THE ESSENTIAL Cosmic Perspective

Ninth Edition

Bennett | Donahue | Schneider | Voit

This page intentionally left blank

THE ESSENTIAL Cosmic Perspective

NINTH 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

Content Management: Jeanne Zalesky, Deborah Harden, Harry Misthos
Content Production: Kristen Flathman, Shercian Kinosian, Mary Tindle, Troutt Visual Services, Tod Regan, Jenny Moryan, Ziki Dekel, Katie Foley, Jayne Sportelli, David Hoogewerff, Mark Ong, Gary Hespenheide
Product Management: Christopher Hess, Jessica Moro
Product Marketing: Candice Madden, Rosemary Morton
Rights and Permissions: Ben Ferrini, Matthew Perry, Zosef Sotheo M. Herrero

Please contact https://support.pearson.com/getsupport/s/ with any queries on this content

Cover Image by Carlos Fernandez/Moment/Getty Images

ScoutAutomatedPrintCode

Library of Congress Cataloging-in-Publication Data

Names: Bennett, Jeffrey O., author. | Donahue, M. (Megan), 1962- author. | Schneider, Nicholas, author. | Voit, Mark, author.
Title: The essential cosmic perspective / Jeffrey Bennett, University of Colorado at Boulder, Megan Donahue, Michigan State University, Nicholas Schneider, University of Colorado at Boulder, Mark Voit, Michigan State University.
Description: Ninth edition. | Hoboken, NJ: Pearson, [2022] | Includes index.
Identifiers: LCCN 2020056435 (print) | LCCN 2020056436 (ebook) | ISBN 9780135795033 (paperback) | ISBN 9780135795125 (ebook)
Subjects: LCSH: Astronomy--Textbooks. | LCGFT: Textbooks.
Classification: LCC QB43.3 .B46 2022 (print) | LCC QB43.3 (ebook) | DDC 520--dc23
LC record available at https://lccn.loc.gov/2020056435
LC ebook record available at https://lccn.loc.gov/2020056436

Pearson

Access Code Card
ISBN-10: 0-135-79512-5
ISBN-13: 978-0-135-79512-5

Rental
ISBN-10: 0-135-79503-6
ISBN-13: 978-0-135-79503-3

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

Contents

PART IV Stars

PART V Galaxies and Beyond

Preface

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 tells the story of modern astronomy and the new perspective, *The Essential Cosmic Perspective,* that astronomy gives us on ourselves and our planet.

Who Is This Book For?

The Essential Cosmic Perspective provides a survey of modern astronomy suitable for anyone who is curious about the universe, regardless of prior background in astronomy or physics. However, it is designed primarily to serve as a textbook for college courses in introductory astronomy.

The Essential Cosmic Perspective is the mid-level of the three general astronomy textbooks we offer. Our longer book, *The Cosmic Perspective*, provides enough depth to fill a two-semester introductory astronomy sequence. This book, *The Essential Cosmic Perspective*, is trimmed down to fit what can realistically be covered in a one-semester survey course. Our shortest textbook, *The Cosmic Perspective Fundamentals,* covers only the most fundamental topics in astronomy.

New to This Edition

The underlying philosophy, goals, and structure of *The Essential Cosmic Perspective* remain the same as in past editions, but we have thoroughly updated the text and made a number of other improvements. Here, briefly, is a list of the significant changes you'll find in this ninth edition:

- **Major Chapter-Level Changes:** We have made numerous significant changes both to update the science and to improve the pedagogical flow in this edition. The full list is too long to put here, but major changes include the following:
  - In **Chapter 2**, we have reworked the section on eclipses with new artwork and revised pedagogy to reflect the fact that many students will have heard about or witnessed the 2017 eclipse.
  - **Chapter 5** has a new learning goal relating to multi-messenger astronomy, focusing on neutrinos, cosmic ways and gravitational waves. The chapter also has a new Common Misconception box on "Light Paths, Lasers, and Shadows."
  - **Chapters 7 through 9** have numerous scientific updates based on recent planetary missions, including the most recent missions to Mars; updated discussions of asteroids and comets based on the *Dawn*, *Rosetta*, *Hayabusa 2,* and *Osiris-REX* missions; the *Juno* mission, the *New Horizons* encounter with Arrokoth, and more.
  - **Chapter 10** covers the fast-moving topic of extrasolar planets and hence has numerous scientific updates and new figures.
  - In **Chapter 14**, we have almost completely rewritten Section 14.4, revising it to have three learning goals instead of two, to include the detections of gravitational waves from neutron star and black hole mergers.
  - **Chapter 16** has been updated to include the Event Horizon Telescope image of the black hole in M87, and to present the latest view of galactic evolution, some of which is based on the work of two of the authors of this book (Donahue and Voit). The chapter also now honors the work of Henrietta Swan Leavitt by referring to her period-luminosity relation as Leavitt's law.
  - **Chapter 19** has significant updates concerning evidence for early life on Earth and the search for life on Mars and other worlds in our solar system.
- **Revamped Exercises Sets:** We have reorganized the end-of-chapter exercise sets in order to place greater emphasis on questions designed to promote discussion and group work.
- **New Feature—*Inclusive Astronomy*:** The astronomical community is engaged in broad and wide-ranging conversations about inclusion and the persistent lack of diversity in the fields of astronomy and other sciences. To provide sample openings for discussions of inclusion in the classroom, we have (1) added a new set of exercises in every chapter under the heading "Inclusive Astronomy," written to support student discussions about topics centered on inclusiveness in astronomy; and (2) added a similar set of additional exercises that you can find in the set of Group Activities available in the Study Area of Mastering Astronomy.
- **New Content in Mastering Astronomy**: *The Essential Cosmic Perspective* is much more than a textbook; it is a complete "learning package" that combines the textbook with deeply integrated, interactive media developed to support every chapter of our book. We continually update the material on the Mastering Astronomy web site, and for this edition we call your attention to nearly 100 new "prelecture videos," all written by (and most narrated by) the authors, designed to help students understand key concepts. Students can watch the videos at any time in the Study Area, while instructors can find assignable tutorials based on the videos in the instructor-accessible Item Library. In addition to the new videos and their corresponding tutorials, you will find many other new tutorials in the Item Library, as well as a fully updated set of reading, concept, and visual quizzes for each chapter, available in both the Study Area and the assignable Item Library. These resources should be especially valuable to instructors who wish to offer assignments ensuring that students are prepared before class and to those using "flipped classroom" strategies.

The Pedagogical Approach of The Cosmic Perspective

The Essential Cosmic Perspective offers a broad survey of our modern understanding of the cosmos and of how we have built that understanding. Such a survey can be presented in a number of different ways. We have chosen to build *The Essential Cosmic Perspective* around a set of key themes designed to engage student interest and a set of pedagogical principles designed to ensure that all material comes across as clearly as possible to students.

Themes

Most students enrolled in introductory astronomy courses have little connection to astronomy when their course begins, and many have little understanding of how science actually works. The success of these students therefore depends on getting them engaged in the subject matter. To help achieve this, we have chosen to focus on the following five themes, which are interwoven throughout the book.

- **Theme 1**: *We are a part of the universe and can therefore learn about our origins by studying the universe*. This is the overarching theme of *The Essential Cosmic Perspective*, as we continually emphasize that learning about the universe helps us understand ourselves. Studying the intimate connections between human life and the cosmos gives students a reason to care about astronomy and also deepens their appreciation of the unique and fragile nature of our planet and its life.
- **Theme 2:** *The universe is comprehensible through scientific principles that anyone can understand*. The universe is comprehensible because the same physical laws appear to be at work in every aspect, on every scale, and in every age of the universe. Moreover, while professional scientists generally have discovered the laws, anyone can understand their fundamental features. Students can learn enough in one or two terms of astronomy to comprehend the basic reasons for many phenomena that they see around them—phenomena ranging from seasonal changes and phases of the Moon to the most esoteric astronomical images that appear in the news.
- **Theme 3:** *Science is not a body of facts but rather a process through which we seek to understand the world around us*. Many students assume that science is just a laundry list of facts. The long history of astronomy can show them that science is a process through which we learn about our universe—a process that is not always a straight line to the truth. That is why our ideas about the cosmos sometimes change as we learn more, as they did dramatically when we first recognized that Earth is a planet going around the Sun rather than the center of the universe. In this book, we continually emphasize the nature of science so that students can understand how and why modern theories have gained acceptance and why these theories may change in the future.
- **Theme 4:** *Astronomy belongs to everyone*. Astronomy has played a significant role throughout history in virtually every culture, and the modern science of astronomy owes a debt to these early and largely unsung astronomers. We therefore strive throughout the book to make sure that students understand that astronomical knowledge belongs to everyone, that people of all backgrounds have made and continue to make contributions to astronomical understanding, and that everyone should have the opportunity to study astronomy. Moreover, we seek to motivate students enough to ensure that they will remain engaged in the ongoing human adventure of astronomical discovery throughout their lives, no matter whether they choose to do that only by following the news media or by entering careers relating to astronomy.
- **Theme 5:** *Astronomy affects each of us personally with the new perspectives it offers*. We all conduct the daily business of our lives with reference to some "world view"—a set of personal beliefs about our place and purpose in the universe, which we have developed through a combination of schooling, religious training, and personal thought. This world view shapes our beliefs and many of our actions. Although astronomy does not mandate a particular set of beliefs, it does provide perspectives on the architecture of the universe that can influence how we view ourselves and our world, and these perspectives can potentially affect our behavior. For example, someone who believes Earth to be at the center of the universe might treat our planet quite differently from someone who views it as a tiny and fragile world in the vast cosmos. In many respects, the role of astronomy in shaping world views may represent the deepest connection between the universe and the everyday lives of humans.

Pedagogical Principles

No matter how an astronomy course is taught, it is very important to present material according to well-established pedagogical principles. The following list briefly summarizes the major pedagogical principles that we apply throughout this book.*

- *Stay focused on the big picture*. Astronomy is filled with interesting facts and details, but they are meaningless unless they fit into a big picture view of the universe. We therefore take care to stay focused on the big picture (essentially the themes discussed above) at all times. A major benefit of this approach is that although students may forget individual facts and details after the course is over, the big-picture framework should stay with them for life.
- *Always provide context first*. We all learn new material more easily when we understand why we are learning it. In essence, this is simply the idea that it is easier to get somewhere when you know where you are going. We therefore begin the book (Chapter 1) with a broad overview of modern understanding of the cosmos, so that students know what they will be studying in the rest of the book. We maintain this "context first" approach throughout the book by always telling students what they will be learning, and why, before diving into the details.
- *Make the material relevant*. It's human nature to be more interested in subjects that seem relevant to our lives. Fortunately, astronomy is filled with ideas that touch each

* More detail on these pedagogical principles can be found in the Instructor Guide and in the book *On Teaching Science* by Jeffrey Bennett (Big Kid Science, 2014).

of us personally. For example, the study of our solar system helps us better understand and appreciate our planet Earth, and the study of stars and galaxies helps us learn how we have come to exist. By emphasizing our personal connections to the cosmos, we make the material more meaningful, inspiring students to put in the effort necessary to learn it.

- *Emphasize conceptual understanding over "stamp collecting" of facts*. If we are not careful, astronomy can appear to be an overwhelming collection of facts that are easily forgotten when the course ends. We therefore emphasize a few key conceptual ideas, which we use over and over again. For example, the laws of conservation of energy and conservation of angular momentum (introduced in Section 4.3) reappear throughout the book, and the wide variety of features found on the terrestrial planets are described in terms of just a few basic geological processes. Research shows that, long after the course is over, students are far more likely to retain such conceptual learning than individual facts or details.
- *Proceed from the more familiar and concrete to the less familiar and abstract*. It's well known that children learn best by starting with concrete ideas and then generalizing to abstractions later. The same is true for many adults. We therefore always try to "build bridges to the familiar"— that is, to begin with concrete or familiar ideas and then gradually draw more general principles from them.
- *Use plain language*. Surveys have found that the number of new terms in many introductory astronomy books is larger than the number of words taught in many first-year courses on a foreign language. In essence, this means the books are teaching astronomy in what looks to students like a foreign language! Clearly, it is much easier for students to understand key astronomical concepts if they are explained in plain English without resorting to unnecessary jargon. We have gone to great lengths to eliminate jargon or, at minimum, to replace difficult jargon with terms that are easier to remember in the context of the subject matter.
- *Recognize and address student misconceptions*. Students do not arrive as blank slates. Most students enter our courses not only lacking the knowledge we hope to teach but also holding misconceptions about astronomical ideas. Therefore, to teach correct ideas, we must help students recognize the paradoxes in their prior misconceptions. We address this issue in a number of ways, the most obvious being the presence of many Common Misconceptions boxes. These summarize commonly held misconceptions and explain why they cannot be correct.

The Organizational Structure of *The Essential Cosmic Perspective*

The Essential Cosmic Perspective is organized into six broad topical areas (the six parts in the table of contents), each corresponding to a set of chapters along with related content in Mastering Astronomy. Note that the above themes and pedagogical principles are woven into this structure at every level.

Part Structure

The six parts of *The Essential Cosmic Perspective* each approach their set of chapters in a distinctive way designed to help maintain the focus on the five themes discussed earlier. Here, we summarize the philosophy and content of each part. Note that each part concludes with a two-page Cosmic Context spread designed to tie the part content together into a coherent whole.

PART I Developing Perspective (Chapters 1–3)

Guiding Philosophy: Introduce the big picture, the process of science, and the historical context of astronomy.

The basic goal of these chapters is to give students a big-picture overview and context for the rest of the book, as well as to help them develop an appreciation for the process of science and how science has developed through history. Chapter 1 outlines our modern understanding of the cosmos, so that students gain perspective on the entire universe before diving into its details. Chapter 2 introduces basic sky phenomena, including seasons and phases of the Moon, and provides perspective on how phenomena we experience every day are tied to the broader cosmos. Chapter 3 discusses the nature of science, offering a historical perspective on the development of science and giving students perspective on how science works and how it differs from nonscience.

The Cosmic Context for Part I appears on pp. 80–81.

PART II Key Concepts for Astronomy (Chapters 4–5)

Guiding Philosophy: Connect the physics of the cosmos to everyday experiences.

These chapters lay the groundwork for understanding astronomy through what is sometimes called the "universality of physics"—the idea that a few key principles governing matter, energy, light, and motion explain both the phenomena of our daily lives and the mysteries of the cosmos. Chapter 4 covers the laws of motion, the crucial conservation laws of angular momentum and energy, and the universal law of gravitation. Chapter 5 deals with the nature of light and matter, spectra, and telescopes.

The Cosmic Context for Part II appears on pp. 134–135.

PART III Learning from Other Worlds (Chapters 6–10)

Guiding Philosophy: Learn about Earth by studying other planets in our solar system and beyond.

This set of chapters begins in Chapter 6 with a broad overview of the solar system and its formation, including a 10-page tour that highlights some of the most important and interesting features of the Sun and each of the planets. Chapters 7 to 9 focus, respectively, on the terrestrial planets, the jovian planets, and the small bodies of the solar system. Finally, Chapter 10 turns to the exciting topic of other planetary systems that have been discovered in recent years. Note that Part III is essentially independent of Parts IV and V, and can be covered either before or after them.

The Cosmic Context for Part III appears on pp. 288–289.

PART IV Stars (Chapters 11–14)

Guiding Philosophy: We are intimately connected to the stars.

These are our chapters on stars and stellar life cycles. Chapter 11 covers the Sun in depth, so that it can serve as a concrete model for building an understanding of other stars. Chapter 12 describes the general properties of stars, how we measure these properties, and how we classify stars using the H-R diagram. Chapter 13 covers stellar evolution, tracing the birth-to-death lives of both low- and high-mass stars. Chapter 14 focuses on the end points of stellar evolution: white dwarfs, neutron stars, and black holes.

The Cosmic Context for Part IV appears on pp. 386–387.

PART V Galaxies and Beyond (Chapters 15–18)

Guiding Philosophy: Present galaxy evolution and cosmology together as intimately related topics.

These chapters cover galaxies and cosmology. Chapter 15 presents the Milky Way as a paradigm for galaxies in much the same way that Chapter 11 uses the Sun as a paradigm for stars. Chapter 16 describes the variety of galaxies, how we determine key parameters such as galactic distances and age, and current understanding of galaxy evolution. Chapter 17 focuses on the Big Bang theory and the evidence supporting it, setting the stage for Chapter 18, which explores dark matter and its role in galaxy formation, as well as dark energy and its implications for the fate of the universe.

The Cosmic Context for Part V appears on pp. 496–497.

PART VI Life on Earth and Beyond (Chapter 19)

Guiding Philosophy: The study of life on Earth helps us understand the search for life in the universe.

This part consists of a single chapter. It may be considered optional, to be used as time allows. Those who wish to teach a more detailed course on astrobiology may consider the text *Life in the Universe,* by Jeffrey Bennett and Seth Shostak.

The Cosmic Context for Part VI appears on pp. 534–535.

Chapter Structure

Each chapter is carefully structured to ensure that students understand the goals up front, learn the details, and pull all the ideas together at the end. Note the following key structural elements of each chapter:

- **Chapter Learning Goals:** Each chapter opens with a page offering an enticing image and a brief overview of the chapter, including a list of the section titles and associated learning goals. The learning goals are presented as key questions designed to help students both to understand what they will be learning about and to stay focused on these key goals as they work through the chapter.
- **Introduction:** The main chapter text begins with a one- to three-paragraph introduction.
- **Section Structure:** Chapters are divided into numbered sections, each addressing one key aspect of the chapter material. Each section begins with a short introduction that leads into a set of learning goals relevant to the section—the same learning goals listed at the beginning of the chapter.
- **The Big Picture:** Every chapter narrative ends with this feature, designed to help students put what they've learned in the chapter into the context of the overall goal of gaining a broader perspective on ourselves, our planet, and prospects for life beyond Earth. The final entry in this section is always entitled "My Cosmic Perspective,"; it aims to help students see a personal connection between themselves and the chapter content, with the goal of encouraging them to think more critically about the meaning of all that they learn in their astronomy course.
- **Chapter Summary:** The end-of-chapter summary offers a concise review of the learning goal questions, helping reinforce student understanding of key concepts from the chapter. Thumbnail figures are included to remind students of key illustrations and photos in the chapter.
- **End-of-Chapter Exercises:** Each chapter includes an extensive set of exercises that can be used for study, discussion, or assignment. All of the end-of-chapter exercises are organized into the following subsets:
  - **Visual Skills Check:** A set of questions designed to help students build their skills at interpreting the many types of visual information used in astronomy
  - **Chapter Review Questions:** Questions that students should be able to answer from the reading alone
  - **Does It Make Sense?** (or similar title): A set of short statements, each of which students are expected to evaluate critically so that they can explain why it does or does not make sense. These exercises are generally easy once students understand a particular concept, but difficult otherwise; this makes these questions an excellent probe of comprehension.
  - **Quick Quiz:** A short multiple-choice quiz that allows students to check their basic understanding. Note that, for further self-testing, every chapter also has a Reading, Concept, and Visual quiz available on the Mastering Astronomy web site.
  - **Inclusive Astronomy:** These questions are designed to stimulate discussion about participation in science, and in particular on the ideas that: (1) astronomy belongs to everyone; (2) all cultures have made contributions to astronomical understanding; (3) opportunities for women and minorities have historically been limited; and (4) the scientific community can take active steps to provide more equitable opportunities for the future.
  - **Process of Science Questions:** These questions, which can be used for discussion or essays, are designed to help students think about how science progresses over time. This set always concludes with an activity designed for group work, in order to promote collaborative learning in class.

