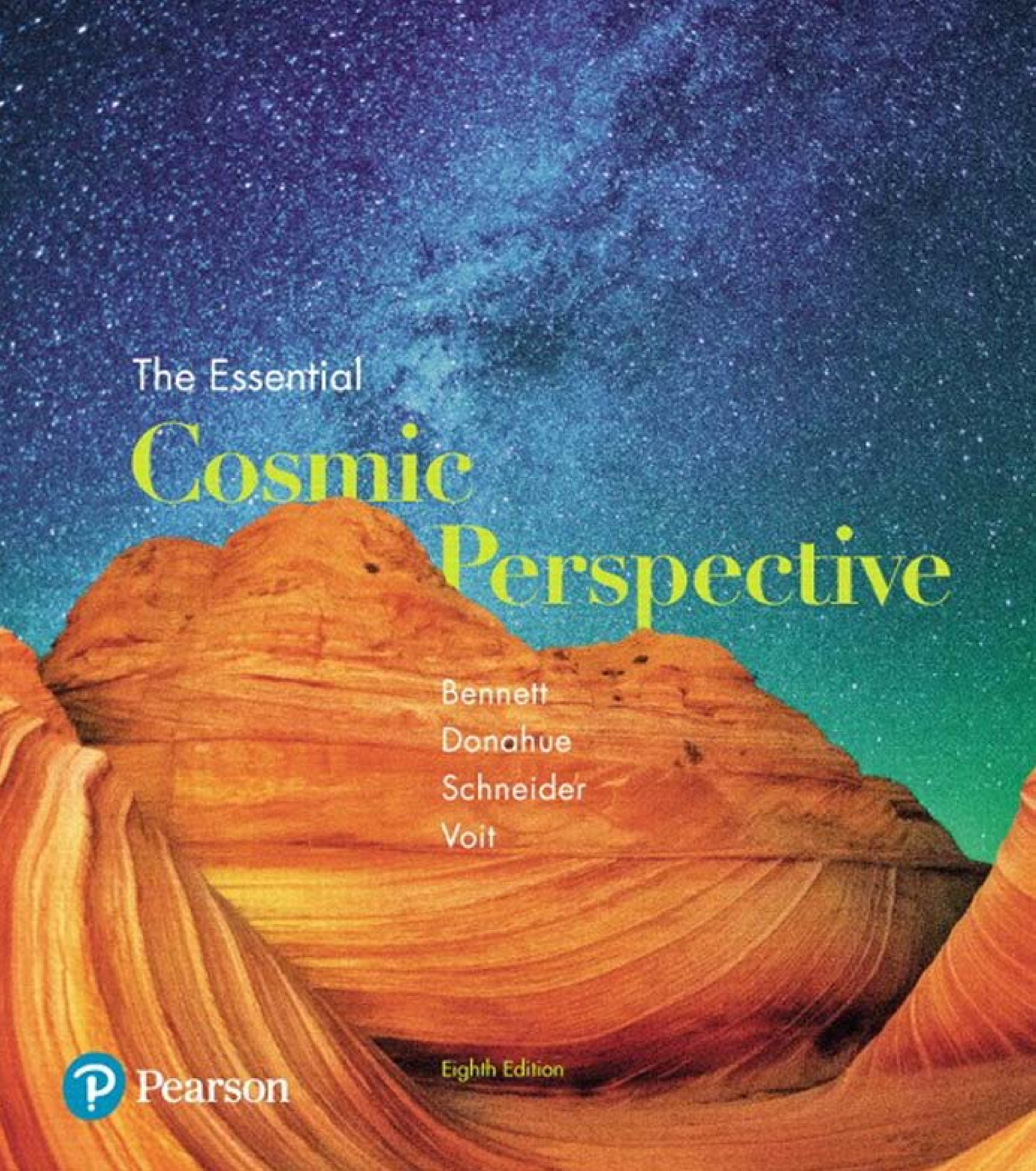

The Essential Cosmic Perspective

Bennett
Donahue
Schneider
Voit

Eighth Edition

Pearson

THE ESSENTIAL Cosmic Perspective

EIGHTH EDITION

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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

PART I Developing Perspective

PART II Key Concepts for Astronomy

PART III Learning from Other Worlds

PART IV Stars

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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 is designed as a textbook for college courses in introductory astronomy, but is suitable for anyone who is curious about the universe. We assume no prior knowledge of astronomy or physics, and the book is especially written for students who do not intend to major in mathematics or science.

The Essential Cosmic Perspective is the mid-level of the three general astronomy textbooks we offer. Our longer book, *The Cosmic Perspective*, provides a comprehensive survey of modern astronomy with 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 of astronomy, though it may also be used with two-semester sequences. Our shortest textbook, *The Cosmic Perspective Fundamentals,* covers only the most fundamental topics in astronomy and is designed for courses that address a more limited set of topics.

