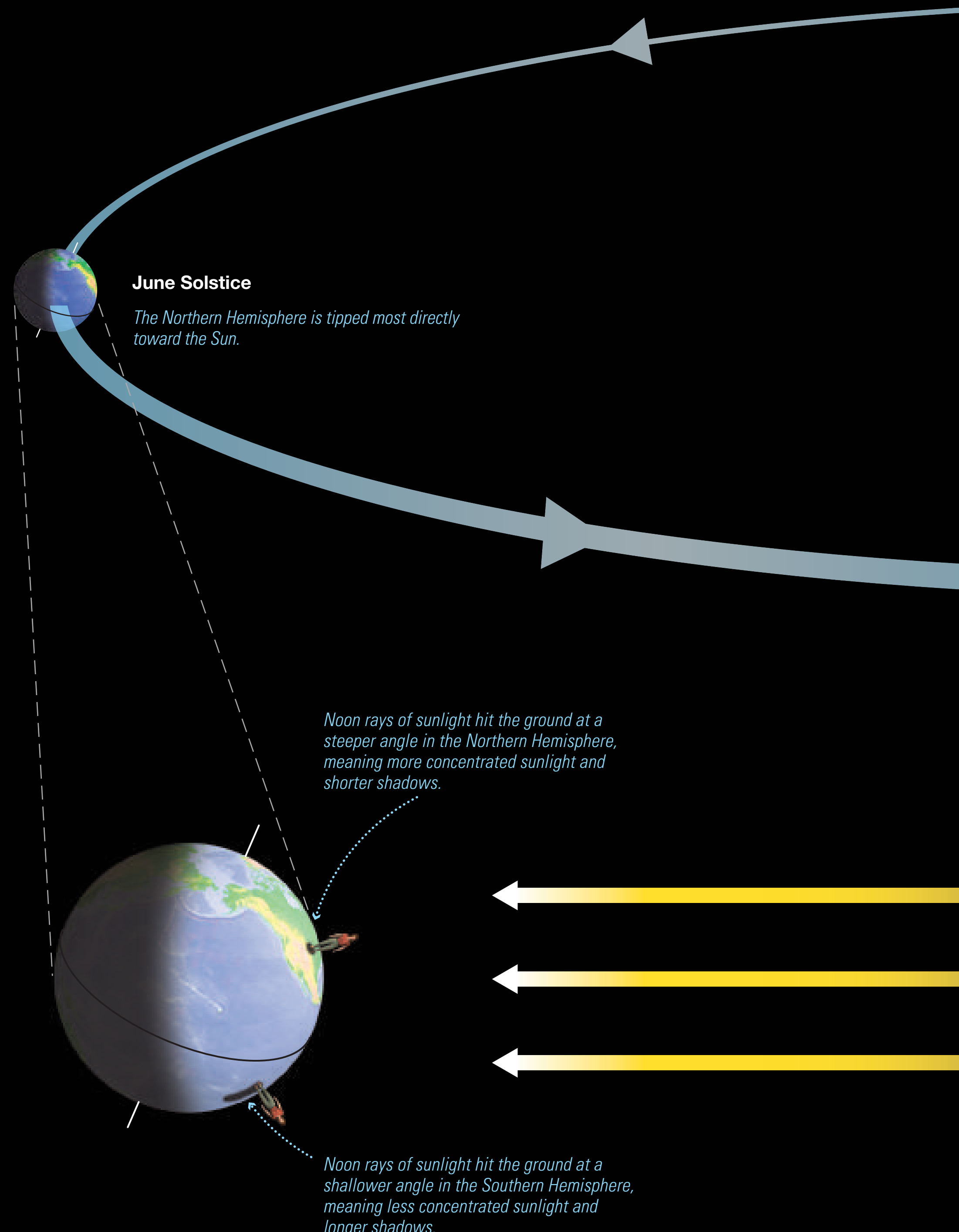
cosmic context FIGURE 2.3 The Cause of Seasons

Earth's seasons are caused by the tilt of its rotation axis, which is why the seasons are opposite in the two hemispheres. The seasons do *not* depend on Earth's distance from the Sun, which varies only slightly throughout the year.

1. **Axis Tilt:** Earth's axis points in the same direction throughout the year, which causes changes in Earth's orientation *relative to the Sun*.



2. **Northern Summer/Southern Winter:** In June, sunlight falls more directly on the Northern Hemisphere, which makes it summer there because solar energy is more concentrated and the Sun follows a longer and higher path through the sky. The Southern Hemisphere receives less direct sunlight, making it winter.

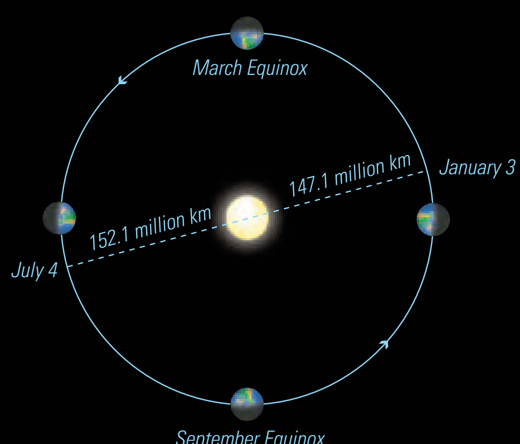


Interpreting the Diagram

To interpret the seasons diagram properly, keep in mind:

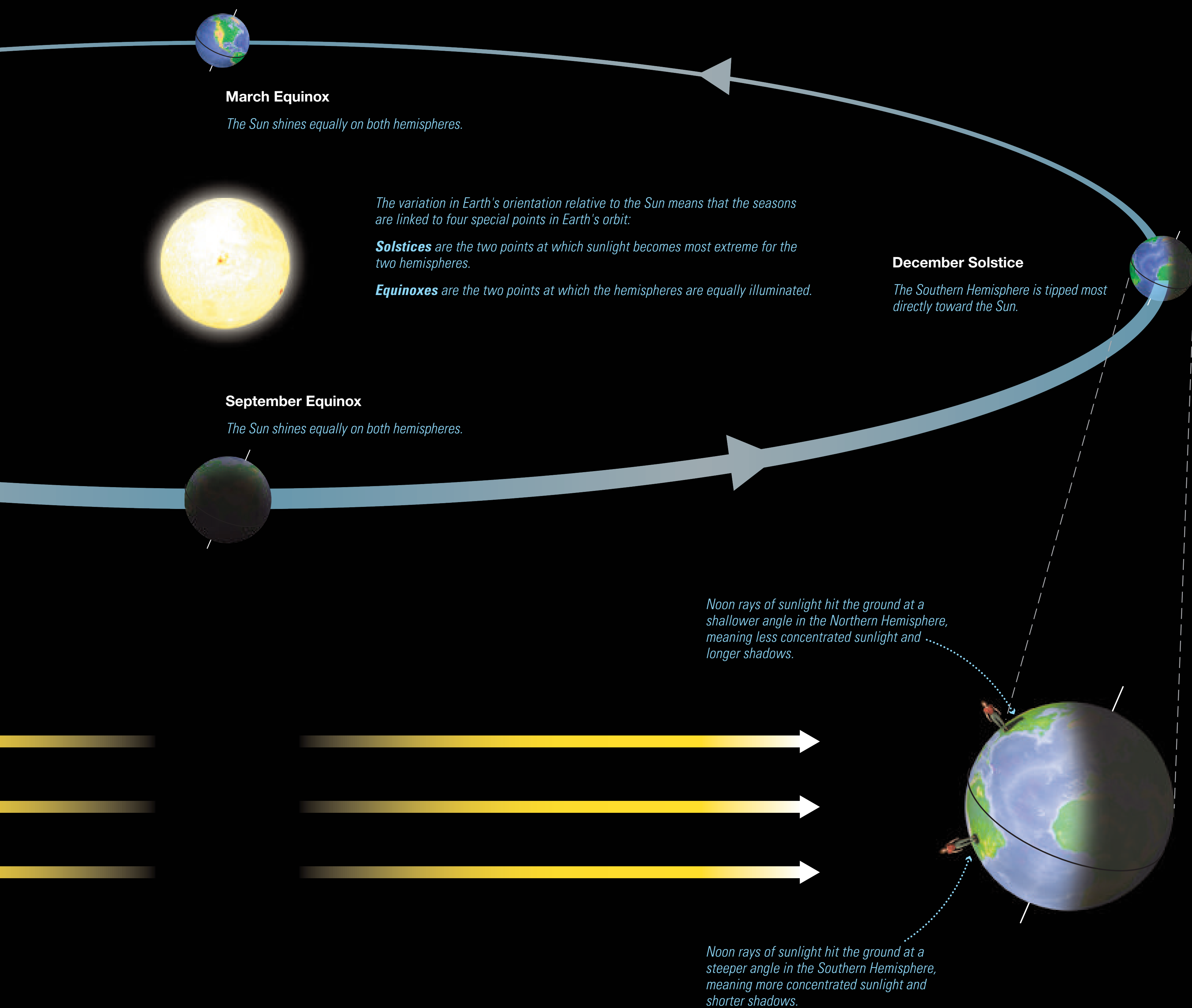
1. Earth's size relative to its orbit would be microscopic on this scale, meaning that both hemispheres are at essentially the same distance from the Sun.