- **Investigate Further:** The remaining questions are designed for home assignment and are intended to go beyond the earlier review questions. These questions are separated into two groups: (1) Short-Answer/Essay questions that focus on conceptual interpretation, and sometimes on outside research or experiment; (2) Quantitative Problems that require some mathematics, usually based on topics covered in the Mathematical Insight boxes.

Additional Pedagogical Features

You'll find a number of other features designed to increase student understanding, both within individual chapters and at the end of the book, including the following:

- **Think About It:** This feature, which appears throughout the book in the form of short questions integrated into the narrative, gives students the opportunity to reflect on important new concepts. It also serves as an excellent starting point for classroom discussions.
- **See It for Yourself:** This feature also occurs throughout the book, integrated into the narrative; it gives students the opportunity to conduct simple observations or experiments that will help them understand key concepts.
- **Common Misconceptions:** These boxes address popularly held but incorrect ideas related to the chapter material.
- **Special Topic Boxes:** These boxes address supplementary discussion topics related to the chapter material but not prerequisite to the continuing discussion.
- **Extraordinary Claims Boxes:** Carl Sagan made famous the statement "extraordinary claims require extraordinary evidence." These boxes provide students with examples of extraordinary claims about the universe and how they were either supported or debunked as scientists collected more evidence.
- **Cosmic Calculations Boxes:** These boxes contain most of the mathematics used in the book and can be covered or skipped depending on the level of mathematics that you wish to include in your course.
- **Annotated Figures:** Key figures in each chapter use the research-proven technique of annotation—the placement on the figure of carefully crafted text (in blue) to guide students through interpreting graphs, following process figures, and translating between different representations.
- **Cosmic Context Two-Page Figures:** These two-page spreads provide visual summaries of key processes and concepts.
- **Wavelength/Observatory Icons:** For astronomical images, simple icons indicate whether the image is a photo, artist's impression, or computer simulation; whether a photo came from ground-based or space-based observations; and the wavelength band used to take the photo.
- **Video Icons:** These point to videos available in the Study Area of Mastering Astronomy that are relevant to the topic at hand. Tutorial assessments based on these videos are also available for assignment in the instructor Item Library.
- **Cross-References:** When a concept is covered in greater detail elsewhere in the book, we include a cross-reference in brackets to the relevant section (e.g., [**Section 5.2**]).
- **Glossary:** A detailed glossary makes it easy for students to look up important terms.
- **Appendixes:** The appendixes contain a number of useful references and tables including key constants (Appendix A), key formulas (Appendix B), key mathematical skills (Appendix C), and numerous data tables and star charts (Appendixes D–I).

Mastering Astronomy

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 learning and studying on their own. 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 adaptive learning designed to coach them individually—responding to their errors with specific, targeted feedback and giving optional hints for those who need additional guidance. For professors, Mastering Astronomy provides unprecedented ability to automatically monitor and record students' step-by-step work and evaluate the effectiveness of assignments and exams.

Note that nearly all the content available at the Mastering Astronomy site for *The Essential Cosmic Perspective* has been written by the textbook authors. This means that students 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 can study in the most efficient possible way.

All students registered for Mastering Astronomy receive full access to the Study Area which includes three self-study multiple-choice quizzes for each chapter; a large set of "prelecture videos," "narrated figures," "interactive figures," and "math review" videos; a set of interactive "self-guided tutorials" that go in depth on topics that some students find particularly challenging; a downloadable set of group activities; and much more.

Instructors have access to many additional resources, including a large "Item Library" of assignable material that includes more than 250 author-written tutorials, all of the end-of-chapter exercises, all the questions from the self-study quizzes in the Study Area, and a test bank. Instructors also have access to the author-written Instructor Guide and teaching resources including PowerPoint Lecture Outlines, a complete set of high-resolution JPEGs of all images from the book, and PRS-enabled clicker quizzes based on the book and book-specific interactive media.

Supplements for *The Essential Cosmic Perspective*

The Essential Cosmic Perspective is much more than just a textbook. It is a complete package of teaching, learning, and assessment resources designed to help both teachers and students. In addition to MasteringAstronomy (described above), the following supplements are available with this book:

- **SkyGazer v5.0**: Based on *Voyager V*, SkyGazer, one of the world's most popular planetarium programs now available for download, makes it easy for students to learn constellations and explore the wonders of the sky through interactive exercises and demonstrations. Accompanying activities are available in LoPresto's Astronomy Media Workbook, Seventh Edition, available both on the MasteringAstronomy study area and on the SkyGazer site. Ask your Pearson sales representative for details.
- **Starry Night™ College** (ISBN 0-137-34608-5): Now available as an additional option with *The Essential Cosmic Perspective*, Starry Night has been acclaimed as the world's most realistic desktop planetarium software. This special version has an easy-to-use point-and-click interface and is available as an additional bundle. The Starry Night Activity Workbook, consisting of thirty-five worksheets for homework or lab, based on Starry Night planetarium software, is available for download in the MasteringAstronomy study area or with a Starry Night College access code. Ask your Pearson sales representative for details.
- **Lecture Tutorials for Introductory Astronomy** (ISBN 0-135-80702-6) by Edward E. Prather, Jeffrey P. Adams, Gina Brissenden, and Colin S. Wallace: Over forty lecture tutorials are designed to engage students in critical reasoning and spark classroom discussion.
- **Sky and Telescope: Special Student Supplement** (ISBN 0-321-70620-X): The nine articles, each with an assessment following, provide a general review as well as covering such topics as the process of science, the scale of the universe, and our place in the universe. The supplement is available for bundling; ask your Pearson sales representative for details.
- **Observation Exercises in Astronomy** (ISBN 0-321-63812-3): This manual includes fifteen observation activities that can be used with a number of different planetarium software packages.
- **McCrady/Rice Astronomy Labs: A Concept Oriented Approach** (ISBN: 0-321-86177-9): This customizable lab is available in the Pearson Custom Library. It consists of 40 conceptually oriented introductory astronomy labs that focus on the mid to higher levels of Bloom's taxonomy: application, synthesis, and analysis. The labs are all written to minimize equipment requirements and are largely created to maximize the use of inexpensive everyday objects such as flashlights, construction paper, and theater gels.

Instructor-Only Supplements

Several additional supplements are available for instructors only. Contact your local Pearson sales representative to find out more about the following supplements:

- **The Instructor Resources tab** in MasteringAstronomy provides a wealth of lecture and teaching resources, including high-resolution JPEGs of all images from the book for in-class projection, Narrated Figures, based on figures from the book, pre-built PowerPoint Lecture Outlines, answers to SkyGazer and Starry Night workbooks, and PRS-enabled Clicker Quizzes based on the book and book-specific interactive media.
- **Instructor Guide** (ISBN 0-135-79513-3): This guide contains a detailed overview of the text, sample syllabi for courses of different emphasis and duration, suggestions for teaching strategies, answers or discussion points for all Think About It and See It for Yourself questions in the text, solutions to end-of-chapter problems, and a detailed reference guide summarizing media resources available for every chapter and section in the book. Word files can be downloaded from the instructor resource section of MasteringAstronomy.
- **Test Bank** (ISBN 0-135-87704-0): The Test Bank includes hundreds of multiple-choice, true/false, and short-answer questions, plus Process of Science questions for each chapter. TestGen and Word files can be downloaded from the instructor resource section of the study area in MasteringAstronomy.

Acknowledgments

Our textbook carries only four author names, but in fact it is the result of hard work by a long list of committed individuals. We could not possibly list everyone who has helped, but we would like to call attention to a few people who have played particularly important roles. First, we thank our past and present editors and production managers, including Bill Poole, Robin Heyden, Joan Marsh, Sami Iwata, Ben Roberts, Adam Black, Nancy Whilton, Sally Lifland, Jeanne Zalesky, and Deb Harden, along with many others who have contributed to making our books possible. For this edition, we thank those who have helped with our supplements and final accuracy checks: James Cooney, Andy Sustich, and Wes Tobin.

We've also been fortunate to have an outstanding group of reviewers, whose extensive comments and suggestions helped us shape the book. We thank all those who have reviewed drafts of the book in various stages, including the following individuals (listed with their affiliations at the time they contributed their reviews):

Eric Agol, *University of Washington*
Marilyn Akins, *Broome Community College*
Caspar Amman, *NCAR*
Christopher M. Anderson, *University of Wisconsin*
John Anderson, *University of North Florida*
Peter S. Anderson, *Oakland Community College*
Nahum Arav, *Virginia Technical University*
Phil Armitage, *University of Colorado*
Keith Ashman
Thomas Ayres, *University of Colorado*
Simon P. Balm, *Santa Monica College*
Reba Bandyopadhyay, *University of Florida*
Nadine Barlow, *Northern Arizona University*
Cecilia Barnbaum, *Valdosta State University*

John Beaver, *University of Wisconsin at Fox Valley*
Peter A. Becker, *George Mason University*
Timothy C. Beers, *National Optical Astronomy Observatory*
Jim Bell, *Arizona State University*
Priscilla J. Benson, *Wellesley College*
Zach Berta-Thompson, *University of Colorado*
Rick Binzel, *Massachusetts Institute of Technology*
Philip Blanco, *Grossmont College*
Jeff R. Bodart, *Chipola College*
Howard Bond, *Space Telescope Science Institute*
Bernard W. Bopp, *University of Toledo*
Sukanta Bose, *Washington State University*
David Brain, *University of Colorado*
David Branch, *University of Oklahoma*
John C. Brandt, *University of New Mexico*
James E. Brau, *University of Oregon*
Jean P. Brodie, *UCO/Lick Observatory, University of California, Santa Cruz*
Erik Brogt, *University of Canterbury*
James Brooks, *Florida State University*
Daniel Bruton, *Stephen F. Austin State University*
Thomas Burbine, *Moraine Valley Community College*
Debra Burris, *University of Central Arkansas*
Scott Calvin, *Sarah Lawrence College*
Amy Campbell, *Louisiana State University*
Humberto Campins, *University of Central Florida*
Robin Canup, *Southwest Research Institute*
Eugene R. Capriotti, *Michigan State University*
Eric Carlson, *Wake Forest University*
David A. Cebula, *Pacific University*
Supriya Chakrabarti, *University of Massachusetts, Lowell*
Clark Chapman, *Southwest Research Institute*
Kwang-Ping Cheng, *California State University, Fullerton*
Dipak Chowdhury, *Indiana University—Purdue University Fort Wayne*
Chris Churchill, *New Mexico State University*
Kelly Cline, *Carroll College*
Josh Colwell, *University of Central Florida*
James Cooney, *University of Central Florida*
Anita B. Corn, *Colorado School of Mines*
Philip E. Corn, *Red Rocks Community College*
Kelli Corrado, *Montgomery County Community College*
Peter Cottrell, *University of Canterbury*
John Cowan, *University of Oklahoma*
Kevin Crosby, *Carthage College*
Christopher Crow, *Indiana University—Purdue University Fort Wayne*
Manfred Cuntz, *University of Texas at Arlington*
Charles Danforth, *University of Colorado*
Christopher De Vries, *California State University, Stanislaus*
John M. Dickey, *University of Minnesota*
Mark Dickinson, *National Optical Astronomy Observatory*
Matthias Dietrich, *Worcester State University*
Jim Dove, *Metropolitan State College of Denver*
Doug Duncan, *University of Colorado*
Bryan Dunne, *University of Illinois, Urbana-Champaign*
Suzan Edwards, *Smith College*
Robert Egler, *North Carolina State University at Raleigh*
Paul Eskridge, *Minnesota State University*
Dan Fabrycky, *University of Chicago*
David Falk, *Los Angeles Valley College*
Timothy Farris, *Vanderbilt University*
Harry Ferguson, *Space Telescope Science Institute*
Robert A. Fesen, *Dartmouth College*
Tom Fleming, *University of Arizona*
Douglas Franklin, *Western Illinois University*
Sidney Freudenstein, *Metropolitan State College of Denver*
Martin Gaskell, *University of Nebraska*
Richard Gelderman, *Western Kentucky University*
Harold A. Geller, *George Mason University*
Donna Gifford, *Pima Community College*
Mitch Gillam, *Marion L. Steele High School*
Bernard Gilroy, *The Hun School of Princeton*
Owen Gingerich, *Harvard–Smithsonian* (Historical Accuracy Reviewer)
David Graff, *U.S. Merchant Marine Academy*
Richard Gray, *Appalachian State University*
Kevin Grazier, *Jet Propulsion Laboratory*
Robert Greeney, *Holyoke Community College*
Henry Greenside, *Duke University*
Alan Greer, *Gonzaga University*
John Griffith, *Lin-Benton Community College*
David Griffiths, *Oregon State University*
David Grinspoon, *Planetary Science Institute*
John Gris, *University of Delaware*
Bruce Gronich, *University of Texas at El Paso*
Thomasana Hail, *Parkland University*
Andrew Hamilton, *University of Colorado*
Jim Hamm, *Big Bend Community College*
Paul Harderson, *Planetary Science Institute*
Charles Hartley, *Hartwick College*
J. Hasbun, *University of West Georgia*
Joe Heafner, *Catawba Valley Community College*
Todd Henry, *Georgia State University*
David Herrick, *Maysville Community College*
Dennis Hibbert, *Everett Community College*
Scott Hildreth, *Chabot College*
Tracy Hodge, *Berea College*
Lynnette Hoerner, *Red Rocks Community College*
Mark Hollabaugh, *Normandale Community College*
Richard Holland, *Southern Illinois University, Carbondale*
Seth Hornstein, *University of Colorado*
Joseph Howard, *Salisbury University*
James Christopher Hunt, *Prince George's Community College*
Richard Ignace, *University of Wisconsin*
James Imamura, *University of Oregon*
Douglas R. Ingram, *Texas Christian University*
Assad Istephan, *Madonna University*
Bruce Jakosky, *University of Colorado*
Adam G. Jensen, *University of Colorado*
Dave Jewitt, *University of California, Los Angeles*
Adam Johnston, *Weber State University*
Lauren Jones, *Gettysburg College*
Kishor T. Kapale, *Western IIIinois University*
William Keel, *University of Alabama*
Julia Kennefick, *University of Arkansas*
Steve Kipp, *University of Minnesota, Mankato*
Kurtis Koll, *Cameron University*
Ichishiro Konno, *University of Texas at San Antonio*
John Kormendy, *University of Texas at Austin*
Eric Korpela, *University of California, Berkeley*
Arthur Kosowsky, *University of Pittsburgh*
Julia Kregenow, *Penn State University*
Kevin Krisciunas, *Texas A&M*
Emily Lakdawalla, *The Planetary Society*

David Lamp, *Texas Technical University*
Ted La Rosa, *Kennesaw State University*
Kenneth Lanzetta, *Stony Brook University*
Kristine Larsen, *Central Connecticut State University*
Ana Marie Larson, *University of Washington*
Stephen Lattanzio, *Orange Coast College*
Chris Laws, *University of Washington*
Larry Lebofsky, *University of Arizona*
Patrick Lestrade, *Mississippi State University*
Nancy Levenson, *University of Kentucky*
Hal Levison, *Southwest Research Institute*
David M. Lind, *Florida State University*
Mario Livio, *Space Telescope Science Institute*
Abraham Loeb, *Harvard University*
Michael LoPresto, *Henry Ford Community College*
William R. Luebke, *Modesto Junior College*
Ihor Luhach, *Valencia Community College*
Darrell Jack MacConnell, *Community College of Baltimore City*
Marie Machacek, *Massachusetts Institute of Technology*
Loris Magnani, *University of Georgia*
Steven Majewski, *University of Virginia*
J. McKim Malville, *University of Colorado*
Geoff Marcy, *University of California, Berkeley*
Mark Marley, *Ames Research Center*
Linda Martel, *University of Hawaii*
Phil Matheson, *Salt Lake Community College*
John Mattox, *Fayetteville State University*
Marles McCurdy, *Tarrant County College*
Stacy McGaugh, *Case Western University*
Kevin McLin, *University of Colorado*
Michael Mendillo, *Boston University*
Steven Merriman, *Moraine Valley Community College*
Barry Metz, *Delaware County Community College*
William Millar, *Grand Rapids Community College*
Dinah Moche, *Queensborough Community College of City University, New York*
Steve Mojzsis, *University of Colorado*
Irina Mullins, *Houston Community College–Central*
Stephen Murray, *University of California, Santa Cruz*
Zdzislaw E. Musielak, *University of Texas at Arlington*
Charles Nelson, *Drake University*
Gerald H. Newsom, *Ohio State University*
Francis Nimmo, *University of California, Santa Cruz*
Tyler Nordgren, *University of Redlands*
Lauren Novatne, *Reedley College*
Brian Oetiker, *Sam Houston State University*
Richard Olenick, *University of Dallas*
John P. Oliver, *University of Florida*
Rachel Osten, *Space Telescope Science Institute*
Stacy Palen, *Weber State University*
Russell L. Palma, *Sam Houston State University*
Bob Pappalardo, *Jet Propulsion Laboratory*
Mark Pecaut, *Rockhurst University*
Jon Pedicino, *College of the Redwoods*
Bryan Penprase, *Pomona College*
Eric S. Perlman, *Florida Institute of Technology*
Peggy Perozzo, *Mary Baldwin College*
Greg Perugini, *Burlington County College*
Charles Peterson, *University of Missouri, Columbia*
Cynthia W. Peterson, *University of Connecticut*
Jorge Piekarewicz, *Florida State University*
Lawrence Pinsky, *University of Houston*
Stephanie Plante, *Grossmont College*
Jascha Polet, *California State Polytechnic University, Pomona*
Matthew Price, *Oregon State University*
Harrison B. Prosper, *Florida State University*
Monica Ramirez, *Aims College, Colorado*
Christina Reeves-Shull, *Richland College*
Todd M. Rigg, *City College of San Francisco*
Elizabeth Roettger, *DePaul University*
Roy Rubins, *University of Texas at Arlington*
April Russell, *Siena College*
Carl Rutledge, *East Central University*
Bob Sackett, *Saddleback College*
Rex Saffer, *Villanova University*
John Safko, *University of South Carolina*
James A. Scarborough, *Delta State University*
Britt Scharringhausen, *Ithaca College*
Ann Schmiedekamp, *Pennsylvania State University, Abington*
Joslyn Schoemer, *Denver Museum of Nature and Science*
James Schombert, *University of Oregon*
Gregory Seab, *University of New Orleans*
Bennett Seidenstein, *Arundel High School*
Larry Sessions, *Metropolitan State College of Denver*
Michael Shara, *American Museum of Natural History*
Anwar Shiekh, *Colorado Mesa University*
Seth Shostak, *SETI Institute*
Ralph Siegel, *Montgomery College, Germantown Campus*
Philip I. Siemens, *Oregon State University*
Caroline Simpson, *Florida International University*
Paul Sipiera, *William Harper Rainey College*
Earl F. Skelton, *George Washington University*
Evan Skillman, *University of Minnesota*
Michael Skrutskie, *University of Virginia*
Mark H. Slovak, *Louisiana State University*
Norma Small-Warren, *Howard University*
Jessica Smay, *San Jose City College*
Dale Smith, *Bowling Green State University*
Brad Snowder, *Western Washington University*
Brent Sorenson, *Southern Utah University*
James R. Sowell, *Georgia Technical University*
Kelli Spangler, *Montgomery County Community College*
John Spencer, *Southwest Research Institute*
Darryl Stanford, *City College of San Francisco*
George R. Stanley, *San Antonio College*
Bob Stein, *Michigan State University*
Peter Stein, *Bloomsburg University of Pennsylvania*
Adriane Steinacker, *University of California, Santa Cruz*
Glen Stewart, *University of Colorado*
John Stolar, *West Chester University*
Irina Struganova, *Valencia Community College*
Jack Sulentic, *University of Alabama*
Andy Sustich, *Arkansas State University*
C. Sean Sutton, *Mount Holyoke College*
Beverley A. P. Taylor, *Miami University*
Brett Taylor, *Radford University*
Jeff Taylor, *University of Hawaii*
Donald M. Terndrup, *Ohio State University*
Dave Tholen, *University of Hawaii*
Nick Thomas, *University of Bern*
Frank Timmes, *Arizona State University*
Wes Tobin, *Indiana University East*