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 eighth 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:
  - **Chapter 7** has been significantly rewritten to reflect new results from *MESSENGER* at Mercury, *Curiosity* and *MAVEN* at Mars, and the latest data on global warming.
  - **Chapter 9** has been reorganized and rewritten to reflect recent developments in the study of small bodies, particularly the revolutionary new views provided by recent spacecraft including *Dawn*, *Rosetta*, and *New Horizons*.
  - **Chapter 10** has been heavily revised in light of thousands of new discoveries of extrasolar planets since the prior edition.
  - In **Chapter 14,** we have almost completely rewritten Section 14.4 to focus on events in which black holes can form and neutron star mergers.
  - **Chapter 15** has been revised to reduce jargon and to include a new full-page figure showing the Milky Way in different wavelengths. In addition, Section 15.4 on the galactic center has been rewritten and features a new two-page Cosmic Context spread.
  - **Chapter 16** has been significantly revised in light of new research into galactic evolution.
  - **Chapter 19** has been significantly rewritten, particularly in Sections 19.2 and 19.3 (which has also been completely reorganized), thanks to new understanding of the potential habitability of Mars, Titan, and extrasolar planets.
- **Fully Updated Science:** Astronomy is a fast-moving field, and numerous new developments have occurred since the prior edition was published. In addition to the major chapter-level changes above, other scientific updates in this edition include the following:
  - New results and images from spacecraft exploring our solar system, including *Curiosity* and *MAVEN* at Mars, *Cassini* at Saturn, *MESSENGER* at Mercury, *Dawn* at Ceres, *New Horizons* at Pluto, and more
  - Recent results from major space observatories, including *Hubble* and *Kepler*, and from powerful ground-based observatories such as ALMA
  - Updated data and models on topics including the formation of planetary systems, global warming, and galaxy formation and evolution
  - Major new discoveries and statistics relating to the study of extrasolar planets, new research on the timing and possible origin of life on Earth, and much more
- **Reinforced Focus on Critical Thinking:** We have always placed a strong emphasis on helping students develop critical thinking skills, both by showing students the process through which we have acquired our current understanding of the universe and through features that encourage critical thinking, such as our Think About It and See It for Yourself questions and many of our exercises. To further reinforce the importance of critical thinking, we have added the following new features to this edition:
  - **New Feature—Extraordinary Claims boxes:** Carl Sagan made famous the statement "extraordinary claims require extraordinary evidence." With this new feature, we provide students with examples of extraordinary claims about the universe and how they were either supported or debunked as scientists collected more evidence. The first of these features appears in Chapter 3, where the context of Sagan's dictum is also explained. Nine additional Extraordinary Claims boxes are sprinkled throughout the rest of the text. Instructors will find assignable tutorials based on these boxes on the Mastering Astronomy® site.
  - **New Feature—My Cosmic Perspective:** As in prior editions, every chapter ends with a feature titled "The

  Big Picture," designed to help students put the chapter content into the context of a larger cosmic perspective. For this edition, we have added in each of these sections a final entry entitled "My Cosmic Perspective," which aims to focus on a more personal connection between students and the cosmos. We believe that such a personal connection encourages students to think more critically about the meaning of all that they learn in their astronomy course.

  - **New Icons:** You'll see a new icon designed to call attention to a few of the features that promote critical thinking: ◯ (a "C" for "critical"). While we believe the entire structure of the book promotes critical thinking, you can use the features identified by these icons for special assignments to help students with these skills.

- **New Content in MasteringAstronomy®:** We have reached the point where *The Essential Cosmic Perspective* is no longer just a textbook; rather, it is a "learning package" that combines a printed book with deeply integrated, interactive media developed to support every chapter of our book. For students, the MasteringAstronomy® Study Area provides a wealth of tutorials and activities to build understanding, while quizzes and exercises allow them to test what they've learned. For instructors, the MasteringAstronomy® Item Library provides the unprecedented ability to quickly build, post, and automatically grade pre- and post-lecture diagnostic tests, weekly homework assignments, and exams of appropriate difficulty, duration, and content coverage. It also provides the ability to record detailed information on the step-by-step work of every student directly into a powerful and easy-to-use gradebook, and to evaluate results with a sophisticated suite of diagnostics. Among the changes you'll find to the MasteringAstronomy® site for this edition are numerous new narrated video tours of key figures from the textbook; numerous new tutorials in the Item Library; and a fully updated set of reading, concept, and visual quizzes in both the Study Area and the Item Library.