2. The diagram is a side view of Earth's orbit. A top-down view (below) shows that Earth orbits in a nearly perfect circle and comes closest to the Sun in January.



(3) **Spring/Fall:** Spring and fall begin when sunlight falls equally on both hemispheres, which happens twice a year: In March, when spring begins in the Northern Hemisphere and fall in the Southern Hemisphere; and in September, when fall begins in the Northern Hemisphere and spring in the Southern Hemisphere.

(4) **Northern Winter/Southern Summer:** In December, sunlight falls less directly on the Northern Hemisphere, which makes it winter because solar energy is less concentrated and the Sun follows a shorter and lower path through the sky. The Southern Hemisphere receives more direct sunlight, making it summer.



▲ **FIGURE 2.4**
This sequence of photos shows the progression of the Sun all the way around the horizon on the June solstice from a location near the Arctic Circle. Notice that the Sun skims the northern horizon at midnight, then gradually rises higher, reaching its highest point when it is due south at noon.

on the summer solstice—than other days in between. Second, we usually think of the seasons in terms of weather, and the warmest summer weather tends to come 1 to 2 months after the solstice. To understand why, think about what happens when you heat a pot of cold soup. Even though you may have the stove turned on high from the start, it takes a while for the soup to warm up. In the same way, it takes some time for sunlight to heat the ground and oceans from the cold of winter to the warmth of summer. "Midsummer" in terms of weather therefore comes in late July and early August for the Northern Hemisphere, which makes the June solstice a pretty good choice for the "first day of summer." Similar logic applies to the starting times for spring, fall, and winter.

Seasons Around the World The seasons have different characteristics in different parts of the world. High latitudes have more extreme seasons. For example, Vermont has much longer summer days and much longer winter nights than Florida. At the Arctic Circle (latitude $66\frac{1}{2}°$), the Sun remains above the horizon all day long on the June solstice (Figure 2.4), and never rises on the December solstice (although bending of light by the atmosphere makes the Sun *appear* to be about a half-degree higher than it really is). The most extreme cases occur at the North and South Poles, where the Sun remains above the horizon for 6 months in summer and below the horizon for 6 months in winter.

Seasons also differ in equatorial regions, because the equator gets its most direct sunlight on the two equinoxes and its least direct sunlight on the solstices. As a result, instead of the four seasons experienced at higher latitudes, equatorial regions generally have rainy and dry seasons, with the rainy seasons coming when the Sun is higher in the sky.

common misconceptions

High Noon

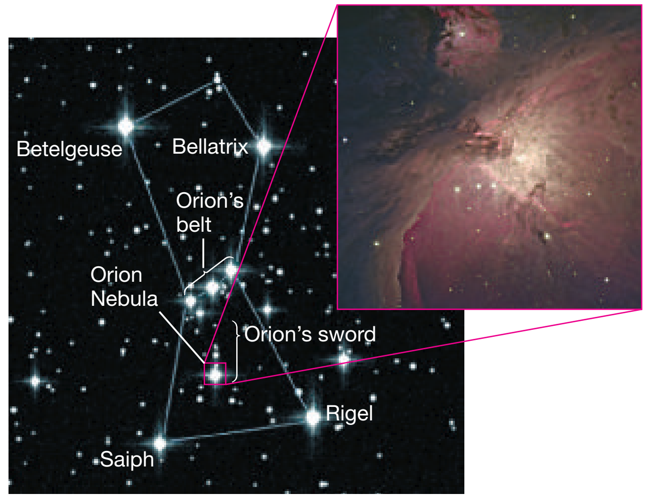
When is the Sun directly overhead in your sky? Many people answer "at noon." It's true that the Sun reaches its *highest* point each day when it crosses the meridian, giving us the term "high noon" (though the meridian crossing is rarely at precisely 12:00). However, unless you live in the tropics (between latitudes 23.5°S and 23.5°N), the Sun is *never* directly overhead. In fact, anytime you can see the Sun as you walk around, you can be sure it is *not* at your zenith. Unless you are lying down, seeing an object at the zenith requires tilting your head back into a very uncomfortable position.

◆ Why do the constellations we see depend on the time of year?

We have seen how and why we have seasonal changes in the weather and in the Sun's daily path through the sky. You can also track the seasons and the time of year by observing the nighttime sky. For example, the stars of Orion shine prominently on clear evenings in January (Figure 2.5), but are not visible at all on evenings in July. To understand why, we must first understand the general appearance of the night sky.

Constellations People of nearly every culture gave names to patterns they saw in the sky. We usually refer to such patterns as *constellations*, but to astronomers the term has a more precise meaning: A **constellation** is a *region* of the sky with well-defined borders, and just as every spot of land in the continental United States is part of some state, every spot in the sky belongs to some constellation. The familiar patterns of stars merely help us locate these constellations. For example, while we identify Orion by recognizing the pattern of stars outlined in Figure 2.5, even the seemingly empty spots in that region of the sky are part of the constellation Orion.

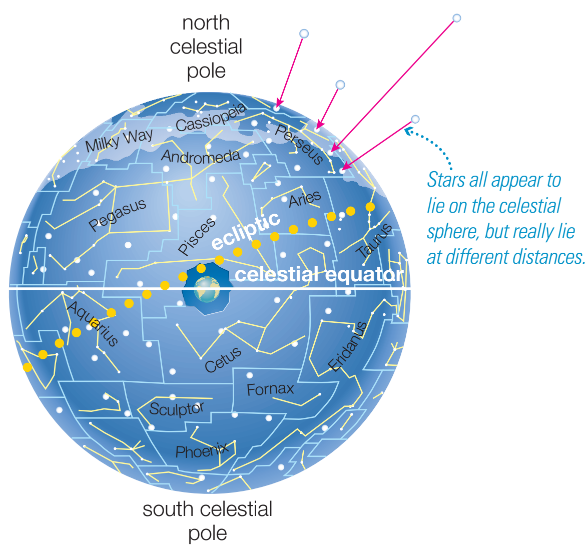
The patterns of stars in the constellations have seemed to remain fixed on the time scale of human civilization, but stars actually move at fairly high speeds relative to one another. Their positions seem to stay fixed only because they are so far away that their movements are not noticeable to the naked eye, even over many centuries. However, if you could watch a time-lapse movie made over tens of thousands of years, you would see dramatic changes in the patterns of the constellations.



▲ **FIGURE 2.5**
The constellation Orion is prominent in the evening sky during Northern Hemisphere winter (Southern Hemisphere summer). With binoculars or a telescope, you can see that one of its fainter "stars" is actually an interstellar cloud, called the Orion Nebula, in which many stars are being born. (Note: Viewed from the Southern Hemisphere, the constellation Orion would appear rotated compared to the photo shown here, and you would see it in the northern half of the sky rather than the southern half.)

The Celestial Sphere Together, all the constellations appear to fill a great **celestial sphere** surrounding Earth (Figure 2.6). Of course, the entire celestial sphere is an illusion: The sky looks like a great sphere only because the stars are so far away that we have no depth perception when we look into space, and Earth seems to be in the center of the celestial sphere only because it is where we are located as we look into space. Nevertheless, the celestial sphere is a useful illusion, because it allows us to map the sky as seen from Earth. For reference, we identify four special points and circles on the celestial sphere:

- The **north celestial pole** is the point directly over Earth's North Pole.
- The **south celestial pole** is the point directly over Earth's South Pole.
- The **celestial equator**, which is a projection of Earth's equator into space, makes a complete circle around the celestial sphere.
- The **ecliptic** is the path the Sun follows as it appears to circle around the celestial sphere once each year. It crosses the celestial equator at a $23\frac{1}{2}°$ angle, because that is the tilt of Earth's axis.