David Trott, *Metro State College*
David Vakil, *El Camino College*
Trina Van Ausdal, *Salt Lake Community College*
Dimitri Veras, *Cambridge University*
Licia Verde, *Institute of Cosmological Studies, Barcelona*
Nicole Vogt, *New Mexico State University*
Darryl Walke, *Rariton Valley Community College*
Fred Walter, *State University of New York, Stony Brook*
Marina Walther-Antonio, *Mayo Clinic*
James Webb, *Florida International University*
John Weiss, *Carleton College*
Mark Whittle, *University of Virginia*
Paul J. Wiita, *The College of New Jersey*
Francis Wilkin, *Union College*
Lisa M. Will, *Mesa Community College*
Jonathan Williams, *University of Hawaii*
Terry Willis, *Chesapeake College*
Grant Wilson, *University of Massachusetts, Amherst*
Jeremy Wood, *Hazard Community College*
J. Wayne Wooten, *Pensacola Junior College*
Guy Worthey, *Washington State University, Pullman*
Jason Wright, *Penn State University*
Scott Yager, *Brevard College*
Don Yeomans, *Jet Propulsion Laboratory*
Andrew Young, *Casper College*
Arthur Young, *San Diego State University*
Tim Young, *University of North Dakota*
Min S. Yun, *University of Massachusetts, Amherst*
Dennis Zaritsky, *University of Arizona*
Robert L. Zimmerman, *University of Oregon*

Finally, we thank the many people who have greatly influenced our outlook on education and our perspective on the universe over the years, including Tom Ayres, Fran Bagenal, Forrest Boley, Robert A. Brown, George Dulk, Erica Ellingson, Katy Garmany, Jeff Goldstein, David Grinspoon, Robin Heyden, Don Hunten, Joan Marsh, Catherine McCord, Dick McCray, Dee Mook, Cherilynn Morrow, Charlie Pellerin, Carl Sagan, Mike Shull, John Spencer, and John Stocke.

Jeff Bennett
Megan Donahue
Nick Schneider
Mark Voit

About the Authors

Jeffrey Bennett

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 latest project is a free, online curriculum for middle school science, found at grade8science.com. Learn more about Jeff and his projects at his personal and educational web sites, which respectively are www.jeffreyBennett.com and www.BigKidScience.com.

Megan Donahue

Megan Donahue is a University Distinguished 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. She was the President of the American Astronomical Society from 2018–2020. Her research, published in over 200 articles, exploits 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. They collaborate on many projects, including this textbook series, many peer-reviewed jointly-authored astrophysics papers, and the adventure of parenting of three adult children, Michaela, Sebastian, and Angela. Megan has run three full marathons, including Boston. These days she runs trails with friends and plays piano and bass guitar in garage bands for fun and no profit.

Nicholas Schneider

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, NASA's Exceptional Scientific Achievement Medal, in addition to university and national teaching awards. Off the job, Nick enjoys exploring the outdoors with his family and figuring out how things work.

Mark Voit

Mark Voit is a full professor in the Department of Physics and Astronomy and served as 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 her terrific meals. 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 help 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 paragraphs 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 (e.g., Common Misconceptions, Special Topics) 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 Chapter Summary, 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 Review and 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.
- 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 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, but 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 found 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.
- All answers and other writing fully self-contained. A good check is to imagine that a friend will be reading your work and to ask yourself whether the friend will 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. 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.

Foreword

The Meaning of *The Cosmic Perspective*

by Neil deGrasse Tyson

Astrophysicist Neil deGrasse Tyson is the Frederick P. Rose Director of New York City's Hayden Planetarium at the American Museum of Natural History. He has written numerous books and articles, has hosted the PBS series NOVA scienceNOW *and the globally popular* Cosmos: A Spacetime Odyssey, *and was named one of the "Time 100"—Time magazine's list of the 100 most influential people in the world.*

Of all the sciences cultivated by mankind, Astronomy is acknowledged to be, and undoubtedly is, the most sublime, the most interesting, and the most useful. For, by knowledge derived from this science, not only the bulk of the Earth is discovered . . . ; but our very faculties are enlarged with the grandeur of the ideas it conveys, our minds exalted above [their] low contracted prejudices.

James Ferguson, *Astronomy Explained Upon Sir Isaac Newton's Principles, and Made Easy To Those Who Have Not Studied Mathematics* (1757)

LONG BEFORE ANYONE knew that the universe had a beginning, before we knew that the nearest large galaxy lies two and a half million light-years from Earth, before we knew how stars work or whether atoms exist, James Ferguson's enthusiastic introduction to his favorite science rang true.

But who gets to think that way? Who gets to celebrate this cosmic view of life? Not the migrant farm worker. Not the sweatshop worker. Certainly not the homeless person rummaging through the trash for food. You need the luxury of time not spent on mere survival. You need to live in a nation whose government values the search to understand humanity's place in the universe. You need a society in which intellectual pursuit can take you to the frontiers of discovery, and in which news of your discoveries can be routinely disseminated.

When I pause and reflect on our expanding universe, with its galaxies hurtling away from one another, embedded with the ever-stretching, four-dimensional fabric of space and time, sometimes I forget that uncounted people walk this Earth without food or shelter, and that children are disproportionately represented among them.

When I pore over the data that establish the mysterious presence of dark matter and dark energy throughout the universe, sometimes I forget that every day—every twenty-four-hour rotation of Earth—people are killing and being killed, in the name of someone's ideology.

When I track the orbits of asteroids, comets, and planets, each one a pirouetting dancer in a cosmic ballet choreographed by the forces of gravity, sometimes I forget that too many people act in wanton disregard for the delicate interplay of Earth's atmosphere, oceans, and land, with consequences that our children and our children's children will witness and pay for with their health and well-being.

And sometimes I forget that powerful people rarely do all they can to help those who cannot help themselves.

I occasionally forget those things because, however big the world is—in our hearts, our minds, and our outsize atlases—the universe is even bigger. A depressing thought to some, but a liberating thought to me.

Consider an adult who tends to the traumas of a child: a broken toy, a scraped knee, a schoolyard bully. Adults know that kids have no clue what constitutes a genuine problem, because inexperience greatly limits their childhood perspective.

As grown-ups, dare we admit to ourselves that we, too, have a collective immaturity of view? Dare we admit that our thoughts and behaviors spring from a belief that the world revolves around us? Part the curtains of society's racial, ethnic, religious, national, and cultural conflicts, and you find the human ego turning the knobs and pulling the levers.

Now imagine a world in which everyone, but especially people with power and influence, holds an expanded view of our place in the cosmos. With that perspective, our problems would shrink—or never arise at all—and we could celebrate our earthly differences while shunning the behavior of our predecessors who slaughtered each other because of them.

* * *

Back in February 2000, the newly rebuilt Hayden Planetarium featured a space show called "Passport to the Universe," which took visitors on a virtual zoom from New York City to the edge of the cosmos. En route the audience saw Earth, then the solar system, then the 100 billion stars of the Milky Way galaxy shrink to barely visible dots on the planetarium dome.

I soon received a letter from an Ivy League professor of psychology who wanted to administer a questionnaire to visitors, assessing the depth of their depression after viewing the show. Our show, he wrote, elicited the most dramatic feelings of smallness he had ever experienced.

How could that be? Every time I see the show, I feel alive and spirited and connected. I also feel large, knowing that the goings-on within the three-pound human brain are what enabled us to figure out our place in the universe.

Allow me to suggest that it's the professor, not I, who has misread nature. His ego was too big to begin with, inflated by delusions of significance and fed by cultural assumptions that human beings are more important than everything else in the universe.

In all fairness to the fellow, powerful forces in society leave most of us susceptible. As was I . . . until the day I learned in biology class that more bacteria live and work in one centimeter of my colon than the number of people who have ever existed in the world. That kind of information makes you think twice about who—or what—is actually in charge.

From that day on, I began to think of people not as the masters of space and time but as participants in a great cosmic chain of being, with a direct genetic link across species both living and extinct, extending back nearly 4 billion years to the earliest single-celled organisms on Earth.

✳ ✳ ✳

Need more ego softeners? Simple comparisons of quantity, size, and scale do the job well.

Take water. It's simple, common, and vital. There are more molecules of water in an eight-ounce cup of the stuff than there are cups of water in all the world's oceans. Every cup that passes through a single person and eventually rejoins the world's water supply holds enough molecules to mix 1,500 of them into every other cup of water in the world. No way around it: some of the water you just drank passed through the kidneys of Socrates, Genghis Khan, and Joan of Arc.

How about air? Also vital. A single breathful draws in more air molecules than there are breathfuls of air in Earth's entire atmosphere. That means some of the air you just breathed passed through the lungs of Napoleon, Beethoven, Lincoln, and Billy the Kid.

Time to get cosmic. There are more stars in the universe than grains of sand on any beach, more stars than seconds have passed since Earth formed, more stars than words and sounds ever uttered by all the humans who ever lived.

Want a sweeping view of the past? Our unfolding cosmic perspective takes you there. Light takes time to reach Earth's observatories from the depths of space, and so you see objects and phenomena not as they are but as they once were. That means the universe acts like a giant time machine: The farther away you look, the further back in time you see—back almost to the beginning of time itself. Within that horizon of reckoning, cosmic evolution unfolds continuously, in full view.

Want to know what we're made of? Again, the cosmic perspective offers a bigger answer than you might expect. The chemical elements of the universe are forged in the fires of high-mass stars that end their lives in stupendous explosions, enriching their host galaxies with the chemical arsenal of life as we know it. We are not simply in the universe. The universe is in us. Yes, we are stardust.

✳ ✳ ✳

Again and again across the centuries, cosmic discoveries have demoted our self-image. Earth was once assumed to be astronomically unique, until astronomers learned that Earth is just another planet orbiting the Sun. Then we presumed the Sun was unique, until we learned that the countless stars of the night sky are suns themselves. Then we presumed our galaxy, the Milky Way, was the entire known universe, until we established that the countless fuzzy things in the sky are other galaxies, dotting the landscape of our known universe.

The cosmic perspective flows from fundamental knowledge. But it's more than just what you know. It's also about having the wisdom and insight to apply that knowledge to assessing our place in the universe. And its attributes are clear:

- The cosmic perspective comes from the frontiers of science, yet is not solely the provenance of the scientist. It belongs to everyone.
- The cosmic perspective is humble.
- The cosmic perspective is spiritual—even redemptive—but is not religious.
- The cosmic perspective enables us to grasp, in the same thought, the large and the small.
- The cosmic perspective opens our minds to extraordinary ideas but does not leave them so open that our brains spill out, making us susceptible to believing anything we're told.
- The cosmic perspective opens our eyes to the universe, not as a benevolent cradle designed to nurture life but as a cold, lonely, hazardous place.
- The cosmic perspective shows Earth to be a mote, but a precious mote and, for the moment, the only home we have.
- The cosmic perspective finds beauty in the images of planets, moons, stars, and nebulae but also celebrates the laws of physics that shape them.
- The cosmic perspective enables us to see beyond our circumstances, allowing us to transcend the primal search for food, shelter, and sex.
- The cosmic perspective reminds us that in space, where there is no air, a flag will not wave—an indication that perhaps flag waving and space exploration do not mix.
- The cosmic perspective not only embraces our genetic kinship with all life on Earth but also values our chemical kinship with any yet-to-be discovered life in the universe, as well as our atomic kinship with the universe itself.

✳ ✳ ✳

At least once a week, if not once a day, we might each ponder what cosmic truths lie undiscovered before us, perhaps awaiting the arrival of a clever thinker, an ingenious experiment, or an innovative space mission to reveal them. We might further ponder how those discoveries may one day transform life on Earth.

Absent such curiosity, we are no different from the provincial farmer who expresses no need to venture beyond the county line, because his forty acres meet all his needs. Yet if all our predecessors had felt that way, the farmer would instead be a cave dweller, chasing down his dinner with a stick and a rock.

During our brief stay on planet Earth, we owe ourselves and our descendants the opportunity to explore—in part because it's fun to do. But there's a far nobler reason. The day our knowledge of the cosmos ceases to expand, we risk regressing to the childish view that the universe figuratively and literally revolves around us. In that bleak world, arms-bearing, resource-hungry people and nations would be prone to act on their "low contracted prejudices." And that would be the last gasp of human enlightenment—until the rise of a visionary new culture that could once again embrace the cosmic perspective.

▲ Astronauts get a unique opportunity to experience a cosmic perspective. Here, astronaut John Grunsfeld has a CD of *The Cosmic Perspective* floating in front of him while orbiting Earth during the Space Shuttle's final servicing mission to the Hubble Space Telescope (May 2009).

1 A Modern View of the Universe

This Hubble Space Telescope photo shows thousands of galaxies in a region of the sky so small you could cover it with a grain of sand held at arm's length.

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?

1.3 Spaceship Earth
- How is Earth moving through space?
- How do galaxies move within the universe?

ESSENTIAL PREPARATION

1. How to Succeed in Your Astronomy Course **[pages xx–xxi]**
2. Powers of 10 **[Appendixes C.1 and C.2]**
3. Working with Units **[Appendix C.3]**
4. The Metric System (SI) **[Appendix C.4]**

Far from city lights on a clear night, you can gaze upward at a sky filled with stars. Lie back and watch for a few hours, and you will observe the stars marching steadily across the sky. Confronted by the seemingly infinite heavens, you might wonder how Earth and the universe came to be. If you do, you will be sharing an experience common to humans around the world and in thousands of generations past.

Modern science offers answers to many of our fundamental questions about the universe and our place within it. We now know the basic content and scale of the universe. We know the ages of Earth and the universe. And, although much remains to be discovered, we are rapidly learning how the simple ingredients of the early universe developed into the incredible diversity of life on Earth—and, perhaps, of life on other worlds as well.

In this first chapter, we will survey the scale, history, and motion of the universe. This "big picture" perspective on our universe will provide a base on which you'll be able to build a deeper understanding in the rest of the book.

A Modern View of the Universe

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 in a vast universe.

The historical path to this knowledge was long and complex. In later chapters, we'll see that the ancient belief in an Earth-centered (or *geocentric*) universe changed only when people were confronted by strong evidence to the contrary, and we'll explore how the method of learning that we call *science* enabled us to acquire this evidence. First, however, it's useful to have a general picture of the universe as we know it today.

What is our place in the universe?

Take a look at the remarkable photo that opens this chapter (on page 1). This photo, taken by the Hubble Space Telescope, 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 it covers an almost unimaginable expanse of both space and time: Nearly every object within it is a *galaxy* containing billions of stars, and some of the smaller smudges are galaxies so far away that their light has taken billions of years to reach us. Let's begin our study of astronomy by exploring what a photo like this one tells us about our own place in the universe.

Our Cosmic Address The galaxies that we see in the Hubble Space Telescope photo make up just one of several key levels of structure in our universe, all illustrated as our "cosmic address" in Figure 1.1.

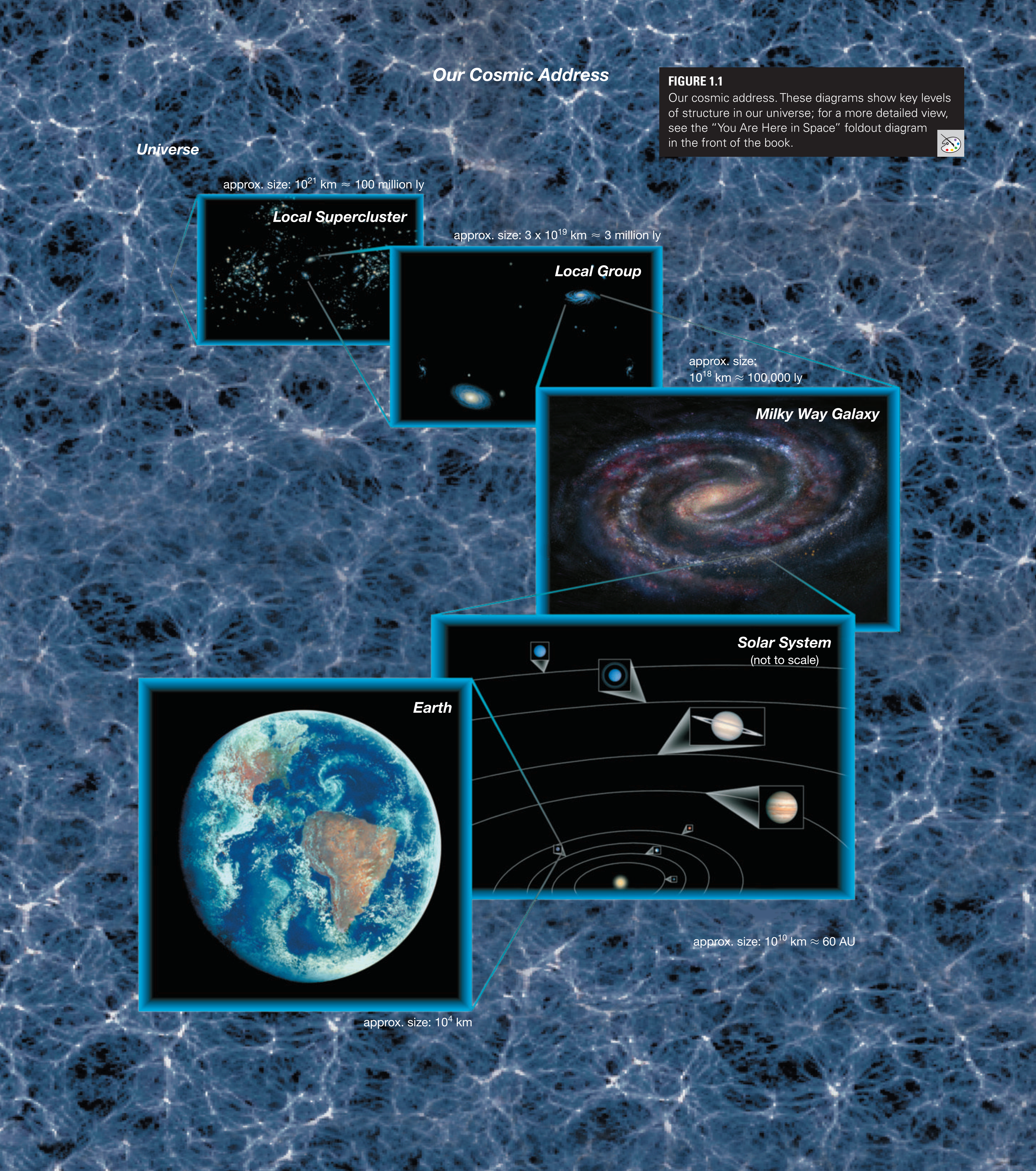


FIGURE 1.1
Our cosmic address. These diagrams show key levels of structure in our universe; for a more detailed view, see the "You Are Here in Space" foldout diagram in the front of the book.