Themes of *The Essential 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 interweave a few key themes throughout the book, each selected to help make the subject more appealing to students who may never have taken any formal science courses and who may begin the course with little understanding of how science works. Our book is built around the following five key themes:

- **Theme 1:** *We are a part of the universe and thus can 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.
- **Theme 2:** *The universe is comprehensible through scientific principles that anyone can understand.* We can understand the universe 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—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 shows 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:** *A course in astronomy is the beginning of a lifelong learning experience.* Building on the prior themes, we emphasize that what students learn in their astronomy course is not an end but a beginning. By remembering a few key physical principles and understanding the nature of science, students can follow astronomical developments for the rest of their lives. We therefore seek to motivate students to continue to participate in the ongoing human adventure of astronomical discovery.
- **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 that 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, which can potentially affect our behavior. 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 of *The Essential Cosmic Perspective*

No matter how an astronomy course is taught, it is very important to present material according to a clear set of pedagogical principles. The following list briefly summarizes the major pedagogical principles that we apply throughout this book. (The Instructor Guide describes these principles in more detail.)

- **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. We therefore begin the book (in 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 of us personally. 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 the "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 concepts that 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 we find that the wide variety of features found on the terrestrial planets can be understood through just a few basic geological processes. Research shows that, long after the course is over, students are far more likely to retain such conceptual ideas than individual facts or details.
- **Emphasize critical thinking and understanding of the process of science.** One of the major problems in public understanding of science is that too many people don't understand the difference between evidence-based science and opinion or faith. For that reason, we place particular focus on making sure students can think critically about scientific evidence and how we have arrived at current scientific understanding. For example, we discuss the nature of science in detail in Chapter 3 and then continue to show examples of how science has progressed throughout the book, while also encouraging students to think critically about the evidence that has led to this progression.
- **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. 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 develop 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 foreign language courses. This means that most books are teaching astronomy in what looks to students like a foreign language! 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 as much as possible or, at minimum, to replace standard 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 often holding misconceptions about astronomical ideas. Therefore, to teach correct ideas, we must also help students recognize the paradoxes in their prior misconceptions. We address this issue in a number of ways, most overtly with Common Misconceptions boxes. These summarize commonly held misconceptions and explain why they cannot be correct.

The Topical (Part) 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 approached in a distinctive way designed to help maintain the focus on the themes discussed earlier. Here, we summarize the guiding philosophy through which we have approached each topic. Every part concludes with a two-page Cosmic Context figure, which ties together into a coherent whole the diverse ideas covered in the individual chapters.

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 and 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 covers 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. 286–287.

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 covers the end points of stellar evolution: white dwarfs, neutron stars, and black holes.

The Cosmic Context for Part IV appears on pp. 384–385.

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 presents the variety of galaxies, how we determine key parameters such as galactic distances and age, and current understanding of galaxy evolution. Chapter 17 then presents 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. 494–495.

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. 532–533.

Pedagogical Features of *The Essential Cosmic Perspective*

Alongside the main narrative, *The Essential Cosmic Perspective* includes a number of pedagogical devices designed to enhance student learning:

- **Basic Chapter Structure** Each chapter is carefully structured to ensure that students understand the goals up front, learn the details, and pull together all the ideas at the end. In particular, note the following key structural elements:
    - **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 understand what they will be learning about and stay focused on these key goals as they work through the chapter.
    - **Introduction** The first page of the main chapter text begins with a two- to three-paragraph introduction to the chapter material.
    - **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 our place in the universe.
    - **Chapter Summary** The end-of-chapter summary offers a concise review of the learning goal questions, helping to 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.
    - **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 very difficult otherwise; this makes them an excellent probe of comprehension.

  - **Quick Quiz** A short multiple-choice quiz that allows students to check their basic understanding.
  - **Process of Science Questions** Essay or discussion questions that help students focus on how science progresses over time.
  - **Group Work Exercise** A suggested activity designed for collaborative learning in class.
  - **Short-Answer/Essay Questions** Questions that go beyond the Review Questions in asking for conceptual interpretation.
  - **Quantitative Problems** Problems that require some mathematics, usually based on topics covered in the Cosmic Calculations boxes.
  - **Discussion Questions** Open-ended questions for class discussions.
  - **Web Projects** A few suggestions for additional Web-based research.
- **Additional 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:
  - **Annotated Figures** Key figures in each chapter incorporate the research-proven technique of "annotation"—carefully crafted text placed on the figure (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.
  - **Think About It** This feature, which appears throughout the book as 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, and 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 contain 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.
  - **Cross-References** When a concept is covered in greater detail elsewhere in the book, we include a cross-reference, printed in blue and surrounded by 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 include 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).