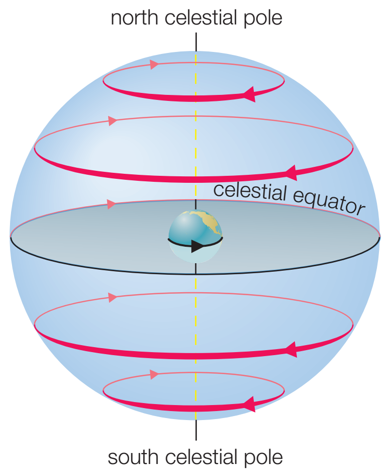
▲ **FIGURE 2.6**
The constellations appear to fill a great celestial sphere that surrounds Earth.

Daily Paths of Stars Through the Sky Stars appear to move through the sky during the night for the same reason the Sun appears to move through the sky during the day: Earth's daily west-to-east rotation causes everything on the celestial sphere to appear to move around us from east to west (Figure 2.7). If we could stop Earth from rotating, the stars would appear motionless.

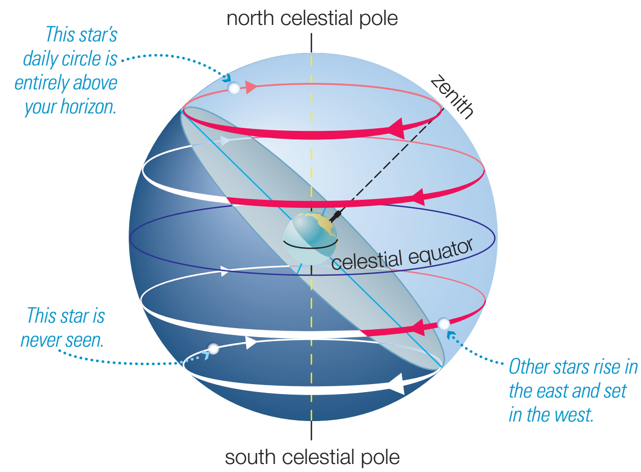
The daily motion of the sky looks very simple if you visualize it on the celestial sphere, with each object appearing to make a daily circle around Earth (Figure 2.7). However, the motion looks a little more complex in the local sky, because your horizon cuts the celestial sphere in half. Figure 2.8 shows the idea for a typical Northern Hemisphere location (latitude 40°N). Because your location means you are standing at an angle to Earth's equator, your horizon appears to slice through the celestial sphere at the same angle to the celestial equator. This angle causes the daily circles of the stars on the celestial sphere to appear tilted in your local sky. Stars that are near the north celestial pole make daily circles above your horizon, like those within the arch in the photo on page 17. Stars that are near the south celestial pole are never visible in your sky. In between, all other stars—along with the Sun, Moon, and planets—appear to rise up from your eastern horizon and set into your western horizon.

think about it Do distant galaxies also rise and set like the stars in our sky? Why or why not?

The same general ideas apply to all locations on Earth, but the details vary with latitude. Because latitude describes the angle that your zenith makes with Earth's equator, it also determines the angle at which your horizon slices through



▲ **FIGURE 2.7**
Earth rotates from west to east (black arrow), making the celestial sphere *appear* to rotate around us from east to west (red arrows).



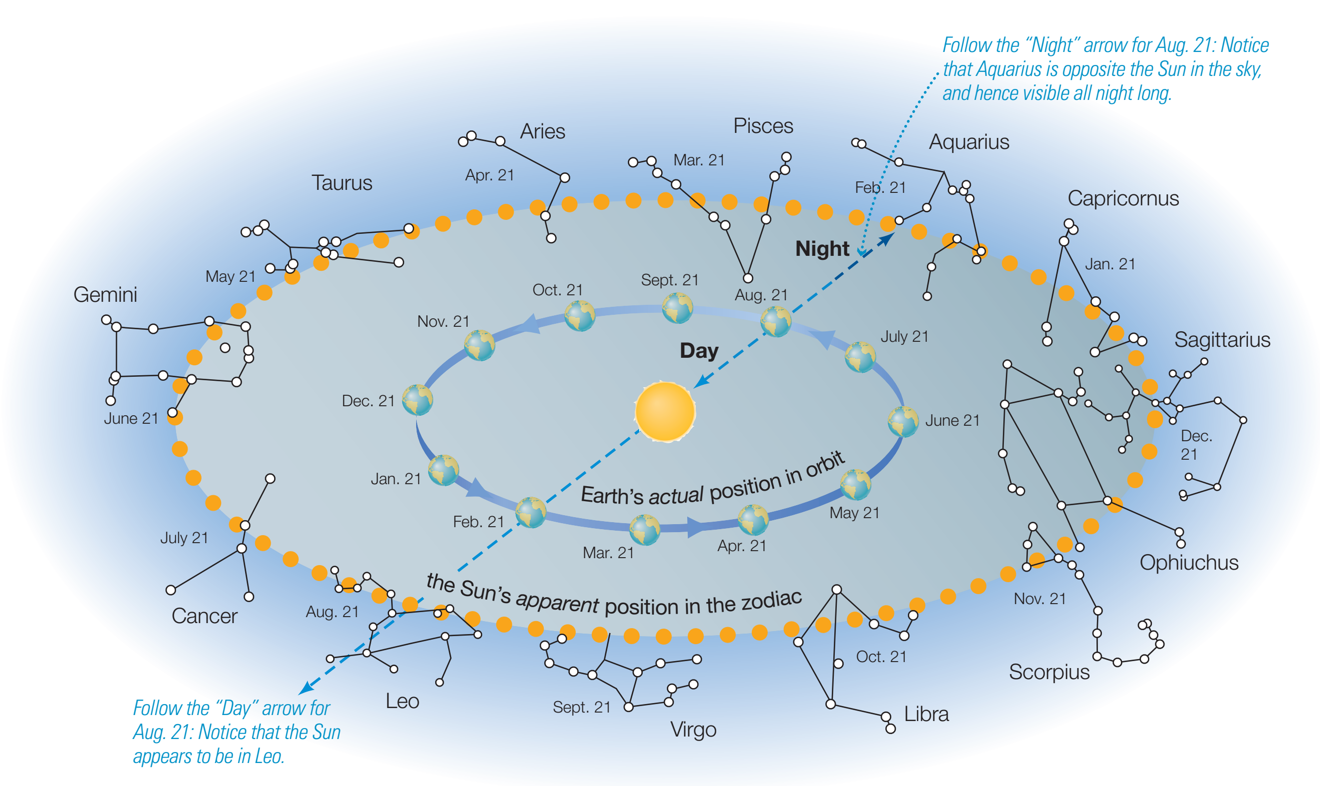
▲ **FIGURE 2.8**
The local sky for a location at latitude 40°N. The horizon slices through the celestial sphere at an angle to the celestial equator, causing the daily circles of stars to appear tilted in the local sky. Note: It is easier to follow the star paths in the local sky if you rotate the page so that the zenith points up.

the celestial sphere. The portion of the celestial sphere that you can see and the daily paths of stars through the sky therefore both depend on your latitude; that is why the night sky looks quite different at the southern latitudes of Australia than it does at the northern latitudes of the United States.

Seasonal Changes in the Night Sky Look back at Figure 2.6 and notice the yellow dots marking the path we call the *ecliptic*. These dots show that the Sun appears to move gradually around the celestial sphere, completing one full circuit in one year. This is a direct consequence of Earth's yearly orbit around the Sun.

Figure 2.9 shows how this works. From our vantage point on Earth, the annual orbit of Earth around the Sun makes the Sun *appear* to move steadily

▼ **FIGURE 2.9**
The Sun appears to move steadily eastward along the ecliptic as Earth orbits the Sun, so we see the Sun against the background of different zodiac constellations at different times of year. For example, on August 21 the Sun appears to be in Leo, because it is between us and the much more distant stars that make up Leo.



eastward along the ecliptic, with the stars of different constellations in the background at different times of year. The constellations along the ecliptic make up what we call the **zodiac**; tradition places 12 constellations along the zodiac, but the official borders include a 13th constellation, Ophiuchus.