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*. 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. Most of these stars are orbited by planets, giving them their own "solar systems" (also called "star systems" or "planetary systems"). 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**.

We live on one planet orbiting one star among more than 100 billion stars and planets in the Milky Way Galaxy, which in turn is one of billions of galaxies in the universe.

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").

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.

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?

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.
- One **light-year (ly)** is the distance that light can travel in 1 year, which is about 10 trillion kilometers (6 trillion miles). We generally use light-years to describe the distances of stars and galaxies.

Be sure to note that a light-year is a unit of *distance*, not of time. Light travels at the speed of light, which is about 300,000 kilometers per second. We therefore say that one *light-second* is about 300,000 kilometers because that is the distance light travels in 1 second. Similarly, one light-minute is the distance that light travels in 1 minute, one light-hour is the distance that light travels in 1 hour, and so on. Cosmic Calculations 1.1 shows that light travels about 10 trillion kilometers in 1 year, so that distance represents a light-year.

Looking Back in Time The speed of light is extremely fast by earthly standards. It is so fast that if you could make light go in circles, it could

Cosmic Calculations 1.1

How Far Is a Light-Year?

We can calculate the distance represented by a light-year by recalling that

$$\text{distance} = \text{speed} \times \text{time}$$

For example, at a speed of 50 km/hr, in 2 hours you travel 50 km/hr × 2 hr = 100 km. To find the distance represented by 1 light-year, we multiply the speed of light by 1 year. Because we are given the speed of light in kilometers per *second* but the time as 1 *year*, we must carry out the multiplication while converting 1 year into seconds. (See Appendix C for a review of unit conversions.) The result is

$$\begin{aligned} 1 \text{ light-year} &= (\text{speed of light}) \times (1 \text{ yr}) \\ &= \left(300{,}000 \frac{\text{km}}{\cancel{\text{s}}}\right) \times (1 \cancel{\text{yr}}) \times \frac{365 \cancel{\text{days}}}{1 \cancel{\text{yr}}} \\ &\quad \times \frac{24 \cancel{\text{hr}}}{1 \cancel{\text{day}}} \times \frac{60 \cancel{\text{min}}}{1 \cancel{\text{hr}}} \times \frac{60 \cancel{\text{s}}}{1 \cancel{\text{min}}} \\ &= 9{,}460{,}000{,}000{,}000 \text{ km} \\ &= 9.46 \text{ trillion km} \end{aligned}$$

That is, 1 light-year is about 9.46 trillion kilometers, which we can approximate as 10 trillion kilometers. This can be easier to write with powers of 10 (see Appendix C.1 for a review); recall that 1 trillion is a 1 followed by 12 zeros, or 10^{12}, so 10 trillion can be written as 10^{13}.

circle Earth nearly eight times in a single second. Nevertheless, even light takes time to travel the vast distances in space. Light takes a little more than 1 second to reach Earth from the Moon, and about 8 minutes to reach Earth from the Sun. Stars are so far away that their light takes years to reach us, which is why we measure their distances in light-years.

Because light takes time to travel through space, we are led to a remarkable fact: **The farther away we look in distance, the further back we look in time.** For example, the brightest star in the night sky, Sirius, is about 8 light-years away, which means its light takes about 8 years to reach us. When we look at Sirius, we are seeing it not as it is today but as it was about 8 years ago.

Light takes time to travel the vast distances in space. When we look deep into space, we also look far into the past.

The effect is more dramatic at greater distances. The Andromeda Galaxy (Figure 1.2) lies about 2.5 million light-years from Earth, 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. Some of the galaxies in the Hubble Space Telescope photo that opens the chapter are more than 12 billion light-years away, meaning we see them as they were more than 12 billion years ago.

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 100,000 years before the light from the near side. Figure 1.2 therefore shows different parts of

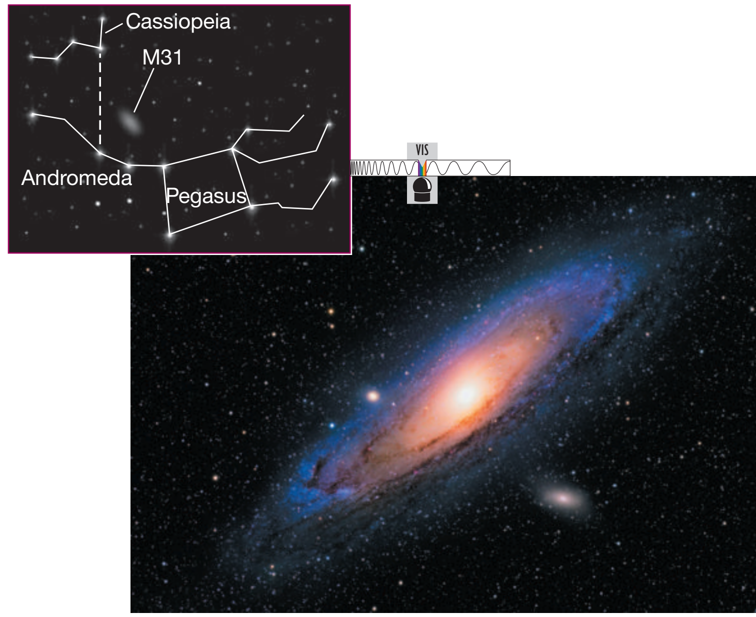


FIGURE 1.2
The Andromeda Galaxy (also known as M31). When we look at this galaxy, we see light that has been traveling through space for 2.5 million years. The inset shows the galaxy's location in the constellation Andromeda.

BASIC ASTRONOMICAL DEFINITIONS

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 has not cleared its orbital path, 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 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 that of millions, billions, or even trillions of stars.

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

supercluster A gigantic region of space in which 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 10 trillion kilometers (more precisely, 9.46 trillion km).

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

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

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 a light-year is 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 reads "It will take me 6 trillion miles to finish this homework," which clearly does not make sense.

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 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, 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 the 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 that 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), we see it as it was 12 billion years ago, when the universe was only 2 billion years old.

Because the universe is about 14 billion years old, we cannot observe light coming from anything more than 14 billion light-years away.

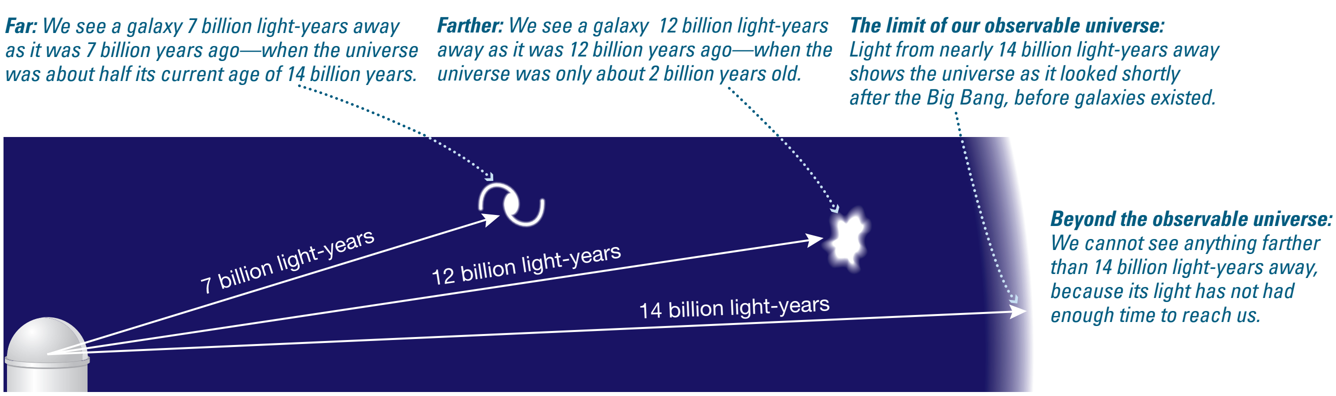
If we tried to look beyond 14 billion light-years, we'd be looking to a time more than 14 billion years ago—which is before the universe existed and therefore means that there is nothing to see. This distance of 14 billion light-years therefore marks the boundary (or *horizon*) of our **observable universe**—the 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 we assume to be far larger than our observable universe. We simply cannot see or study anything beyond the bounds of our observable universe, because the light from such distances has not yet had time to reach us in a 14-billion-year-old universe.

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,

*As we'll discuss in Chapter 16, distances to faraway galaxies can be described in more than one way in an expanding universe; 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.



they are literally astronomical. To help you develop a greater appreciation of our modern view of the universe, we'll discuss a few ways of putting 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 ballpoint 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.

On a scale in which the Sun is the size of a grapefruit, Earth is the size of the ballpoint in a pen, orbiting the Sun at a distance of 15 meters.

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 ballpoint-size Earth is located about 15 meters (49 feet) from the grapefruit-size 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 it would look virtually empty (that's why we call it *space*!).

▲ **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. This portion of the model is located just outside the National Air and Space Museum, which is to the left of the sidewalk.

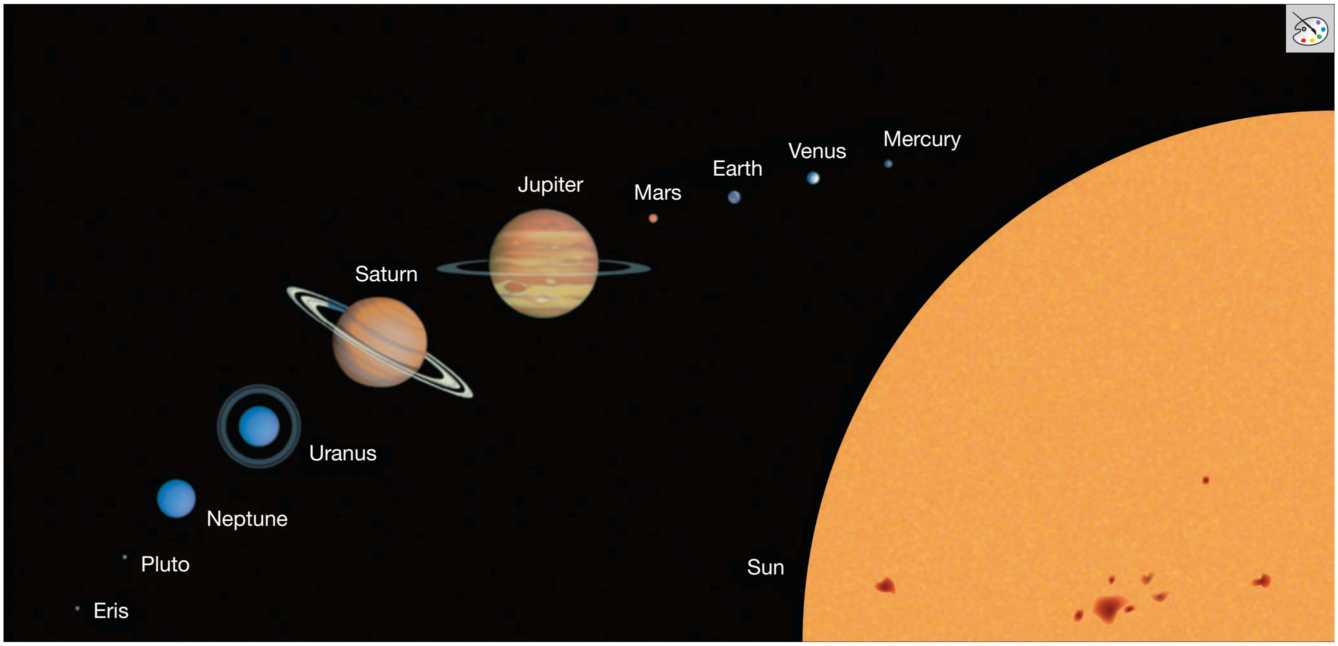
Special Topic — How Many Planets Are in Our Solar System?

Prior to 2006, children were taught that Pluto was one of nine planets in our solar system. But we now call Pluto a *dwarf planet*, leaving the solar system with only eight planets. Why the change?

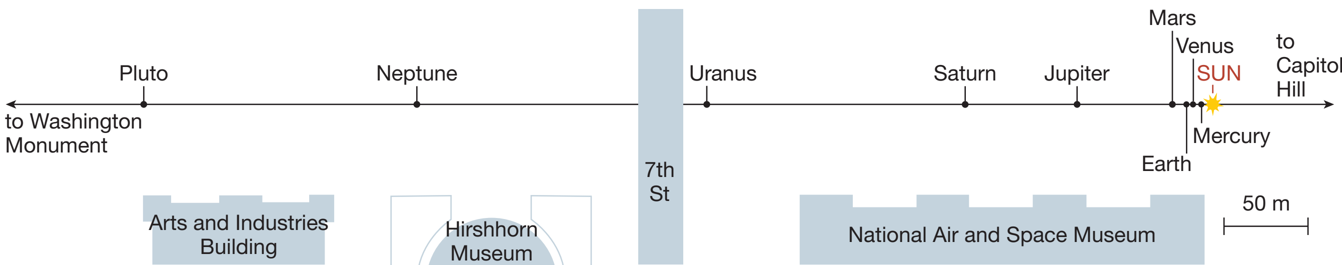
When Pluto was discovered in 1930, it was assumed to be similar to other planets. But by the mid-1990s, it had become clear that Pluto is part of a large group of ice-rich objects that share its region of the solar system (called the *Kuiper belt*, which we'll discuss in Chapter 9). Still, as long as Pluto was the largest known of these objects, most astronomers were content to leave the planetary status quo. Change was forced by the 2005 discovery of an object called Eris. Because Eris is slightly larger in mass than Pluto, astronomers could no longer avoid the question of what objects should count as planets.

Official decisions on astronomical names and definitions rest with the International Astronomical Union (IAU), an organization made up of professional astronomers from around the world. In 2006, an IAU vote defined "planet" in a way that left out Pluto and Eris (see Basic Astronomical Definitions on page 5) but added the "dwarf planet" category to accommodate them. These definitions still spark some controversy, but perhaps are best thought of as an example of the difference between the fuzzy boundaries of nature and the human preference for categories. After all, the argument about whether Pluto is a planet or a dwarf planet is not so different from the argument you may hear over whether a particular waterway is a creek, stream, or river.

A more recent question about the number of planets in our solar system has arisen from calculations based on the orbits of the ice-rich objects of the outer solar system. Some astronomers argue that these orbits show patterns indicating the gravitational tug of an undiscovered "planet nine." If such an object is actually found, astronomers may be forced to revisit the definition of "planet" once again.



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.

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!

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 (1½ 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 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 as fast as that of a commercial jet.

Distances to the 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

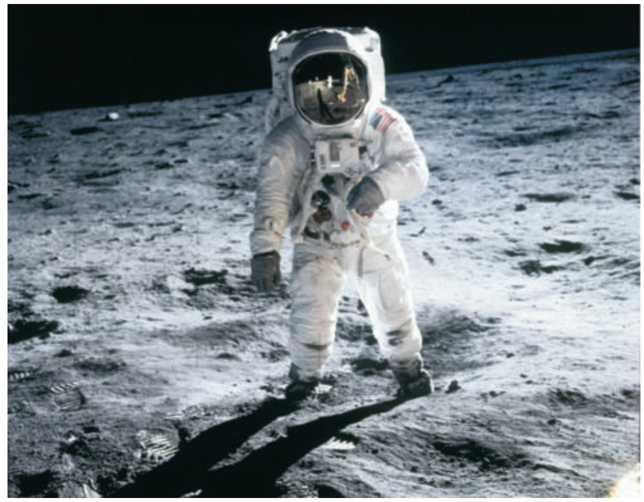
On the same scale on which Pluto is a few minutes' walk from Earth, you'd have to walk across the United States to reach the nearest stars.

(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, or 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 Earth). It may seem remarkable that we can see the 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 ballpoints or marbles orbiting grapefruits in California or beyond. When you consider this challenge, it is all the more remarkable to realize that we now have technology capable of finding such planets **[Section 10.1]**.

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.



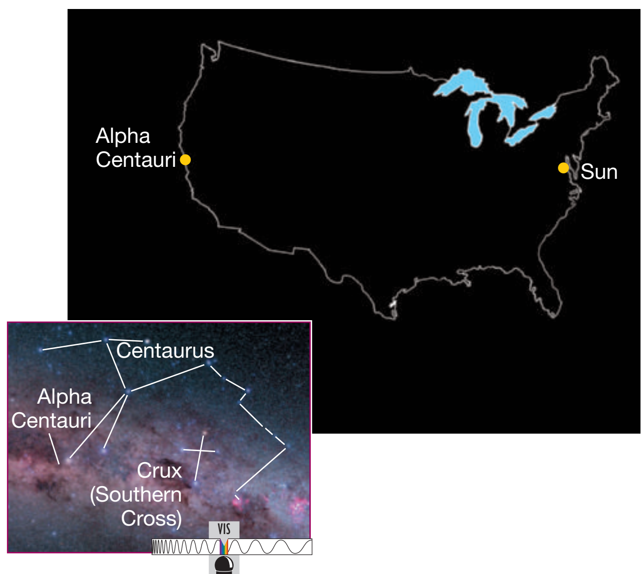
▲ **FIGURE 1.6**
This famous photograph from the first Moon landing (*Apollo 11* in July 1969) shows astronaut Buzz Aldrin, with Neil Armstrong reflected in his visor. Armstrong was the first to step onto the Moon's surface, saying, "That's one small step for a man, one giant leap for mankind." (When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

The Size of the Milky Way Galaxy The vast separation between our solar system and Alpha Centauri is typical of the separations between star systems in our region of the Milky Way Galaxy. We therefore cannot use the 1-to-10-billion scale for thinking about distances beyond the nearest stars, because more distant stars would not fit on Earth with this scale. To visualize the galaxy, let's reduce our scale by another factor of 1 billion (making it a scale of 1 to 10^{19}).

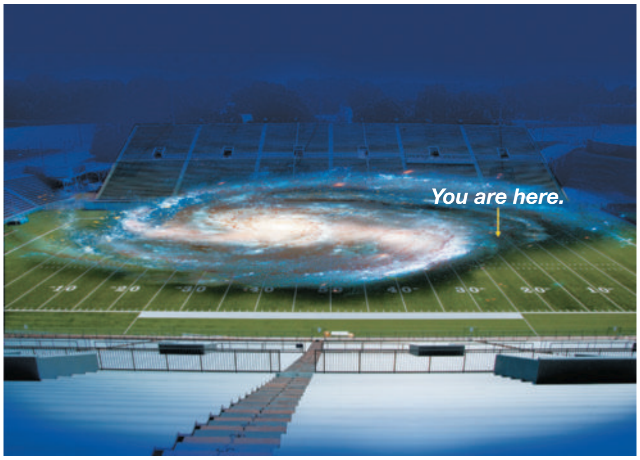
On this new scale, each light-year becomes 1 millimeter, and the 100,000-light-year diameter of the Milky Way Galaxy becomes 100 meters, or about the length of a football field. Visualize a football field with a scale model of our galaxy centered over midfield (Figure 1.8). Our entire solar system is 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!

It would take thousands of years just to count out loud the number of stars in the Milky Way Galaxy.



▲ **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.



▲ 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.

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 (and many more small 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 is comparable to the number of stars in the observable universe (Figure 1.9).

Roughly speaking, there are as many stars in the observable universe as there are grains of sand on all the beaches on Earth.

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.

Before we begin, you may wonder how we can claim to know anything about what the universe was like in the distant past. We'll devote much of this textbook to understanding how science enables us to do this, but you already know part of the answer: Because looking farther into space means looking further back in time, we can actually *see* parts of the universe as they were long ago, simply by looking far enough away. In other words, telescopes are somewhat like time machines, enabling us to observe the history of the universe.

How did we come to be?

Figure 1.10 (pages 12–13) 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.

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 portion of Figure 1.10 represent the expansion of a small piece of the universe through time.

The rate at which galaxies are moving apart suggests that the universe was born about 14 billion years ago, in the event we call the Big Bang.

The universe as a whole has continued to expand ever since the Big Bang, but on smaller size 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.

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 generate energy from fusion and "dies" when it exhausts its usable fuel.

Stars are born in interstellar clouds, produce energy and new elements through nuclear fusion, and release those new elements in interstellar space when they die.

In its final death throes, a star blows much of its contents 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 future 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 (along with a few manufactured when "dead" stars, such as neutron stars, merge together [Section 14.4]).

We are "star stuff"—made of material that was manufactured by stars from the simple elements born in the Big Bang.

By the time our solar system formed, about 4½ 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.

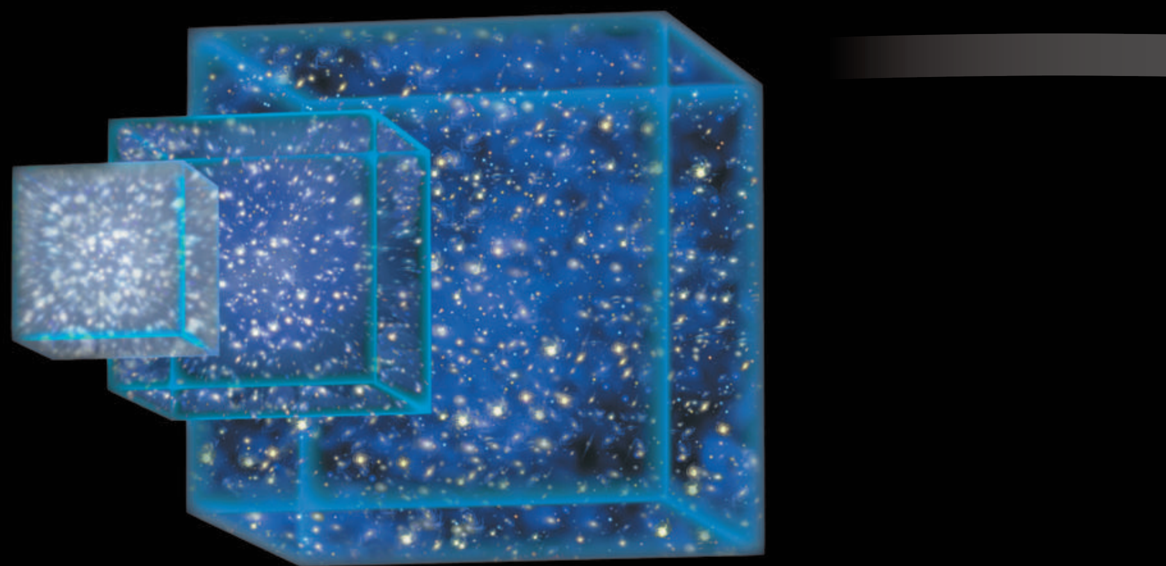
In summary, most of the material from which we and our planet are made was created by stars that lived and died before the birth of our Sun. As astronomer Carl Sagan (1934–1996) said, we are "star stuff."

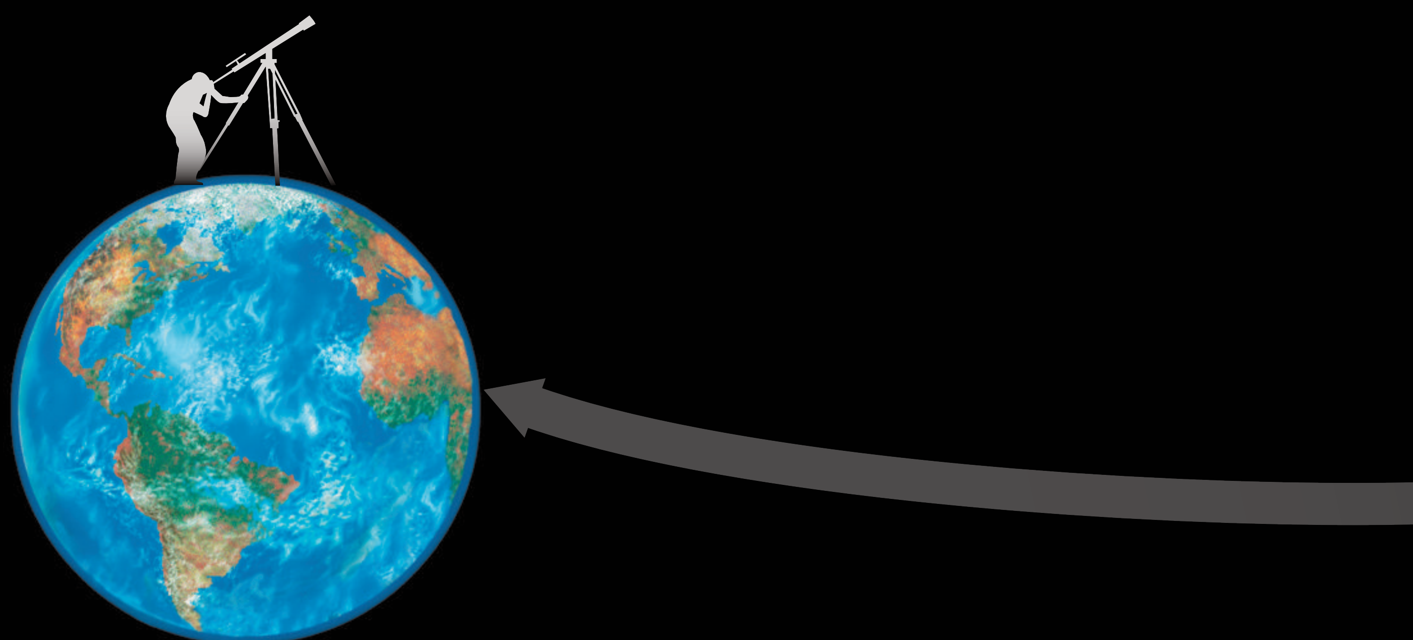
cosmic context

FIGURE 1.10 Our Cosmic Origins

Throughout this book, we will see that human life is intimately connected with the development of the universe as a whole. This illustration presents an overview of our cosmic origins, showing some of the crucial steps that made our existence possible.

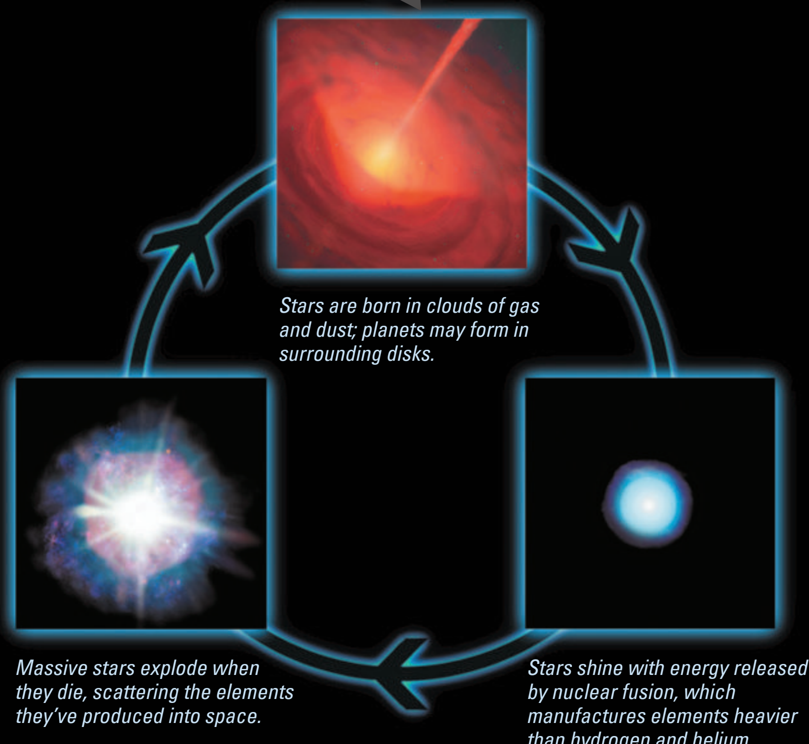
(1) **Birth of the Universe:** The expansion of the universe began with the hot and dense Big Bang. The cubes show how one region of the universe has expanded with time. The universe continues to expand, but on smaller scales gravity has pulled matter together to make galaxies.



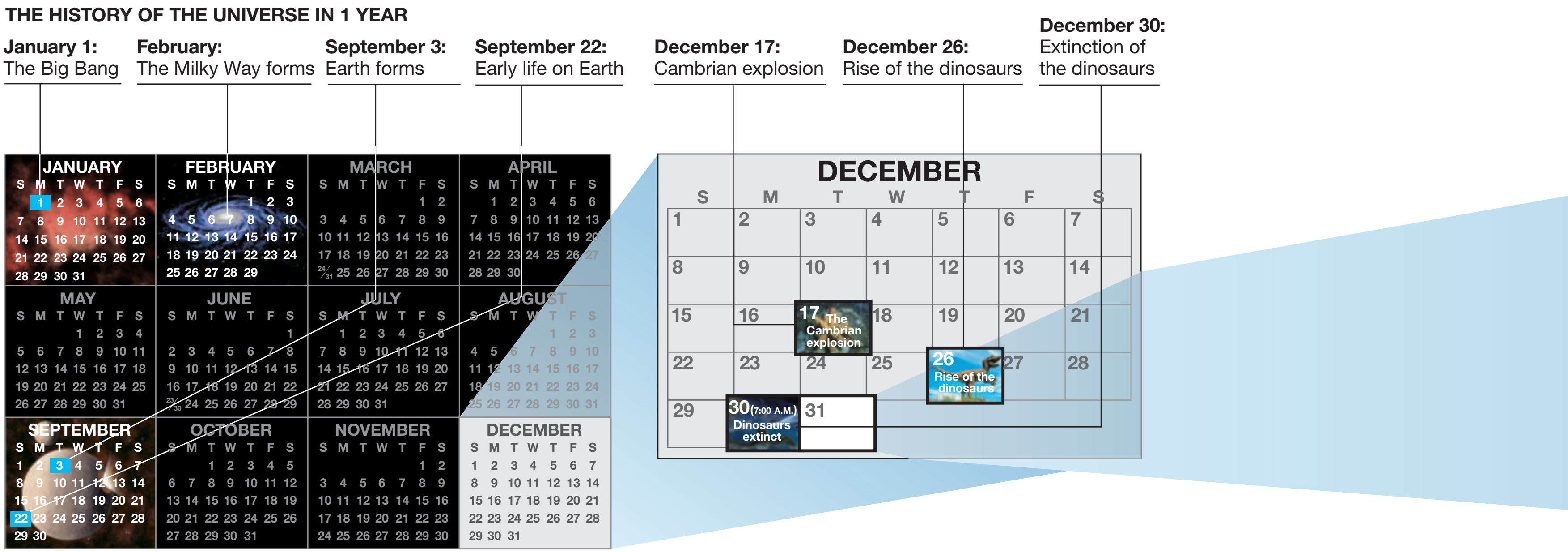


(4) **Earth and Life:** By the time our solar system was born, $4\frac{1}{2}$ billion years ago, about 2% of the original hydrogen and helium had been converted into heavier elements. We are therefore “star stuff,” because we and our planet are made from elements manufactured in stars that lived and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

(2) **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.



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



▲ **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.)

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

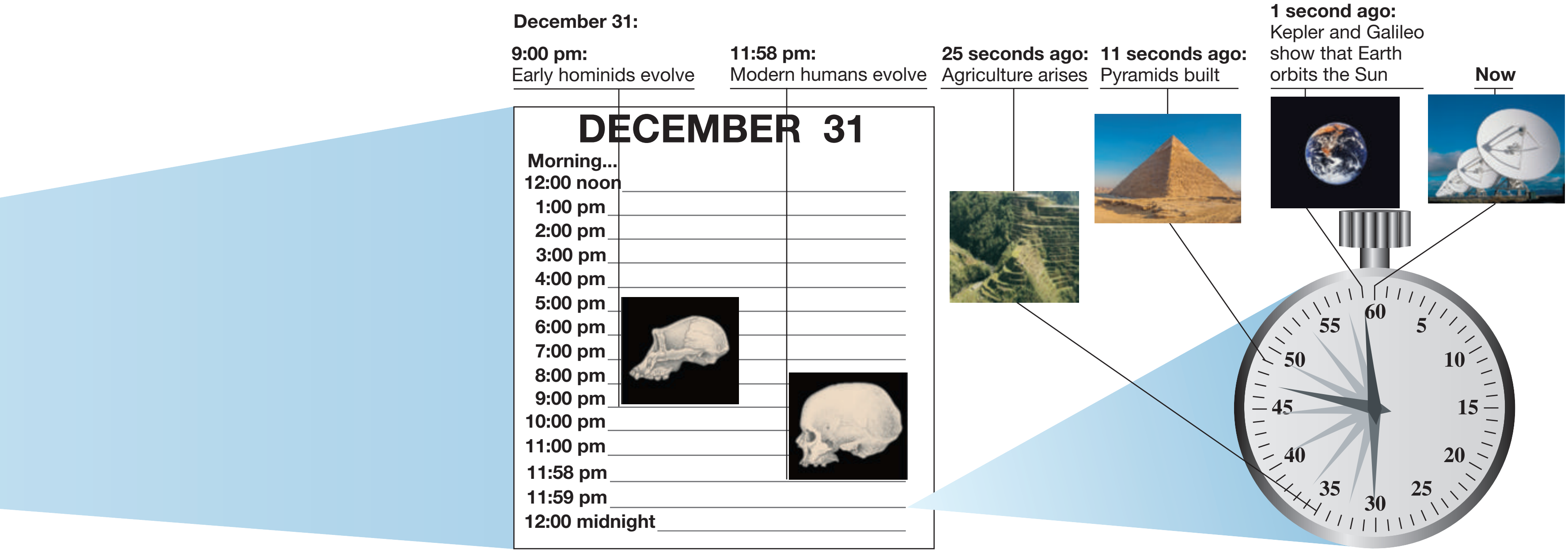
We can put the 14-billion-year age of the universe into perspective by imagining this time compressed into a single year, so each month represents a little more than 1 billion years. On this *cosmic calendar*, the Big Bang occurred at the first instant of January 1, and the present is the stroke of midnight 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 4½ 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 9.5]. 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 inherited Earth. Some 60 million years later, or around 9 P.M. on December 31 of the cosmic calendar, early hominids (human ancestors) began to walk upright.

If we imagine the 14-billion-year history of the universe compressed into 1 year, a human lifetime lasts only a fraction of a second.

Perhaps the most astonishing fact 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 provided the key evidence that led us to understand 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 fold-out in the front of this book. How does an understanding of the scale of time affect your view of human civilization? Explain.

1.3 Spaceship Earth

Wherever you are as you read this book, you probably have the feeling that you're "just sitting here." But, in fact, all of us are moving through space on what noted inventor and philosopher R. Buckminster Fuller (1895–1983) described as *spaceship Earth.*

How is Earth moving through space?

Let's explore the major motions we are all undergoing with our spaceship Earth.

Earth's Rotation and Orbit

Rotation and Orbit The most basic motions of Earth are its daily **rotation** (spin) and its yearly **orbit** (or *revolution*) around the Sun.

Earth rotates once each day around its axis (Figure 1.12), which is the imaginary line connecting the North Pole to the South Pole. Earth rotates from west to east—counterclockwise as viewed from above the North Pole—which is why the Sun and stars appear to rise in the east and set in the west each day. Although the physical effects of rotation are so subtle that our ancestors assumed the heavens revolved around us, the rotation speed is substantial: Unless you live quite far north or south, you are whirling around Earth's axis at a speed of more than 1000 kilometers per hour (600 miles per hour)—faster than most airplanes travel.

Earth rotates once each day and orbits the Sun once each year. Its average orbital distance, called an *astronomical unit* (AU), is about 150 million kilometers.