The Sun's apparent location along the ecliptic determines which constellations we see at night. For example, Figure 2.9 shows that the Sun appears to be in Leo in late August. We therefore cannot see Leo at this time (because it is in our daytime sky), but we can see Aquarius all night long because of its location opposite Leo on the celestial sphere. Six months later, in February, we see Leo at night while Aquarius is above the horizon only in the daytime.

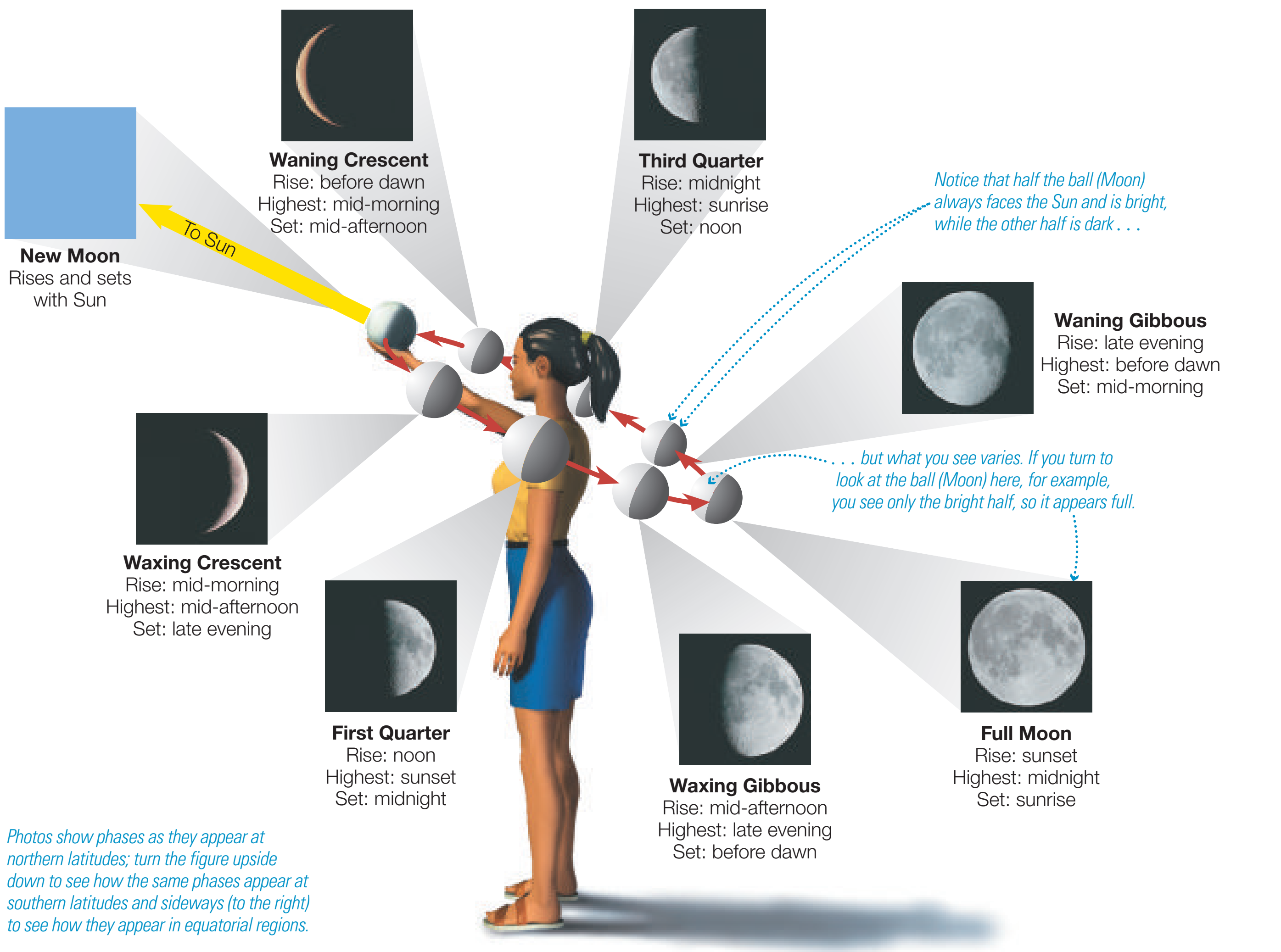
2.2 Understanding the Moon

Aside from the seasons and the daily circling of the sky, the most familiar pattern of change in the sky is that of the phases of the Moon. We will explore these changes in this section—along with the rarer changes that occur with eclipses—and see that they are consequences of the Moon's orbit around Earth.

◆ Why do we see phases of the Moon?

The easiest way to understand lunar phases is with the simple demonstration illustrated in Figure 2.10. Take a ball outside on a sunny day. (If it's dark or cloudy, you can use a flashlight instead of the Sun; put the flashlight on a table a

▼ FIGURE 2.10
In this demonstration, your head represents Earth and the ball represents the Moon as it orbits Earth. The half of the ball (Moon) facing the Sun is always illuminated while the other half is dark, but from your perspective in the middle, you see the ball (Moon) go through the phases shown in the photos. The labels indicate the approximate times of day at which each phase rises, reaches its highest point in the sky, and sets (exact times vary with location, time of year, and orbital details).



common misconceptions

Shadows and the Moon

Many people guess that the Moon's phases are caused by Earth's shadow falling on its surface, but this is not the case. Instead, the Moon's phases are caused by the fact that we see different portions of its daylight and night sides at different times as it orbits around Earth. The only time Earth's shadow falls on the Moon is during the relatively rare event of a lunar eclipse.

few meters away and shine it toward you.) Hold the ball at arm's length to represent the Moon, while your head represents Earth. Slowly spin counterclockwise so that the ball goes around you the way the Moon orbits Earth. (If you live in the Southern Hemisphere, spin clockwise because you view the sky "upside down" compared to someone in the Northern Hemisphere.) As you turn, you'll see the ball go through phases just like the Moon. If you think about what's happening, you'll realize that the phases of the ball result from just two basic facts:

1. Half the ball always faces the Sun (or flashlight) and therefore is bright, while the other half faces away from the Sun and is dark.
2. As you look at the ball at different positions in its "orbit" around your head, you see different combinations of its bright and dark faces.

For example, when you hold the ball directly opposite the Sun, you see only the bright portion of the ball, which represents the "full" phase. When you hold the ball at its "first-quarter" position, half the face you see is dark and the other half is bright.

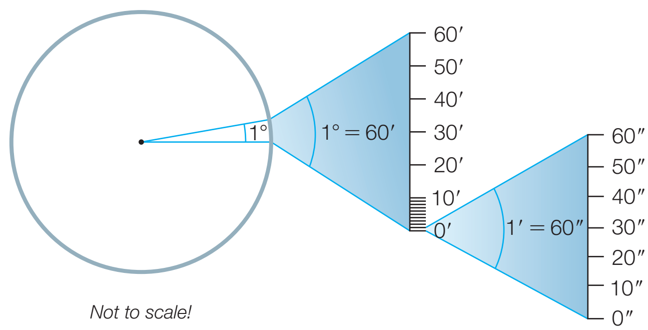
tools of science: Angular Sizes and Distances

Our lack of depth perception on the celestial sphere means we have no way to judge the true sizes or separations of the objects we see in the sky. We can directly measure only *angular* sizes or separations.

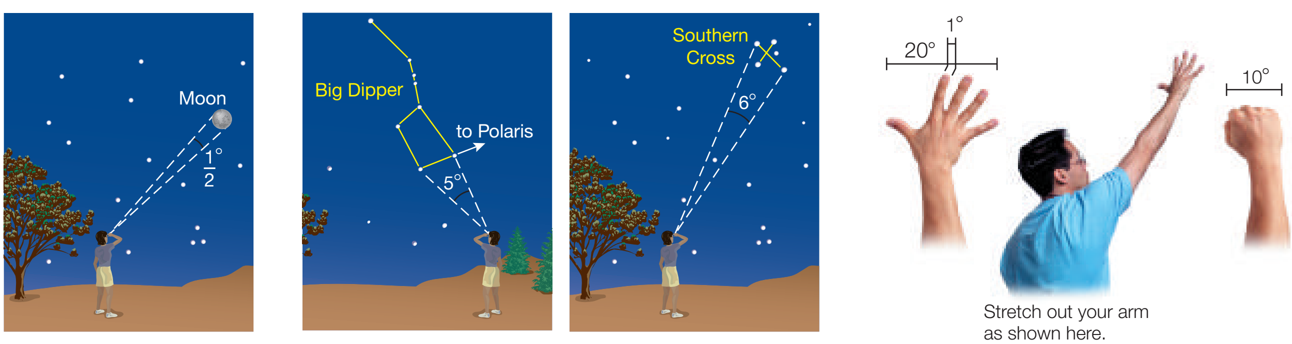
Figure 1 shows the basic idea behind angular measurement. The **angular size** of an object is the angle it appears to span in your field of view. For example, the angular sizes of the Sun and Moon are each about $\frac{1}{2}°$ (Figure 1a). The **angular distance** between a pair of objects in the sky is the angle that appears to separate them. For example, the angular distance between the "pointer stars" at the end of the Big Dipper's bowl is about 5° (Figure 1b). You can use your outstretched hand to estimate angles in the sky (Figure 1c).

For greater precision, we subdivide each degree into 60 **arcminutes** (symbolized by ′) and subdivide each arcminute into 60 **arcseconds** (symbolized by ″), as shown in Figure 2. For example, we read 35°27′15″ as "35 degrees, 27 arcminutes, 15 arcseconds." Note that one arcminute is approximately the thickness of a fingernail at arm's length, and one arcsecond is approximately the thickness of someone else's fingernail viewed from across a football field.

Angular measurements are very useful in astronomy. We use angles to describe the locations of objects in the sky or on the celestial sphere, much as we describe the location of an object on Earth with latitude and longitude. Even more important, angular sizes can help us to calculate physical sizes if we also know an object's true distance, or vice versa. For example, we can use the Moon's distance and angular size to calculate its physical size, or we can use a planet's angular size and physical size to calculate its distance.



▲ FIGURE 2



a The angular sizes of the Sun and the Moon are about 1/2°.

b The angular distance between the "pointer stars" of the Big Dipper is about 5°, and the angular length of the Southern Cross is about 6°.

c You can estimate angular sizes or distances with your outstretched hand.

▲ FIGURE 1

We see lunar phases for the same reason. Half the Moon is always illuminated by the Sun, but the amount of this illuminated half that we see from Earth depends on the Moon's position in its orbit. The photographs in Figure 2.10 show how the phases look. The new moon photo shows blue sky, because a new moon is nearly in line with the Sun and therefore hidden from view in the bright daytime sky.

Each complete cycle of phases, from one new moon to the next, takes about $29\frac{1}{2}$ days—hence the origin of the word *month* (think "moonth"). The phase determines the time the Moon rises, reaches its highest point in the sky, and sets. For example, the full moon must rise around sunset, because it occurs when the Moon is opposite the Sun in the sky. It therefore reaches its highest point in the sky at midnight and sets around sunrise. Similarly, a first-quarter moon must rise around noon, reach its highest point around sunset, and set around midnight, because it occurs when the Moon is about 90° east of the Sun in our sky.

think about it Suppose you go outside in the morning and notice that the visible face of the Moon is half light and half dark. Is this a first-quarter or third-quarter moon? How do you know?

Notice that the phases from new to full are said to be *waxing,* which means "increasing." Phases from full to new are *waning,* or "decreasing." Also notice that no phase is called a "half moon." Instead, we see half the Moon's face at first-quarter and third-quarter phases; these phases mark the times when the Moon is one-quarter or three-quarters of the way through its monthly cycle (which begins at new moon). The phases just before and after new moon are called *crescent,* while those just before and after full moon are called *gibbous* (pronounced with a hard *g* as in "gift").

The Moon's Synchronous Rotation Although we see many *phases* of the Moon, we do not see many *faces.* From Earth, we always see (nearly) the same face of the Moon. This happens because the Moon rotates on its axis in the same amount of time that it takes to orbit Earth, a trait called **synchronous rotation**. A simple demonstration shows this idea (Figure 2.11). Place a ball on a table to represent Earth, while you represent the Moon. The only way you can face the ball at all times is by completing exactly one rotation while you complete one orbit. Note that the Moon's synchronous rotation is *not* a coincidence; it is a consequence of Earth's gravity affecting the Moon in much the same way that the Moon's gravity causes tides on Earth.

The View from the Moon A good way to solidify your understanding of the lunar phases is to imagine that you live on the side of the Moon that faces Earth. For example, what would you see if you looked at Earth when people on Earth saw a new moon? By remembering that a new moon occurs when the Moon is

common misconceptions

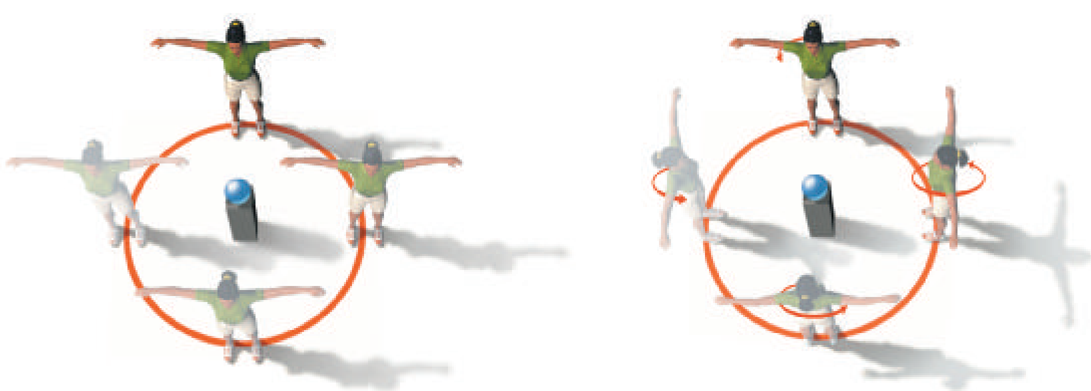
Moon in the Daytime

Night is so closely associated with the Moon in traditions and stories that many people mistakenly believe that the Moon is visible only in the nighttime sky. In fact, the Moon is above the horizon as often in the daytime as at night, though it is easily visible only when its light is not drowned out by sunlight. For example, a first-quarter moon is easy to spot in the late afternoon as it rises through the eastern sky, and a third-quarter moon is visible in the morning as it heads toward the western horizon.

common misconceptions

The "Dark Side" of the Moon

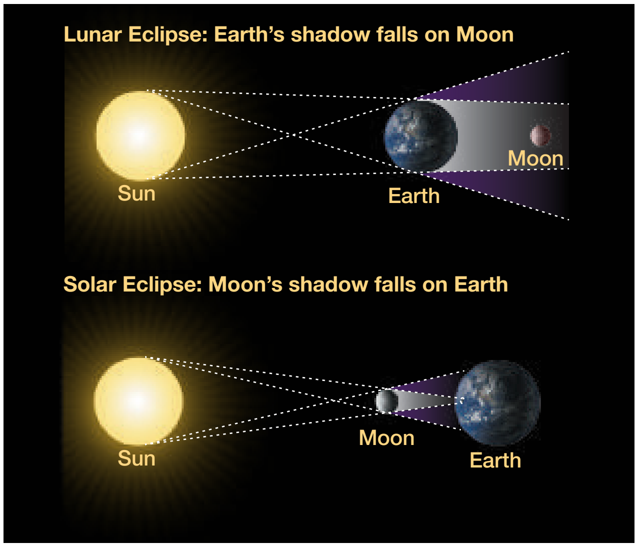
Some people refer to the far side of the Moon—meaning the side that we never see from Earth—as the *dark side*. But this is not correct, because the far side is not always dark. For example, during new moon the far side faces the Sun and hence is completely sunlit. In fact, because the Moon rotates with a period of approximately one month (the same time that it takes to orbit Earth), points on both the near and the far side have two weeks of daylight alternating with two weeks of darkness. The only time the far side is completely dark is at full moon, when it faces away from both the Sun and Earth.