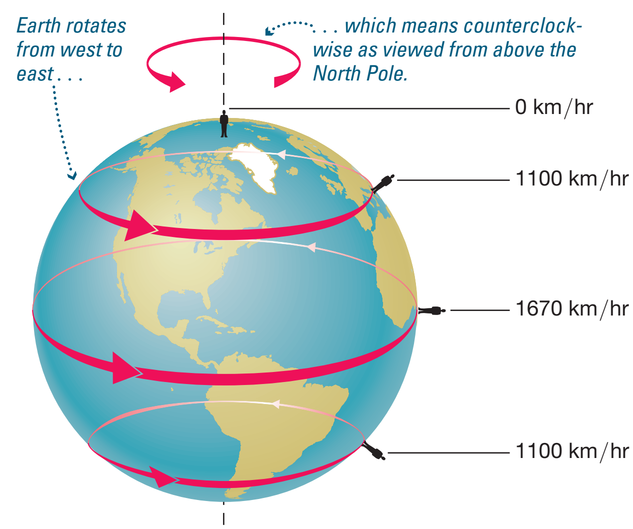
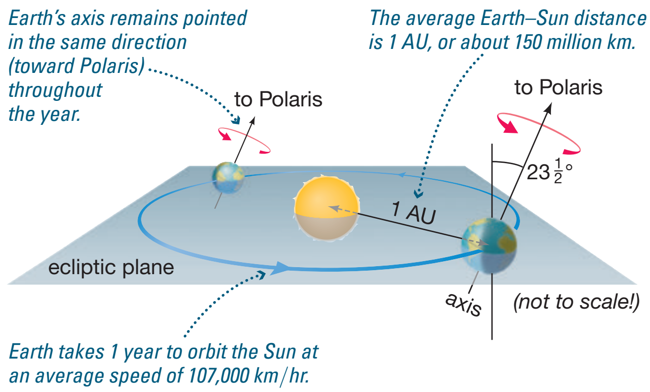


FIGURE 1.12
As Earth rotates, your speed around Earth's axis depends on your location: The closer you are to the equator, the faster you travel with rotation.



▲ **FIGURE 1.13**
This diagram shows key characteristics of Earth's daily rotation and yearly orbit, both of which are counterclockwise as viewed from above the North Pole.

At the same time as it is rotating, Earth also orbits the Sun, completing one orbit each year (Figure 1.13). Earth's orbital distance varies slightly over the course of each year, but as we discussed earlier, the average distance is one astronomical unit (AU), which is about 150 million kilometers. Again, even though we don't feel this motion, the speed is impressive: We are racing around the Sun at a speed in excess of 100,000 kilometers per hour (60,000 miles per hour), which is faster than any spacecraft yet launched.

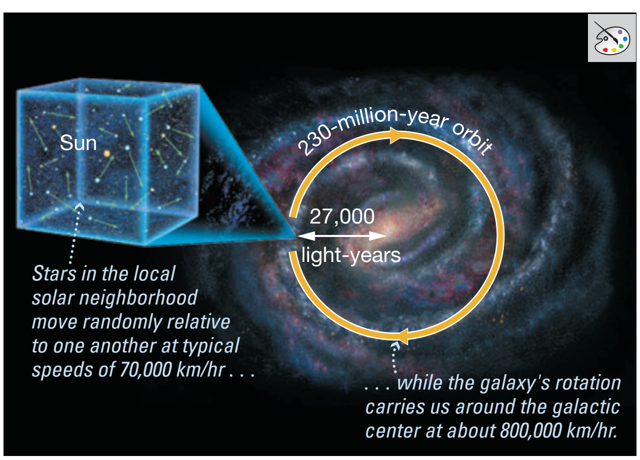
As you study Figure 1.13, notice that Earth's orbital path defines a flat plane that we call the **ecliptic plane**. Earth's axis is tilted by 23½° from a line *perpendicular* to the ecliptic plane. This **axis tilt** happens to be oriented so that the axis points almost directly at a star called *Polaris*, or the *North Star*. Keep in mind that the idea of axis tilt makes sense only in relation to the ecliptic plane. That is, the idea of "tilt" by itself has no meaning in space, where there is no absolute up or down. In space, "up" and "down" mean only "away from the center of Earth (or another planet)" and "toward the center of Earth," respectively.

THINK ABOUT IT If there is no up or down in space, why do you think most globes have the North Pole on top? Would it be equally correct to have the South Pole on top or to turn the globe sideways? Explain.

Notice also that Earth orbits the Sun in the same direction that it rotates on its axis: counterclockwise as viewed from above the North Pole. This is not a coincidence but a consequence of the way our planet was born. As we'll discuss in Chapter 6, strong evidence indicates that Earth and the other planets were born in a spinning disk of gas that surrounded our Sun as it formed, and Earth rotates and orbits in the same direction as the disk was spinning.

Motion Within the Milky Way Galaxy Rotation and orbit are only a small part of the travels of spaceship Earth. Our entire solar system is on a great journey within the Milky Way Galaxy. There are two major components to this motion, both shown in Figure 1.14.

First, our solar system is moving relative to nearby stars in our *local solar neighborhood*, the region of the Sun and nearby stars. The small box in Figure 1.14 shows that stars within the local solar neighborhood (like the stars of any other small region of the galaxy) move essentially at random relative to one another. The speeds are quite fast: On average, our Sun is moving relative to nearby stars at a speed of about 70,000 kilometers per hour (40,000 miles per hour), almost three times as fast as the International Space Station orbits Earth. Given these high speeds, you may wonder why we don't see stars racing around the sky. The answer lies in their vast distances from us. You've probably noticed that a distant airplane appears to move through the sky more slowly than one flying close overhead. Stars are so far away that even at speeds of 70,000 kilometers per hour, their motions would be noticeable to the naked eye only if we watched them for thousands of years. That is why the patterns in the constellations seem to remain fixed. Nevertheless, in 10,000 years the constellations will be noticeably different from those we see today. In 500,000 years they will be unrecognizable. If you could watch a time-lapse movie made over millions of years, you *would* see stars racing across the sky.



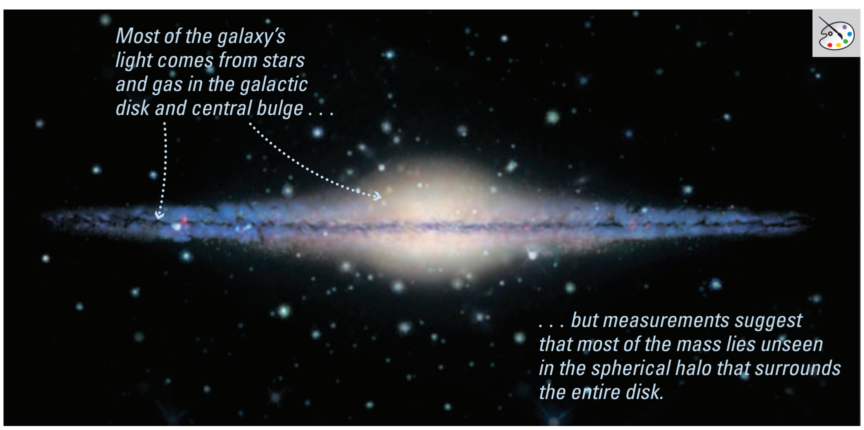
▲ **FIGURE 1.14**
This painting illustrates the motion of our solar system within our local solar neighborhood and around the center of the Milky Way Galaxy.

THINK ABOUT IT Despite the chaos of motion in the local solar neighborhood over millions and billions of years, collisions between star systems are extremely rare. Explain why. (*Hint*: Consider the sizes of star systems, such as the solar system, relative to the distances between them.)

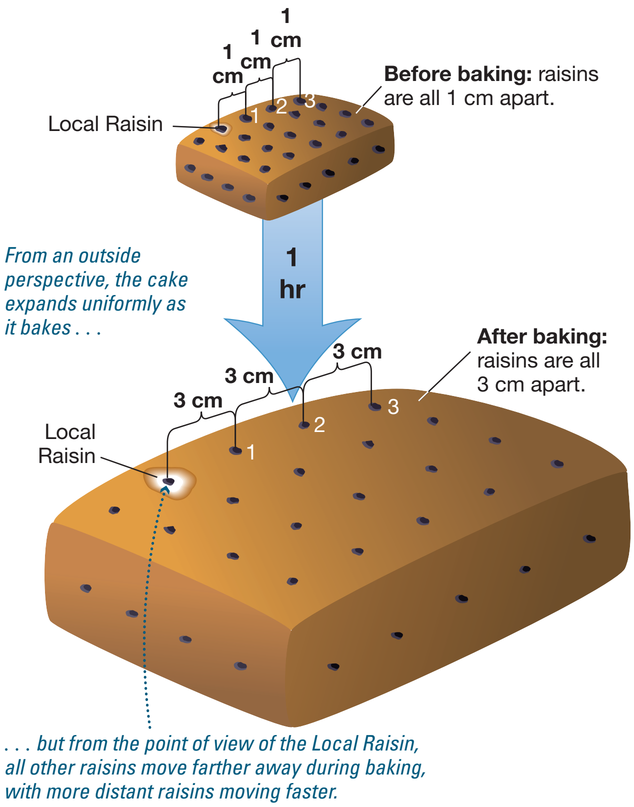
The second motion shown in Figure 1.14 is much more organized. If you look closely at leaves floating in a stream, their motions relative to one another might appear random, just like the motions of stars in the local solar neighborhood. As you widen your view, you see that all the leaves are being carried in the same general direction by the downstream current. In the same way, as we widen our view beyond the local solar neighborhood, the seemingly random motions of its stars give way to a simpler and even faster motion: rotation of the Milky Way Galaxy. Our solar system, located about 27,000 light-years from the galactic center, completes one orbit of the galaxy in about 230 million years. Even if you could watch from outside our galaxy, this motion would be unnoticeable to your naked eye. However, if you calculate the speed of our solar system as we orbit the center of the galaxy, you will find that it is close to 800,000 kilometers (500,000 miles) per hour.

Galactic rotation carries us around the center of the galaxy once every 230 million years.

Careful study of the galaxy's rotation reveals one of the greatest mysteries in science. Stars at different distances from the galactic center orbit at different speeds, and we can learn how mass is distributed in the galaxy by measuring these speeds. Such studies indicate that the stars in the disk of the galaxy represent only the "tip of the iceberg" compared to the mass of the entire galaxy (Figure 1.15). Most of the mass of the galaxy seems to be located outside the visible disk (occupying the galactic *halo* that surrounds the disk), but the matter that makes up this mass is completely invisible to our telescopes. We therefore know very little about the nature of this matter, which we refer to as **dark matter** (because of the lack of light from it). Studies of other galaxies indicate that they also are made mostly of dark matter. These and other observations imply that dark matter significantly outweighs the ordinary matter that makes up planets and stars, making it the dominant source of gravity that has led to the formation of galaxies, clusters, and superclusters. We know even less about the mysterious **dark energy** that astronomers first recognized when they discovered that the expansion of the universe is actually getting faster with time and that scientists have since found to make up the majority of the total energy content of the universe. We'll discuss the mysteries of dark matter and dark energy in Chapter 18.



◀ **FIGURE 1.15**
This painting shows an edge-on view of the Milky Way Galaxy. Study of galactic rotation shows that although most visible stars lie in the disk and central bulge, most of the mass lies in the halo that surrounds and encompasses the disk. Because this mass emits no light that we have detected, we call it *dark matter*.



Distances and Speeds as Seen from the Local Raisin

Raisin Number	Distance Before Baking	Distance After Baking (1 hour later)	Speed
1	1 cm	3 cm	2 cm/hr
2	2 cm	6 cm	4 cm/hr
3	3 cm	9 cm	6 cm/hr
⋮	⋮	⋮	⋮

FIGURE 1.16

An expanding raisin cake offers an analogy to the expanding universe. Someone living in one of the raisins inside the cake could figure out that the cake is expanding by noticing that all other raisins are moving away, with more distant raisins moving away faster. In the same way, we know that we live in an expanding universe because all galaxies outside our Local Group are moving away from us, with more distant ones moving faster.

How do galaxies move within the universe?

The billions of galaxies in the universe also move relative to one another. Within the Local Group (see Figure 1.1), some of the galaxies move toward us, some move away from us, and numerous small galaxies (including the Large and Small Magellanic Clouds) apparently orbit our Milky Way Galaxy. Again, the speeds are enormous by earthly standards. For example, the Milky Way and Andromeda galaxies are moving toward each other at about 300,000 kilometers (180,000 miles) per hour. Despite this high speed, we needn't worry about a collision anytime soon. Even if the Milky Way and Andromeda galaxies are approaching each other head-on, it will be billions of years before any collision begins.

When we look outside the Local Group, however, we find two astonishing facts discovered by Edwin Hubble (1889–1953), for whom the Hubble Space Telescope was named:

1. Virtually every galaxy outside the Local Group is moving *away* from us.
2. The more distant the galaxy, the faster it appears to be racing away.

These facts might make it sound as if we suffer from a cosmic case of chicken pox, but there is a much more natural explanation: *The entire universe is expanding.* We'll save the details for later in the book, but you can understand the basic idea by thinking about a raisin cake baking in an oven.

The Raisin Cake Analogy Imagine that you make a raisin cake in which the distance between adjacent raisins is 1 centimeter. You place the cake in the oven, where it expands as it bakes. After 1 hour, you remove the cake, which has expanded so that the distance between adjacent raisins has increased to 3 centimeters (Figure 1.16). The expansion of the cake seems fairly obvious. But what would you see if you lived *in* the cake, as we live in the universe?

Pick any raisin (it doesn't matter which one) and call it the Local Raisin. Figure 1.16 shows one possible choice, with three nearby raisins also labeled. The accompanying table summarizes what you would see if you lived within the Local Raisin. Notice, for example, that Raisin 1 starts out at a distance of 1 centimeter before baking and ends up at a distance of 3 centimeters after baking, which means it moves a distance of 2 centimeters farther away from the Local Raisin during the hour of baking. Hence, its speed as seen from the Local Raisin is 2 centimeters per hour. Raisin 2 moves from a distance of 2 centimeters before baking to a distance of 6 centimeters after baking, which means it moves a distance of 4 centimeters farther away from the Local Raisin during the hour. Hence, its speed is 4 centimeters per hour, or twice the speed of Raisin 1. Generalizing, the fact that the cake is expanding means that all the raisins are moving away from the Local Raisin, with more distant raisins moving away faster.

Distant galaxies are all moving away from us, with more distant ones moving faster, indicating that we live in an expanding universe.

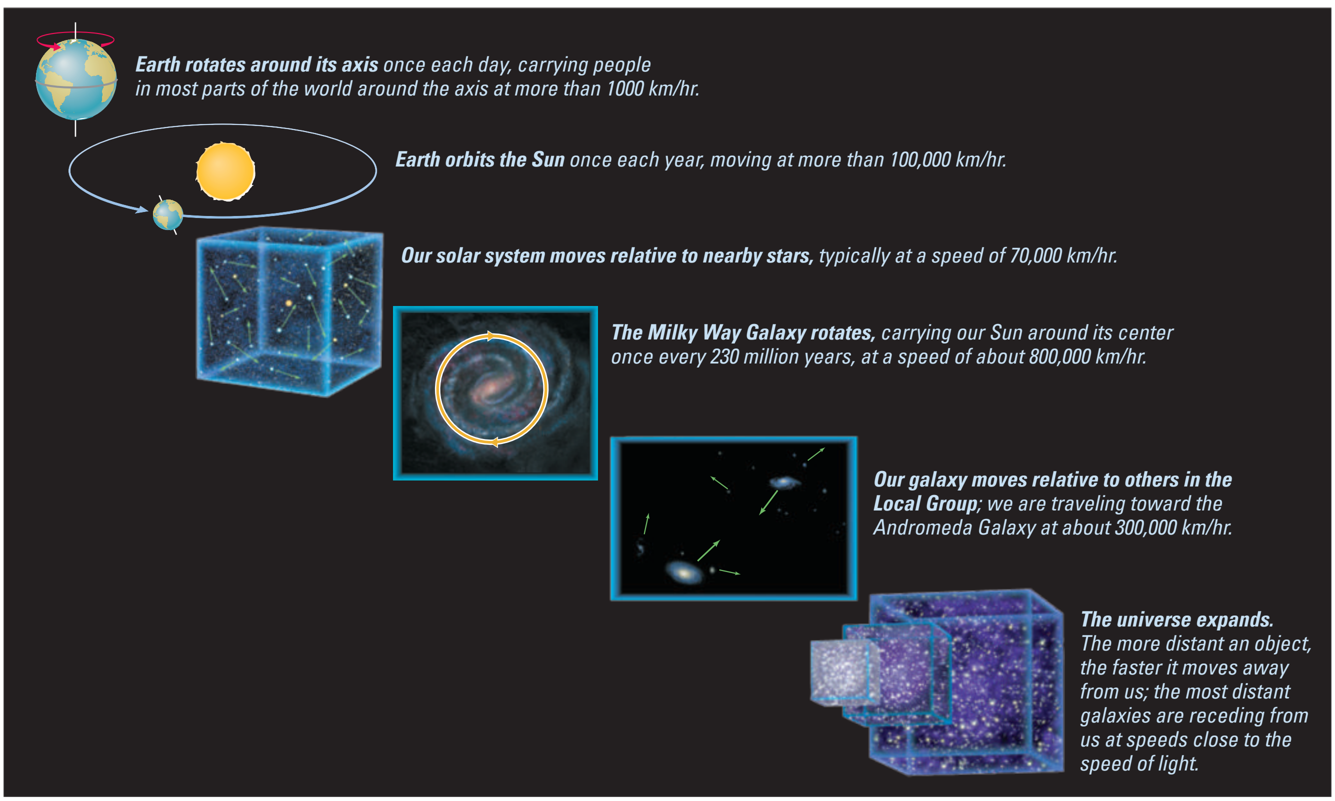
Hubble's discovery that galaxies are moving in much the same way as the raisins in the cake, with most moving away from us and more distant ones moving away faster, implies that the universe is expanding much like the raisin cake. If you now imagine the Local Raisin as representing our Local Group of galaxies and the other raisins as representing more distant galaxies or clusters of galaxies, you have a basic picture of the expansion of the universe. Like the expanding dough between the raisins in the cake, *space* itself is growing between galaxies. More distant galaxies move away from us faster because they are carried along with this expansion like the raisins in the expanding cake. You can also now see how observations of expansion allow us to measure the age of the universe: The faster the rate of expansion, the more quickly the galaxies reached their current positions, and therefore the younger the universe must be. It is by precisely measuring the expansion rate that astronomers have learned that the universe is approximately 14 billion years old.

The Real Universe There's at least one important distinction between the raisin cake and the universe: A cake has a center and edges, but we do not think the same is true of the entire universe. Anyone living in any galaxy in an expanding universe sees just what we see—other galaxies moving away, with more distant ones moving away faster. Because the view from each point in the universe is about the same, no place can claim to be more "central" than any other place.

It's also important to realize that, unlike the case with a raisin cake, we can't actually *see* galaxies moving apart with time—the distances are too vast for any motion to be noticeable on the time scale of a human life. Instead, we measure the speeds of galaxies by spreading their light into spectra and observing what we call *Doppler shifts* **[Section 5.2]**. This illustrates how modern astronomy depends both on careful observations and on using current understanding of the laws of nature to explain what we see.

Motion Summary Figure 1.17 summarizes the motions we have discussed. As we have seen, we are never truly sitting still. We spin around Earth's axis at more than 1000 kilometers per hour, while our planet orbits the Sun at more than 100,000 kilometers per hour. Our solar system moves among the stars of the local solar neighborhood at typical speeds of 70,000 kilometers per hour, while also orbiting the center of the Milky Way Galaxy at a speed of about 800,000 kilometers per hour. Our

FIGURE 1.17
This figure summarizes the basic motions of Earth in the universe, along with their associated speeds.



galaxy moves among the other galaxies of the Local Group, while all other galaxies move away from us at speeds that grow greater with distance in our expanding universe. Spaceship Earth is carrying us on a remarkable journey.

The Big Picture — Putting Chapter 1 into Perspective

In this first chapter, we developed a broad overview of our place in the universe. As we consider the universe in more depth in the rest of the book, remember the following "big picture" ideas:

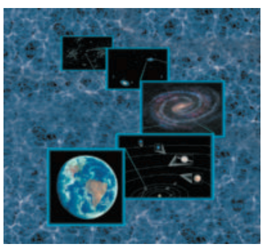
- Earth is not the center of the universe but instead is a planet orbiting a rather ordinary star in the Milky Way Galaxy. The Milky Way Galaxy, in turn, is one of billions of galaxies in our observable universe.
- Cosmic distances are literally astronomical, but we can put them in perspective with the aid of scale models and other scaling techniques. When you think about these enormous scales, don't forget that every star is a sun and every planet is a unique world.
- We are "star stuff." The atoms from which we are made began as hydrogen and helium in the Big Bang and were later fused into heavier elements by massive stars. Stellar deaths released these atoms into space, where our galaxy recycled them into new stars and planets. Our solar system formed from such recycled matter some 4½ billion years ago.
- We are latecomers on the scale of cosmic time. The universe was already more than half its current age when our solar system formed, and it took billions of years more before humans arrived on the scene.
- All of us are being carried through the cosmos on spaceship Earth. Although we cannot feel this motion, the associated speeds are surprisingly high. Learning about the motions of spaceship Earth gives us a new perspective on the cosmos and helps us understand its nature and history.

MY COSMIC PERSPECTIVE The science of astronomy affects all of us on many levels. In particular, it helps us understand how we as humans fit into the universe as a whole, and the history of astronomy has been deeply intertwined with the development of civilization.

Summary of Key Concepts

1.1 The Scale of the Universe

• What is our place in the universe?



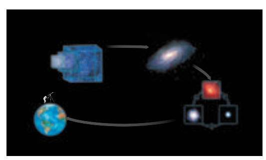
Earth is a planet orbiting the Sun. Our Sun is one of more than 100 billion stars in the **Milky Way Galaxy**. Our galaxy is one of more than 50 galaxies in the **Local Group**. The Local Group is one small part of the **Local Supercluster**, which is one small part of the **universe**.

• How big is the universe?

If we imagine our Sun as a large grapefruit, Earth is a ballpoint that orbits 15 meters away; the nearest stars are thousands of kilometers away on the same scale. Our galaxy contains more than 100 billion stars—so many 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.

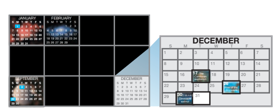
1.2 The History of the Universe

• 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. All the other elements have been produced by stars and recycled within galaxies from one generation of stars to the next, which is why we are "star stuff."

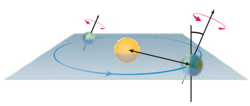
• How do our lifetimes compare to the age of the universe?



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.

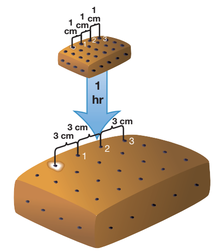
1.3 Spaceship Earth

How is Earth moving through space?



Earth **rotates** on its axis once each day and **orbits** the Sun once each year. At the same time, we move with our Sun in random directions relative to other stars in our local solar neighborhood, while the galaxy's rotation carries us around the center of the galaxy every 230 million years.

How do galaxies move within the universe?



Galaxies move essentially at random within the Local Group, but all galaxies beyond the Local Group are moving away from us. More distant galaxies are moving faster, which tells us that we live in an expanding universe.

Visual Skills Check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. For additional practice, try the Chapter 1 Visual Quiz in the Study Area at www.MasteringAstronomy.com.

The figure at right shows the sizes of Earth and the Moon to scale; the scale used is 1 cm = 4000 km. Using what you've learned about astronomical scale in this chapter, answer the following questions. (*Hint:* If you are unsure of the answers, you can calculate them using the given data.)

Earth–Sun distance = 150,000,000 km

Diameter of Sun = 1,400,000 km

Earth–Moon distance = 384,000 km

Diameter of Earth = 12,800 km

1. If you wanted to show the distance between Earth and the Moon on the same scale, about how far apart would you need to place the two photos above?
   a. 10 centimeters (about the width of your hand)
   b. 1 meter (about the length of your arm)
   c. 100 meters (about the length of a football field)
   d. 1 kilometer (a little more than a half mile)
2. Suppose you wanted to show the Sun on the same scale. About how big would it need to be?
   a. 3.5 centimeters in diameter (the size of a golf ball)
   b. 35 centimeters in diameter (a little bigger than a basketball)
   c. 3.5 meters in diameter (about 11½ feet across)
   d. 3.5 kilometers in diameter (the size of a small town)
3. About how far away from Earth would the Sun be located on this scale?
   a. 3.75 meters (about 12 feet)
   b. 37.5 meters (about the height of a 12-story building)
   c. 375 meters (about the length of four football fields)
   d. 37.5 kilometers (the size of a large city)
4. Could you use the same scale to represent the distances to nearby stars? Why or why not?

Exercises and Problems

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

Chapter Review Questions

Short-Answer Questions Based on the Reading

1. Briefly describe the major levels of structure (such as planet, star, galaxy) in the universe.
2. Define *astronomical unit* and *light-year*.
3. Explain the statement *The farther away we look in distance, the further back we look in time.*
4. What do we mean by the *observable universe*? Is it the same thing as the entire universe?
5. Using techniques described in the chapter, put the following into perspective: the size of our solar system; the distance to nearby stars; the size and number of stars in the Milky Way Galaxy; the number of stars in the observable universe.
6. What do we mean when we say that the universe is *expanding*, and how does expansion lead to the idea of the *Big Bang* and our current estimate of the age of the universe?
7. In what sense are we "star stuff"?
8. Use the cosmic calendar to describe how the human race fits into the scale of time.
9. Briefly explain Earth's daily rotation and annual orbit, defining the terms *ecliptic plane* and *axis tilt.*

10. Briefly describe our solar system's location and motion within the Milky Way Galaxy.
11. Why do scientists suspect that most of our galaxy's mass consists of *dark matter*? Briefly describe the mystery of dark matter and *dark energy*.
12. What key observations lead us to conclude that the universe is expanding? Use the raisin cake model to explain how these observations imply expansion.

Does It Make Sense?

Decide whether or not each of the following statements makes sense (or is clearly true or false). Explain clearly; not all of these have definitive answers, so your explanation is more important than your chosen answer.

Example: I walked east from our base camp at the North Pole.

Solution: The statement does not make sense because east has no meaning at the North Pole—all directions are south from the North Pole.

13. Our solar system is bigger than some galaxies.
14. The universe is billions of light-years in age.
15. It will take me light-years to complete this homework assignment!
16. Someday we may build spaceships capable of traveling a light-year in only a decade.
17. Astronomers discovered a moon that does not orbit a planet.
18. NASA will soon launch a spaceship that will photograph our Milky Way Galaxy from beyond its halo.
19. The observable universe is larger today than it was a few billion years ago.
20. Photographs of distant galaxies show them as they were when they were much younger than they are today.
21. At a nearby park, I built a scale model of our solar system in which I used a basketball to represent Earth.
22. Because nearly all galaxies are moving away from us, we must be located near the center of the universe.

Quick Quiz

Choose the best answer to each of the following. For additional practice, try the Chapter 1 Reading and Concept Quizzes in the Study Area at www.MasteringAstronomy.com.

23. Which of the following correctly lists our "cosmic address" from small to large? (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
24. 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.
25. 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 in the sky. (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.
26. 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 light-years away.
27. The total number of stars in the observable universe is roughly equivalent to (a) the number of grains of sand on all the beaches on Earth. (b) the number of grains of sand on Miami Beach. (c) infinity.
28. 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.
29. If stars existed but galaxies did not, (a) we would probably still exist anyway. (b) we would not exist because life on Earth depends on the light of galaxies. (c) we would not exist because we are made of material that was recycled in galaxies.
30. 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
31. The age of our solar system is about (a) one-third of the age of the universe. (b) three-fourths of the age of the universe. (c) 2 billion years younger than the age of the universe.
32. The fact that nearly all galaxies are moving away from us, with more distant ones moving faster, helped us to conclude that (a) the universe is expanding. (b) galaxies repel each other like magnets. (c) our galaxy lies near the center of the universe.

Inclusive Astronomy

Use these questions to reflect on participation in science.

33. *Group Discussion: What does a scientist look like?* The purpose of this exercise is to help you identify preconceptions that you or others may have about science and scientists.
    a. Working independently, make a simple sketch of a professional scientist and write down five words that describe the scientist in your sketch. Then join with a group of two or three other students to share your sketches and word lists.
    b. Make a list of all the words the group wrote down, then rank them in order of how often they were used.
    c. Discuss any similarities, differences, or patterns you notice among the scientists described by the group members.
    d. Discuss whether the group members feel they have much in common with professional scientists.
    e. Discuss how feelings about what you have (or do not have) in common with scientists might affect your approach to scientific thinking.

The Process of Science

These questions may be answered individually in short-essay form or discussed in groups, except where identified as group-only.

34. *Earth as a Planet.* For most of human history, scholars assumed Earth was the center of the universe. Today, we know that Earth is just one planet orbiting the Sun, and the Sun is just one star in a vast universe. How did science make it possible for us to learn these facts about Earth?
35. *Thinking About Scale.* One key to success in science is finding a simple way to evaluate new ideas, and making a simple scale model is often helpful. Suppose someone tells you that the reason it is warmer during the day than at night is that the day side of Earth is closer to the Sun than the night side. Evaluate this idea by thinking about the size of Earth and its distance from the Sun in a scale model of the solar system.
36. *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 presented in this

chapter—such as the idea that there are billions of galaxies in the universe, or that the universe was born in the Big Bang, or that the galaxy contains more dark matter than ordinary matter—and briefly discuss the type of evidence you would want to see before accepting the idea. (*Hint*: It's okay to look ahead in the book to see the evidence presented in later chapters.)

37. *A Human Adventure.* Astronomical discoveries clearly are important to science, but are they also important to our personal lives? Defend your opinion.
38. *Infant Species.* In the last few tenths of a second before midnight on December 31 of the cosmic calendar, we have developed an incredible civilization and learned a great deal about the universe, but we also have developed technology through which we could destroy ourselves. The midnight bell is striking, and the choice for the future is ours. How far into the next cosmic year do you think our civilization will survive? Defend your opinion.
39. *Group Activity: Counting the Milky Way's Stars.* Work as a group to answer each part. *Note*: This activity works particularly well in groups of four students, with each student taking on one of the following roles: *scribe:* takes notes on the group's activities; *proposer:* suggests tentative explanations to the group; *skeptic:* points out weaknesses in proposed explanations; *moderator:* leads group discussion and makes sure everyone contributes.
    a. Work together to estimate the number of stars in the Milky Way from just these two facts: (1) the number of stars within 12 light-years of the Sun, which you can count in Appendix F, and (2) the total volume of the Milky Way's disk (100,000 light-years in diameter and 1000 light-years thick), which is about 1 billion times the volume of the region of your star count.
    b. Discuss how your value from part a compares to the value given in this chapter. Make a list of possible reasons why your technique may have underestimated or overestimated the actual number.

Investigate Further

Short-Answer/Essay Questions

40. *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 aliens' 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.)
41. *Raisin Cake Universe.* Suppose that all the raisins in a cake are 1 centimeter apart before baking and 4 centimeters apart after baking.
    a. Draw diagrams to represent the cake before and after baking.
    b. Identify one raisin as the Local Raisin on your diagrams. Construct a table showing the distances and speeds of other raisins as seen from the Local Raisin.
    c. Briefly explain how your expanding cake is similar to the expansion of the universe.
42. *The Hubble Extreme Deep Field.* The photo that opens this chapter is called the Hubble Extreme Deep Field. Find this photo on the Hubble Space Telescope website. Learn how it was taken, what it shows, and what we've learned from it. Write a short summary of your findings.
43. *The Cosmic Perspective.* Write a short essay describing how the ideas presented in this chapter affect your perspectives on your own life and on human civilization.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

44. *Distances by Light.* Just as a light-year is the distance that light can travel in 1 year, we define a light-second as the distance that light can travel in 1 second, a light-minute as the distance that light can travel in 1 minute, and so on. Calculate the distance in both kilometers and miles represented by each of the following:
    a. 1 light-second
    b. 1 light-minute
    c. 1 light-hour
    d. 1 light-day
45. *Moonlight and Sunlight.* How long does it take light to travel from
    a. the Moon to Earth?
    b. the Sun to Earth?
46. *Saturn versus the Milky Way.* Photos of Saturn and photos of galaxies can look so similar that children often think the photos show similar objects. In reality, a galaxy is far larger than any planet. About how many times larger is the diameter of the Milky Way Galaxy than the diameter of Saturn's rings? (*Data*: Saturn's rings are about 270,000 km in diameter; the Milky Way is 100,000 light-years in diameter.)
47. *Driving Trips.* Imagine that you could drive your car at a constant speed of 100 km/hr (62 mi/hr), even across oceans and in space. How long would it take to drive
    a. around Earth's equator? (Earth's circumference ≈ 40,000 km)
    b. from the Sun to Earth?
    c. from the Sun to Pluto? (Pluto distance $\approx 5.9 \times 10^9$ km)
    d. to Alpha Centauri (4.4 light-years away)?
48. *Faster Trip.* Suppose you wanted to reach Alpha Centauri in 100 years.
    a. How fast would you have to go, in km/hr?
    b. How many times faster is the speed you found in part a than the speeds of our fastest current spacecraft (around 50,000 km/hr)?
49. *Galaxy Scale.* Consider the 1-to-10^{19} scale, on which the disk of the Milky Way Galaxy fits on a football field. On this scale, how far is it from the Sun to Alpha Centauri (real distance: 4.4 light-years)? How big is the Sun itself on this scale? Compare the Sun's size on this scale to the actual size of a typical atom (about 10^{-10} m in diameter).
50. *Age of the Universe*. Suppose we did not yet know the expansion rate of the universe, and two astronomers came up with two different measurements: Wendy measured an expansion rate for the universe that was 50% faster than the expansion rate Allan measured. Was the age of the universe that Allan inferred older or younger than the age that Wendy inferred? By how much? Explain. (*Hint*: Read the discussion of the raisin cake analogy carefully, and the answer should become clear.)

2 Discovering the Universe for Yourself

LEARNING GOALS

This time-exposure photograph shows star paths at Arches National Park, Utah.

2.1 Patterns in the Night Sky
- What does the universe look like from Earth?
- Why do stars rise and set?
- Why do the constellations we see depend on latitude and time of year?

2.2 The Reason for Seasons
- What causes the seasons?
- How does the orientation of Earth's axis change with time?

2.3 The Moon, Our Constant Companion
- Why do we see phases of the Moon?
- What causes eclipses?

2.4 The Ancient Mystery of the Planets
- Why was planetary motion so hard to explain?
- Why did the ancient Greeks reject the real explanation for planetary motion?

ESSENTIAL PREPARATION

1. What is our place in the universe? [Section 1.1]
2. How big is the universe? [Section 1.1]
3. How is Earth moving through space? [Section 1.3]

We live in an exciting time in the history of astronomy. New and powerful telescopes are scanning the depths of the universe. Sophisticated space probes are exploring our solar system. Rapid advances in computing technology are allowing scientists to analyze the vast amount of new data and to model the processes that occur in planets, stars, galaxies, and the universe.

One goal of this book is to help *you* share in the ongoing adventure of astronomical discovery. One of the best ways to become a part of this adventure is to do what other humans have done for thousands of generations: Go outside, observe the sky around you, and contemplate the awe-inspiring universe of which you are a part. In this chapter, we'll discuss a few key ideas that will help you understand what you see in the sky.

Discovering the Universe for Yourself

2.1 Patterns in the Night Sky

Today we take for granted that we live on a small planet orbiting an ordinary star in one of many galaxies in the universe. But this fact is not obvious from a casual glance at the night sky, and we've learned about our place in the cosmos only through a long history of careful observations. In this section, we'll discuss major features of the night sky and how we understand them in light of our current knowledge of the universe.

What does the universe look like from Earth?

Shortly after sunset, as daylight fades to darkness, the sky appears to fill slowly with stars. On clear, moonless nights far from city lights, more than 2000 stars may be visible to your naked eye, along with the whitish band of light that we call the *Milky Way* (Figure 2.1). As you look at the stars, your mind may group them into patterns that look like familiar shapes or objects. If you observe the sky night after night or year after year, you will recognize the same patterns of stars. These patterns have not changed noticeably in the past few thousand years.

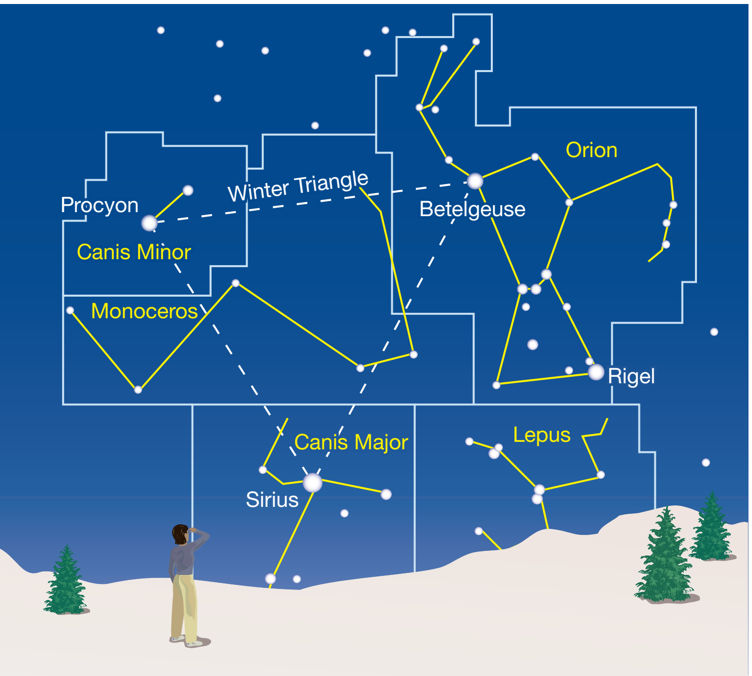
Constellations People of nearly every culture gave names to patterns they saw in the sky. We usually refer to such patterns as constellations, but to astronomers the term has a more precise meaning: A **constellation** is a *region* of the sky with well-defined borders; the familiar patterns of stars merely help us locate these constellations.