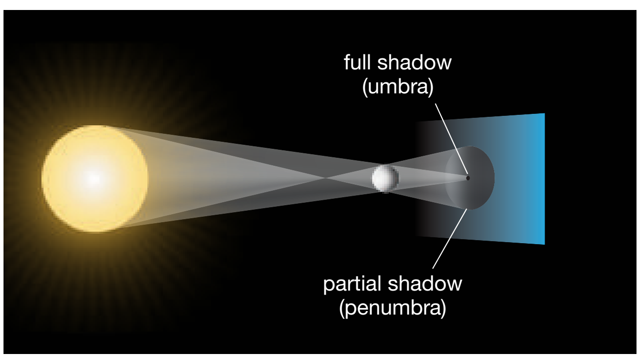
a If you do not rotate while walking around the model, you will not always face it.

b You will face the model at all times only if you rotate exactly once during each orbit.

FIGURE 2.11 The fact that we always see the same face of the Moon means that the Moon must rotate once in the same amount of time that it takes to orbit Earth once. You can see why by walking around a model of Earth while imagining that you are the Moon.



▲ **FIGURE 2.12**
These illustrations show the two basic types of eclipse. The relative sizes of the Moon and Earth are shown to scale, but the relative distance between them is about 50 times that shown here, the Sun is actually about 100 times larger in diameter than Earth, and the Earth-Sun distance is about 400 times the Earth-Moon distance.



▲ **FIGURE 2.13**
This diagram shows the two distinct, cone-shaped regions of the shadow cast on an imaginary screen by a world like Earth or the Moon in sunlight. If you looked back from within the full shadow, you would see the Sun fully blocked from view; if you looked from within the partial shadow, the Sun would be only partly blocked from view.

between the Sun and Earth, you'll realize that from the Moon you'd be looking at Earth's daytime side and hence would see a *full Earth*. Similarly, at full moon you would be facing the night side of Earth and would see a *new Earth*. In general, you'd always see Earth in a phase opposite the phase of the Moon seen by people on Earth at the same time.

think about it About how long would each day and night last if you lived on the Moon? Explain. (*Hint*: Recall that a full cycle of phases lasts about a month.)

◆ What causes eclipses?

Eclipses Part 1

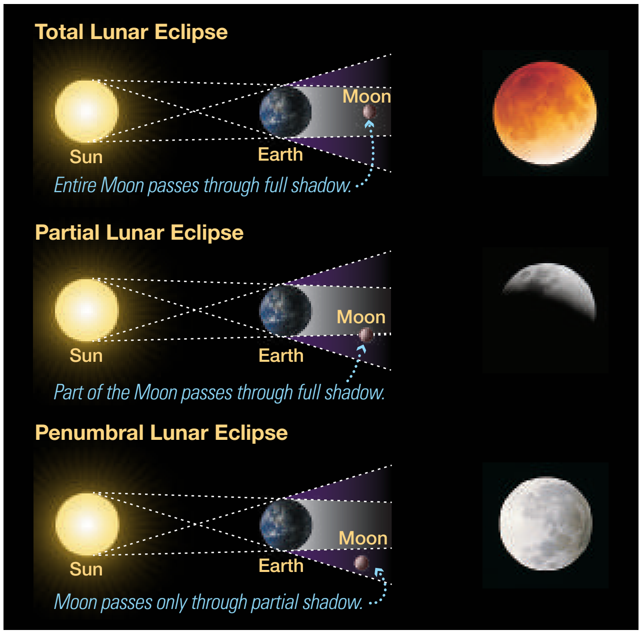
The lunar phases repeat "moonthly," but sometimes the Moon gets involved in more dramatic events: eclipses. There are two basic types of eclipse (Figure 2.12).

- A **lunar eclipse** occurs when Earth comes directly between the Sun and Moon, so that Earth's shadow falls on the Moon.
- A **solar eclipse** occurs when the Moon comes directly between the Sun and Earth, so that the Moon's shadow falls on Earth.

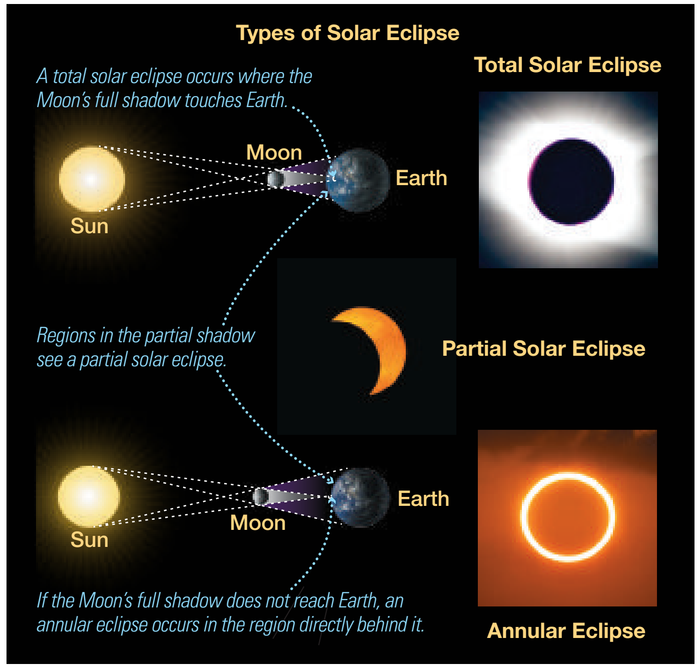
Variations on Eclipses There are variations on the two basic types of eclipse, because the three-dimensional geometry of an eclipse shadow creates two distinct shadow regions (Figure 2.13): a central **full shadow**, or *umbra*, in which sunlight is fully blocked, and a surrounding **partial shadow**, or *penumbra*, in which light from only part of the Sun is blocked.

The shadow geometry leads to three types of lunar eclipse (Figure 2.14). If the Sun, Earth, and Moon are nearly perfectly aligned, the Moon passes through Earth's full shadow to create a **total lunar eclipse**. Earth's shadow gradually progresses across the face of the Moon, with the clear curvature of the full shadow demonstrating that our world is round. **Totality** begins when the Moon is entirely engulfed in the full shadow and typically lasts about an hour, after which we see the shadow gradually move off the Moon. The Moon becomes dark and eerily red during totality, for reasons you can understand by considering the view of an observer on the eclipsed Moon. This observer would see Earth's night side surrounded by the reddish glow of all the sunrises and sunsets occurring on Earth at that moment, which means that this reddish light illuminates the Moon during totality. If the alignment is somewhat less perfect, only part of the full moon passes through the full shadow (with the rest in the partial shadow) and we see a **partial lunar eclipse**. If the Moon passes *only* through Earth's partial shadow (penumbra), we see a **penumbral lunar eclipse**. Penumbral eclipses are the most common, but they are the least visually impressive because the full moon darkens only slightly.

There are also three types of solar eclipse (Figure 2.15), in part because the Moon's distance from Earth varies somewhat over the course of each orbit. If a solar eclipse occurs when the Moon is relatively close to Earth, the Moon's full shadow can cover a small area of Earth's surface (up to about 270 kilometers in diameter). Within this area you will see a **total solar eclipse**. If the eclipse occurs when the Moon is relatively far from Earth, the full shadow may not reach Earth's surface, leading to an **annular eclipse**—a ring of sunlight surrounding the Moon—in the small region of Earth directly behind the full shadow. In either case, the region of totality or annularity will be surrounded by a much larger region (typically about 7000 kilometers in diameter) that falls within the Moon's partial shadow. Here you will see a **partial solar eclipse**, in which only part of the Sun is blocked from view. (Some solar eclipses are only partial, meaning that no locations on Earth see a total or annular eclipse, because the full shadow passes above or below our planet.) The combination of Earth's rotation and the Moon's orbital motion causes the Moon's shadow to race across the face of Earth at a typical speed of about 1700 kilometers



▲ **FIGURE 2.14**
The three types of lunar eclipse. The Moon is actually much dimmer during totality than during the partial eclipse, but it is shown here as the eye tends to notice it because of its coloration.



▲ **FIGURE 2.15**
The three types of solar eclipse. (A partial solar eclipse may also be seen in cases when the Moon's full shadow passes above or below Earth.)

per hour. As a result, the full (or annular) shadow traces a narrow path across Earth, and totality can never last more than a few minutes in any particular place.