The names and borders of the 88 official constellations [Appendix H] were chosen in 1928 by members of the International Astronomical Union. Note that, just as every spot of land in the continental United States is part of some state, every point in the sky belongs to some constellation. For example, Figure 2.2 shows the borders of the constellation Orion and several of its neighbors.

Bright stars help us identify constellations, which officially are regions of the sky.

Recognizing the patterns of just 20 or so constellations is enough to make the sky seem as familiar as your own neighborhood. The best way

FIGURE 2.1
This photo shows the Milky Way rising over Caldera de Taburiente National Park in the Canary Islands (Spain). The bright spot just above (and slightly right of) the center of the band is the planet Jupiter.



▲ **FIGURE 2.2**
Red lines mark official borders of several constellations near Orion. Yellow lines connect recognizable patterns of stars. Sirius, Procyon, and Betelgeuse form the *Winter Triangle*, which spans several constellations. This view shows how it appears (looking south) on winter evenings from the Northern Hemisphere.

to learn the constellations is to go out and view them, guided by a few visits to a planetarium, star charts **[Appendix I]**, or sky-viewing apps.

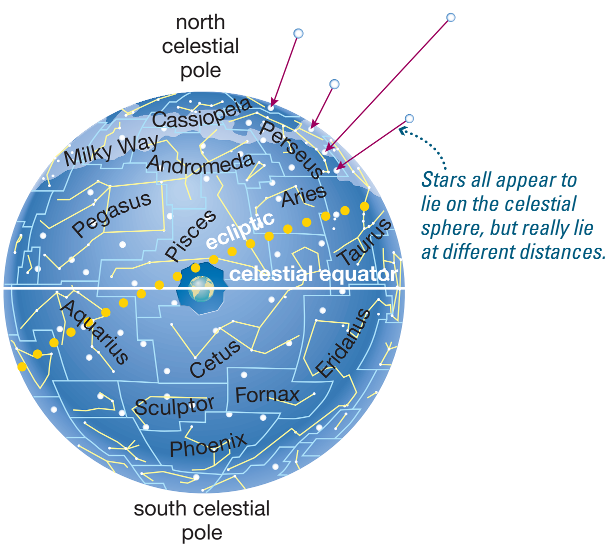
The Celestial Sphere The stars in a particular constellation appear to lie close to one another but may be quite far apart in reality, because they may lie at very different distances from Earth. This illusion occurs because we lack depth perception when we look into space, a consequence of the fact that the stars are so far away **[Section 1.1]**. The ancient Greeks mistook this illusion for reality, imagining the stars and constellations as lying on a great **celestial sphere** that surrounds Earth (Figure 2.3).

All stars appear to lie on the *celestial sphere*, but in reality they lie at different distances from Earth.

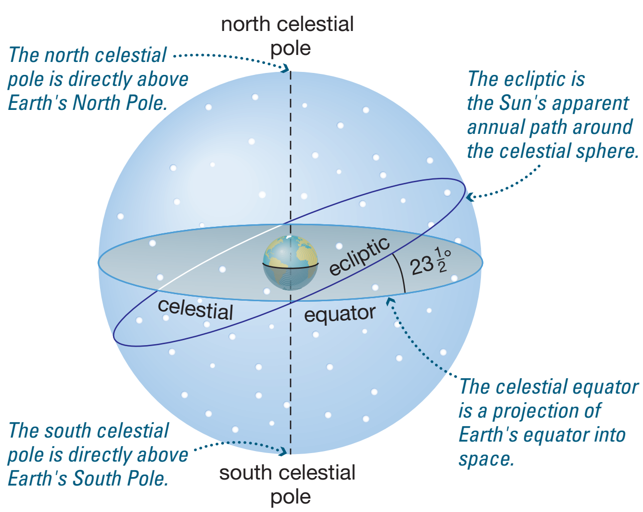
We now know that Earth seems to be in the center of the celestial sphere only because it is where we are located as we look into space. Nevertheless, the celestial sphere is a useful illusion, because it allows us to map the sky as seen from Earth. For reference, we identify two special points and two special circles on the celestial sphere (Figure 2.4).

- 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 23½° angle, because that is the tilt of Earth's axis.

The Milky Way The band of light that we call the *Milky Way* circles all the way around the celestial sphere, passing through more than a dozen constellations, and bears an important relationship to the Milky Way Galaxy: *It traces our galaxy's disk of stars—the galactic plane—as it appears from our location within the galaxy.*



▲ **FIGURE 2.3**
The stars appear to lie on a great celestial sphere that surrounds Earth. This is an illusion created by our lack of depth perception in space, but it is useful for mapping the sky.



▲ **FIGURE 2.4**
This schematic diagram shows key features of the celestial sphere.

Figure 2.5 shows the idea. Our galaxy is shaped like a thin pancake with a bulge in the middle. We view the universe from our location a little more than halfway out from the center of this "pancake." In all directions that we look within the pancake, we see the many stars and vast interstellar clouds that make up the Milky Way in the night sky; that is why the band of light makes a full circle around our sky. The Milky Way appears somewhat wider in the direction of the constellation Sagittarius, because that is the direction in which we are looking toward the galaxy's central bulge. We have a clear view to the distant universe only when we look *away* from the galactic plane, along directions that have relatively few stars and clouds to block our view.

The Milky Way in the night sky is our view in all directions into the disk of our galaxy.

The dark lanes that run down the center of the Milky Way contain the densest clouds, obscuring our view of stars behind them. In most directions, these clouds prevent us from seeing more than a few thousand light-years into our galaxy's disk. As a result, much of our own galaxy remained hidden from view until just a few decades ago, when new technologies allowed us to peer through the clouds by observing forms of light that are invisible to our eyes (such as radio waves, infrared light, and x-rays **[Section 5.1]**).

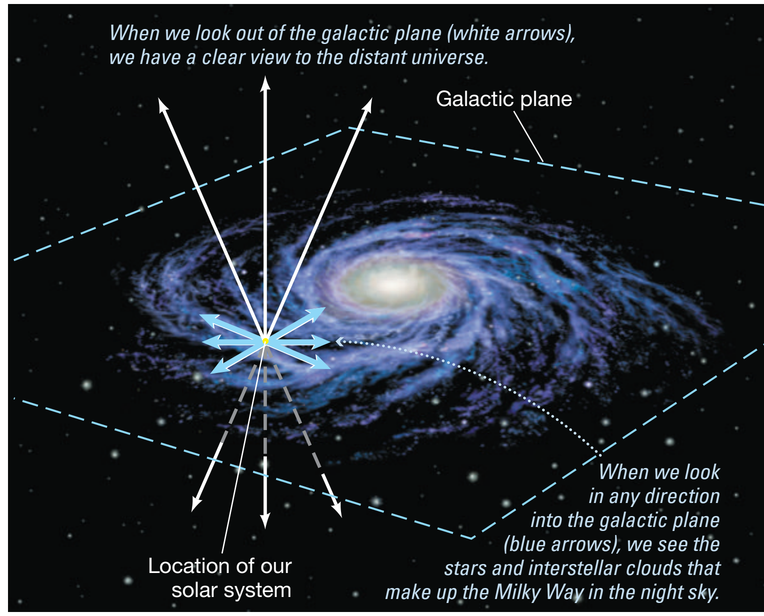


FIGURE 2.5
This painting shows how our galaxy's structure affects our view from Earth.

The Local Sky The celestial sphere provides a useful way of thinking about the appearance of the universe from Earth. But it is not what we actually see when we go outside. Instead, your **local sky**—the sky as seen from wherever you happen to be standing—appears to take the shape of a hemisphere or dome. The dome shape arises from the fact that we see only half of the celestial sphere at any particular moment from any particular location, while the ground blocks the other half from view.

Figure 2.6 shows key reference features of the local sky. 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 pinpoint an object in the local sky by stating its altitude above the horizon and direction along the horizon.

We can pinpoint the position of any object in the local sky by stating its **direction** along the horizon (sometimes stated as *azimuth*, which is degrees clockwise from due north) and its **altitude** above the horizon. For example, Figure 2.6 shows a person pointing to a star located in the southeast direction at an altitude of 60°. Note that the zenith has altitude 90° but no direction, because it is straight overhead.

Angular Sizes and Distances Our lack of depth perception on the celestial sphere makes it difficult to judge the true sizes or separations of the objects we see in the sky. However, we can describe the *angular* sizes or separations of objects without knowing how far away they are.

The farther away an object is, the smaller its angular size.

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 the Moon are each about ½° (Figure 2.7a). Note that angular size does not by itself tell us an object's true size, because angular size also depends on distance. The Sun is about 400 times as large in diameter as the Moon, but it has the same angular size in our sky because it is also about 400 times as far away.

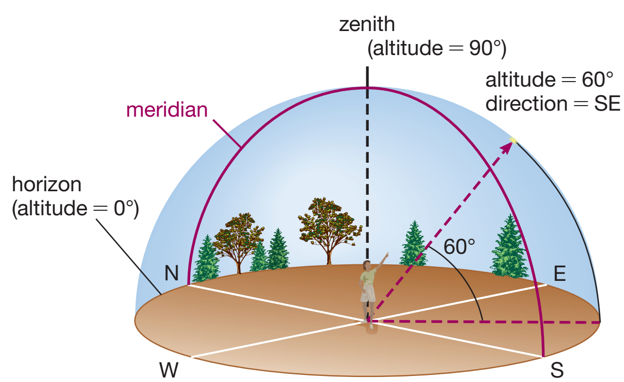
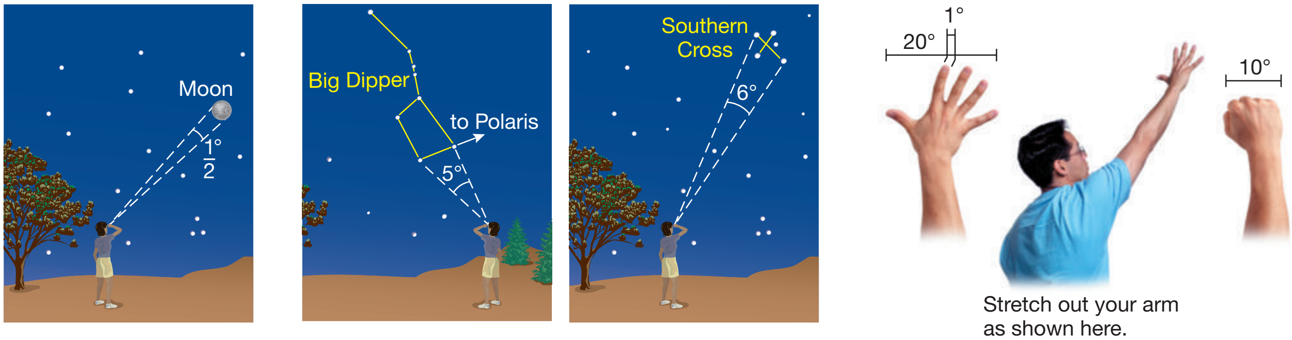


FIGURE 2.6
From any place on Earth, the local sky looks like a dome (hemisphere). This diagram shows key reference points in the local sky. It also shows how we can describe any position in the local sky by its altitude and direction.



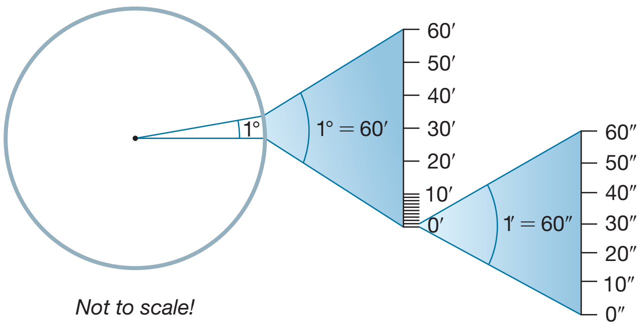
a The angular sizes of the Sun and the Moon are about ½°.

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 2.7**

We measure *angular sizes* or *angular distances*, rather than actual sizes or distances, when we look at objects in the sky.



▲ **FIGURE 2.8**

We subdivide each degree into 60 arcminutes and each arcminute into 60 arcseconds.

THINK ABOUT IT Children often try to describe the sizes of objects in the sky (such as the Moon or an airplane) in inches or miles, or by holding their fingers apart and saying, "It was THIS big." Can we really describe objects in the sky in this way? Why or why not?

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° and the angular length of the Southern Cross is about 6° (Figure 2.7b). You can use your outstretched hand to make rough estimates of angles in the sky (Figure 2.7c).

For greater precision, we subdivide each degree into 60 **arcminutes** (symbolized by ′) and each arcminute into 60 arcseconds (symbolized by ″), as shown in Figure 2.8. For example, we read 35°27′15″ as *35 degrees, 27 arcminutes, 15 arcseconds*.

Common Misconceptions

The Moon Illusion

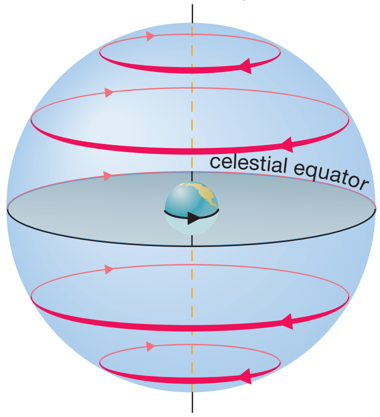
You've probably noticed that the full moon appears to be larger when it is near the horizon than when it is high in your sky. However, this apparent size change is an illusion: If you compare the Moon's angular size to that of a small object (such as a small button) held at arm's length, you'll see that it remains essentially the same throughout the night. The reason is that the Moon's angular size depends on its true size and distance, and while the latter varies over the course of the Moon's monthly orbit, it does not change enough to cause a noticeable effect on a single night. The Moon illusion clearly occurs within the human brain, though its precise cause is still hotly debated. Interestingly, you may be able to make the illusion go away by viewing the Moon upside down between your legs.

Why do stars rise and set?

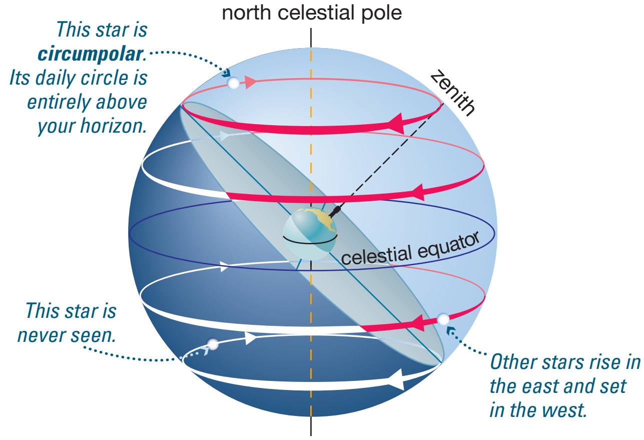
If you spend a few hours out under a starry sky, you'll notice that the universe seems to be circling around us, with stars moving gradually across the sky from east to west. Many ancient people took this appearance at face value, concluding that we lie in the center of a universe that rotates around us each day. Today we know that the ancients had it backward: It is Earth that rotates daily, not the rest of the universe.

We can picture the movement of the sky by imagining the celestial sphere rotating around Earth (Figure 2.9). From this perspective you can see how the universe seems to turn around us: Every object on the celestial sphere appears to make a simple daily circle around Earth. However, the motion can look a little more complex in the local sky, because the horizon cuts the celestial sphere in half. Figure 2.10 shows the idea for a typical Northern Hemisphere location (latitude 40°N). If you study the figure carefully, you'll notice the following key facts about the paths of various stars through the local sky:

- Stars near the north celestial pole are **circumpolar**, meaning that they remain perpetually above the horizon, circling (counterclockwise) around the north celestial pole each day.
- Stars near the south celestial pole never rise above the horizon at all.
- All other stars have daily circles that are partly above the horizon and partly below, which means they appear to rise in the east and set in the west.



▲ **FIGURE 2.9**
Earth rotates from west to east (black arrow), making the celestial sphere *appear* to rotate around us from east to west (red arrows).



▲ **FIGURE 2.10**
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 if you rotate the page so that the zenith points up.

The time-exposure photograph that opens this chapter (page 24) shows a part of the daily paths of stars. Paths of circumpolar stars are visible within the arch; notice that the complete daily circles for these stars are above the horizon, although the photo shows only a portion of each circle. The north celestial pole lies at the center of these circles. The circles grow larger for stars farther from the north celestial pole. If they are large enough, the circles cross the horizon, so that the stars rise in the east and set in the west. The same ideas apply in the Southern Hemisphere, except that circumpolar stars are those near the south celestial pole and they circle clockwise rather than counterclockwise.

Earth's west-to-east rotation makes stars appear to move from east to west through the sky as they circle around the celestial poles.

THINK ABOUT IT Do distant galaxies also rise and set like the stars in our sky? Why or why not?

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

If you stay in one place, the basic patterns of motion in the sky will stay the same from one night to the next. However, if you travel far north or south, you'll see a different set of constellations than you see at home. And even if you stay in one place, you'll see different constellations at different times of year. Let's explore why.

Variation with Latitude **Latitude** measures north-south position on Earth and **longitude** measures east-west position (Figure 2.11). Latitude is defined to be 0° at the equator, increasing to 90°N at the North Pole and 90°S at the South Pole. By international treaty, longitude is defined to be 0° along the **prime meridian**, which passes through Greenwich, England. Stating a latitude and a longitude pinpoints a location on Earth. For example, Miami lies at about 26°N latitude and 80°W longitude.

Cosmic Calculations 2.1

Angular Size, Physical Size, and Distance

If you hold a coin in front of one eye, it can block your entire field of view. But as you move it farther away, it appears to get smaller and it blocks less of your view. As long as a coin or any other object is far enough away so that its angular size is relatively small (less than a few degrees), the following formula relates the object's angular size (in degrees), physical size, and distance:

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

Example: The Moon's angular diameter is about 0.5° and its distance is about 380,000 km. What is the Moon's physical diameter?

Solution: To solve the formula for physical size, we multiply both sides by $2\pi \times$ distance and rearrange:

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

We now plug in the given values of the Moon's angular size and distance:

$$\text{physical size} = 0.5^\circ \times \frac{2\pi \times 380{,}000 \text{ km}}{360^\circ} \approx 3300 \text{ km}$$

The Moon's diameter is about 3300 km. We could find a more exact value (3476 km) by using more precise values for the angular diameter and distance.