A total solar eclipse is a spectacular sight (Figure 2.16). It begins when the disk of the Moon first appears to touch the Sun. Over the next couple of hours, the Moon appears to take a larger and larger "bite" out of the Sun. As totality approaches, the sky darkens and temperatures fall. Birds head back to their nests, and crickets begin their nighttime chirping. During the few minutes of totality, the Moon completely blocks the visible disk of the Sun, allowing the faint *corona* to be seen. The surrounding sky takes on a twilight glow, and planets and bright stars become visible in the daytime. As totality ends, the Sun slowly emerges from behind the Moon. However, because your eyes have adapted to the darkness, totality appears to end far more abruptly than it began.

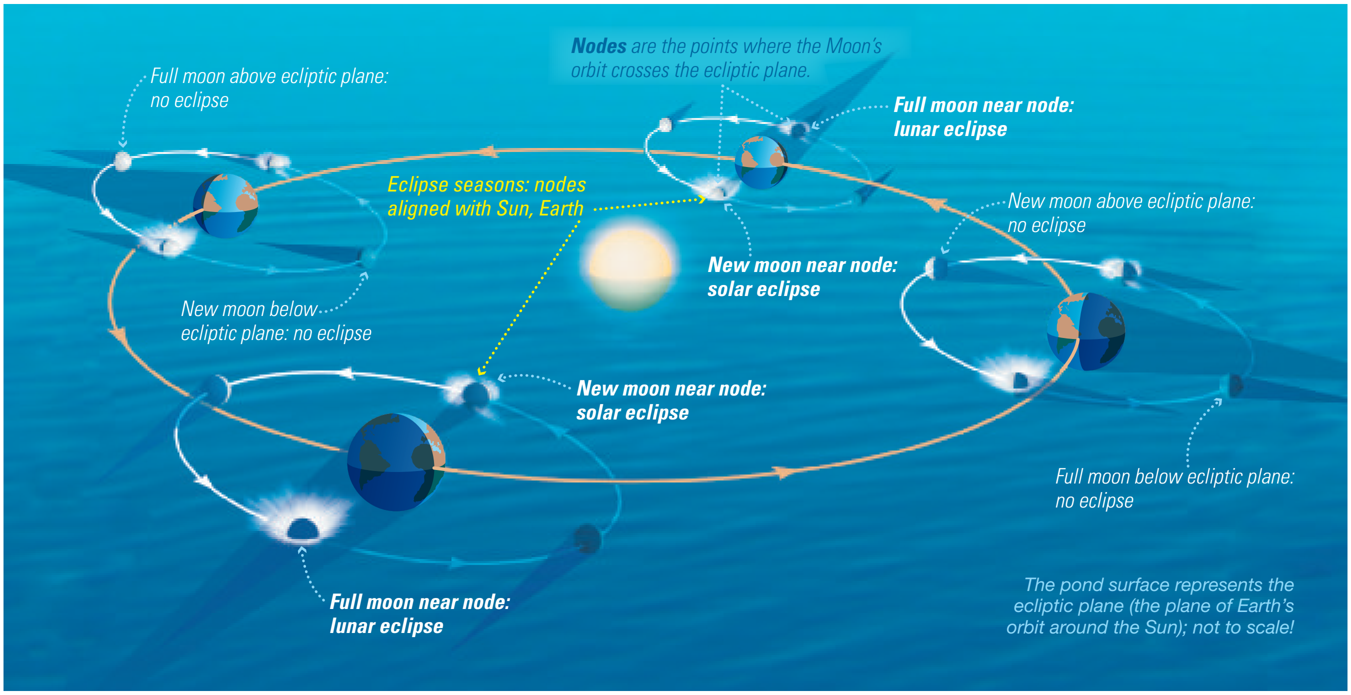
▲ **FIGURE 2.16**
This multiple-exposure photograph shows the progression of the 2017 total solar eclipse over Green River Lake, Wyoming. Totality (central image) lasted about 2 minutes. Note: Download the free app "Totality by Big Kid Science" (created by one of the textbook authors) to learn about upcoming total solar eclipses, including the next one in the United States on April 8, 2024.

Eclipses Part 2

Conditions for Eclipses How often do eclipses occur? If you look at a simple Moon phase diagram (such as Figure 2.10), it might seem as if the Sun, Earth, and Moon would line up with every new and full moon, in which case we'd have both a lunar and a solar eclipse every month. But we don't, and the reason is that the Moon's orbit is slightly inclined (by about 5°) to the ecliptic plane (the plane of Earth's orbit around the Sun).

You can visualize this inclination by imagining the ecliptic plane as the surface of a pond (Figure 2.17). The Moon's orbital inclination means that the Moon spends most of its time either above or below the pond surface (representing the ecliptic plane). The Moon crosses *through* this surface only twice during each orbit—once coming out and once going back in—at the two points called the **nodes** of the Moon's orbit.

Notice that the nodes are aligned approximately the same way (diagonally in Figure 2.17) throughout the year, which means they lie along a nearly straight line with the Sun and Earth about twice each year. Eclipses can occur only during these periods, called **eclipse seasons**, which each last about five weeks (on



▲ **FIGURE 2.17**
This illustration represents the ecliptic plane as the surface of a pond. The Moon's orbit is tilted by about 5° to the ecliptic plane, so the Moon spends half of each orbit above the plane (the pond surface) and half below it. Eclipses occur only during *eclipse seasons*, when the nodes are closely aligned with the Sun and Earth *and* when the lunar phase is either new (for a solar eclipse) or full (for a lunar eclipse).

average). In other words, eclipses occur only during eclipse seasons, with a lunar eclipse occurring at full moon and a solar eclipse at new moon.

think about it Suppose that, today, some parts of the world saw a partial solar eclipse. Is it possible that you will see a lunar eclipse tonight? in two weeks? in two months? Explain.

Predicting Eclipses Few phenomena have so inspired and humbled humans throughout the ages as eclipses. For many cultures, eclipses were mystical events associated with fate or the gods, and countless stories and legends surround them.

Much of the mystery of eclipses probably stems from the relative difficulty of predicting them. Look again at Figure 2.17, focusing on the two eclipse seasons. If this figure told the whole story, eclipse seasons would always occur 6 months apart and predicting eclipses would be easy. For example, if eclipse seasons always occurred in January and July, eclipses would always occur on the dates of new and full moons in those months. Actual eclipse prediction is more difficult than this because of something the figure does not show: The nodes slowly move around the Moon's orbit, causing the eclipse seasons to occur slightly less than 6 months apart (about 173 days apart). As a result, instead of recurring with an annual pattern, eclipses recur in a pattern that repeats about every 18 years $11\frac{1}{3}$ days, which is called the **saros cycle**.

Some ancient civilizations learned to recognize the saros cycle and therefore were able to predict when eclipses would occur. Even then, however, they could not predict all aspects of particular eclipses, including where they would be visible on Earth. Today, we can predict eclipses with great precision because we know the details of the orbits of Earth and the Moon.

THE PROCESS OF SCIENCE IN ACTION

2.3 The Puzzle of Planetary Motion

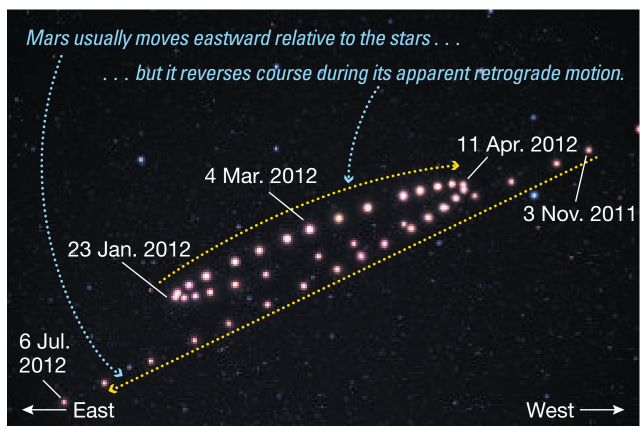
We have already discussed how Earth's rotation leads to the daily rise and set of the Sun, Moon, and stars, and how Earth's orbit makes the Sun appear to move through the constellations. Ancient people did not find it difficult to explain these phenomena, though their explanations differed from the modern ones because they believed in an Earth-centered universe.

Planetary motion posed a much bigger puzzle in ancient times, and we will see in Chapter 3 that the quest to understand this motion ultimately led to the realization about four centuries ago that Earth is a planet in orbit around the Sun. But it was not the first time this idea had been raised: The ancient Greeks also considered the possibility that Earth moves around the Sun. In fact, the Greeks took the idea quite seriously, but most of them rejected it because they could not find sufficient evidence to support it with the observations possible at the time. The story of how the Greeks considered but rejected the correct explanation for planetary motion provides an early example of scientific thinking in action, and demonstrates that ancient civilizations thought more deeply about nature than many people realize.

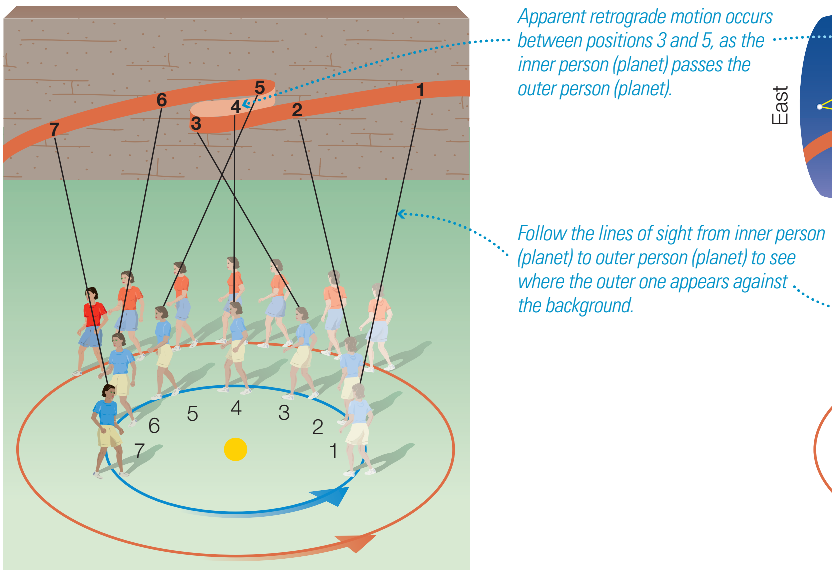
◆ Why did the ancient Greeks reject the real explanation for planetary motion?

Over the course of a single night, planets behave like all other objects in the sky: Earth's rotation makes them appear to rise in the east and set in the west. But if you continue to watch the planets night after night, you will notice that their movements among the constellations are quite complex. Instead of moving steadily eastward relative to the stars, like the Sun and Moon, the planets vary substantially in both speed and brightness. Moreover, while the planets *usually* move eastward through the constellations, they occasionally reverse course, moving westward through the zodiac (Figure 2.18). These periods of **apparent retrograde motion** (*retrograde* means "backward") last from a few weeks to a few months, depending on the planet.

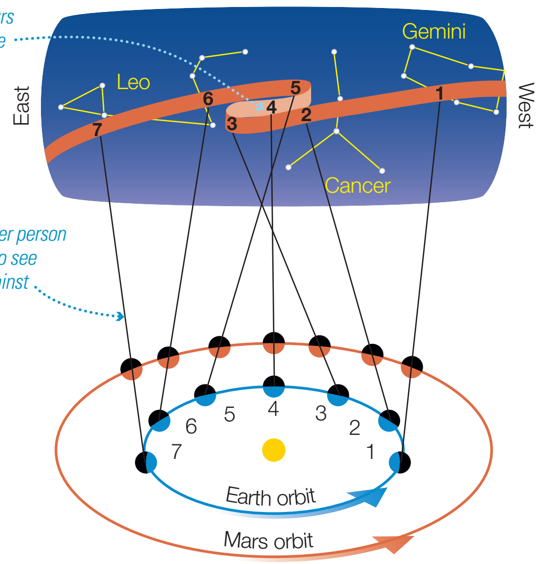
For ancient people who believed in an Earth-centered universe, apparent retrograde motion was very difficult to explain. After all, what could make planets sometimes turn around and go backward? The ancient Greeks came up with some clever ways to explain it, but their explanations (which we'll study in Chapter 3) were quite complex. In contrast, apparent retrograde motion has a simple explanation in a Sun-centered solar system. You can demonstrate it for yourself with the help of a friend (Figure 2.19a). Pick a spot in an open area to represent the Sun. You can represent Earth by walking counterclockwise around the Sun, while your friend represents a more distant planet (such as Mars or Jupiter) by walking in the same direction around the Sun at a greater distance. Your friend should walk more slowly than you, because more distant planets orbit the Sun more slowly. As you walk, watch how your friend appears to move relative to buildings or trees in the distance. Although both of you always walk the same way around the Sun, your friend will appear to move backward against the background during the part of your "orbit" in which you catch up to and pass him or her. Figure 2.19b shows how the same idea applies to Mars. (To understand the apparent retrograde motions of Mercury and Venus, which are closer to the Sun than Earth, simply switch places with your friend and repeat the demonstration.)



▲ **FIGURE 2.18**
This composite of images (taken at 5- to 7-day intervals in 2011–2012) shows a retrograde loop of Mars. Note that Mars is biggest and brightest in the middle of the retrograde loop, because that is where it is closest to Earth in its orbit.



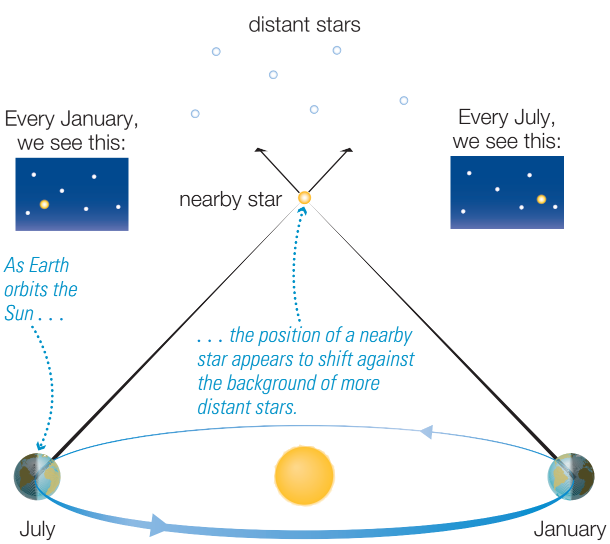
a The retrograde motion demonstration: Watch how your friend (in red) usually appears to move forward against the background of the building in the distance but appears to move backward as you (in blue) catch up to and pass her in your "orbit."



b This diagram shows the same idea applied to a planet. Follow the lines of sight from Earth to Mars in numerical order. Notice that Mars appears to move westward relative to the distant stars (from point 3 to point 5) as Earth passes it by in its orbit.

▲ FIGURE 2.19

Apparent retrograde motion—the occasional "backward" motion of the planets relative to the stars—has a simple explanation in a Sun-centered solar system.



▲ FIGURE 2.20

Stellar parallax is an apparent shift in the position of a nearby star as we look at it from different places in Earth's orbit. This figure is greatly exaggerated; in reality, the amount of shift is far too small to detect with the naked eye.

The ancient Greeks were aware of how simply a Sun-centered system could explain apparent retrograde motion, and this may have been one reason the Greek astronomer Aristarchus proposed in about 260 B.C. that Earth goes around the Sun. However, Aristarchus's contemporaries rejected his idea, and the Sun-centered solar system did not gain wide acceptance until almost 2000 years later.

Although there were many reasons the Greeks were reluctant to abandon the idea of an Earth-centered universe, one of the most important was their inability to detect what we call **stellar parallax**. Extend your arm and hold up one finger. If you keep your finger still and alternately close your left eye and right eye, your finger will appear to jump back and forth against the background. This apparent shifting, called *parallax,* occurs because your two eyes view your finger from opposite sides of your nose. If you move your finger closer to your face, the parallax increases. If you look at a distant tree or flagpole instead of your finger, you may not notice any parallax at all. In other words, parallax depends on distance, with nearer objects exhibiting greater parallax than more distant objects.

If you now imagine that your two eyes represent Earth at opposite sides of its orbit around the Sun and that the tip of your finger represents a relatively nearby star, you have the idea of stellar parallax. Because we view the stars from different places in our orbit at different times of year, nearby stars should *appear* to shift back and forth against the background of more distant stars (Figure 2.20).

Because the Greeks believed that all stars lay on the same celestial sphere, they expected to see stellar parallax in a slightly different way. If Earth orbited the Sun, they reasoned, at different times of year we would be closer to different parts of the celestial sphere and would notice changes in the angular separations