About MasteringAstronomy®

What is the single most important factor in student success in astronomy? Both research and common sense reveal the same answer: *study time*. No matter how good the teacher or how good the textbook, students learn only when they spend adequate time studying. Unfortunately, limitations on resources for grading have prevented most instructors from assigning much homework despite its obvious benefits to student learning. And limitations on help and office hours have made it difficult for students to make sure they use self-study time effectively. That, in a nutshell, is why we created MasteringAstronomy®. For students, it provides adaptive learning designed to coach them *individually*—responding to their errors with specific, targeted feedback and providing optional hints for those who need additional guidance. For professors, MasteringAstronomy® provides the unprecedented ability to automatically monitor and record students' step-by-step work and evaluate the effectiveness of assignments and exams. As a result, we believe that MasteringAstronomy® can change the way astronomy courses are taught: It is now possible, even in large classes, to ensure that each student spends his or her study time on optimal learning activities outside of class.

MasteringAstronomy® provides students with a wealth of self-study resources, including interactive tutorials targeting the most difficult concepts of the course, interactive or narrated versions of key figures and photos, and quizzes and other activities for self-assessment covering every chapter and every week. For professors, MasteringAstronomy® provides a library of tutoring activities that is periodically updated based on the performance of students nationwide. You can create assignments tailored to your specific class goals from among hundreds of activities and problems including pre- and post-lecture diagnostic quizzes, tutoring activities, end-of-chapter problems from this textbook, and test bank questions. MasteringAstronomy® now also includes Learning Catalytics, which provides additional capabilities for in-class learning. Visit MasteringAstronomy® to learn more.

Finally, in a world where everyone claims to have the best website, we'd like to point out three reasons why you'll discover that MasteringAstronomy® really does stand out from the crowd:

- MasteringAstronomy® has been built specifically to support the structure and pedagogy of *The Essential Cosmic Perspective*. You'll find the same concepts emphasized in the book and on the website, using the same terminology and the same pedagogical approaches. This type of consistency ensures that students focus on the concepts, without the risk of becoming confused by different presentations.
- Nearly all MasteringAstronomy® content has been developed either directly by *The Essential Cosmic Perspective* author team or in close collaboration with outstanding educators including Jim Dove, Jim Cooney, Jonathan Williams, Richard Gelderman, Ed Prather, Tim Slater, Daniel Lorenz, and Lauren Jones. The direct involvement of book authors ensures consistency from our website to the textbook, resulting in an effective, high-quality learning program.
- The MasteringAstronomy® platform uses the same unique student-driven engine as the highly successful MasteringPhysics® product (the most widely adopted physics tutorial and assessment system), developed by a group led by MIT physicist David Pritchard. This robust platform gives instructors unprecedented power not only to tailor content to their own courses, but also to evaluate the effectiveness of assignments and exams.

Additional 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®, 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 0-321-71295-1): 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 0-321-82046-0) by Edward E. Prather, Timothy F. Slater, Jeffrey P. Adams, and Gina Brissenden: The forty-four lecture tutorials included 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 0-134-53247-3): 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 0-134-60203-X): 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®.

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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, and proposing and helping to develop the Voyage scale model solar system on the National Mall (Washington, DC). 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, 2008/2011), *Math for Life* (Bid Kid Science, 2014), *What Is Relativity?* (Columbia University Press, 2014), *On Teaching Science* (Big Kid Science, 2014), and *A Global Warming Primer* (Big Kid Science, 2016). He is also the author of six science picture books for children, including *Max Goes to the Moon*, *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. Jeff lives in Boulder, CO with his wife, children, and dog. His personal website is www.jeffreybennett.com.

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Megan Donahue is a full professor in the Department of Physics and Astronomy at Michigan State University (MSU) and a Fellow of the American Association for the Advancement of Science. Her current research is mainly about using X-ray, UV, infrared, and visible light to study galaxies and clusters of galaxies: their contents—dark matter, hot gas, galaxies, active galactic nuclei—and what they reveal about the contents of the universe and how galaxies form and evolve. She grew up on a farm in Nebraska and received an S.B. in physics from MIT, where she began her research career as an X-ray astronomer. She has a Ph.D. in astrophysics from the University of Colorado. Her Ph.D. thesis on theory and optical observations of intergalactic and intracluster gas won the 1993 Trumpler Award from the Astronomical Society for the Pacific for an outstanding astrophysics doctoral dissertation in North America. She continued postdoctoral research as a Carnegie Fellow at Carnegie Observatories in Pasadena, California, and later as an STScI Institute Fellow at Space Telescope. Megan was a staff astronomer at the Space Telescope Science Institute until 2003, when she joined the MSU faculty. She is also actively involved in advising national and international astronomical facilities and NASA, including planning future NASA missions. Megan is married to Mark Voit, and they collaborate on many projects, including this textbook, over 50 peer-reviewed astrophysics papers, and the raising of their children, Michaela, Sebastian, and Angela. Megan has run three full marathons, including Boston. These days she does trail running, orienteers, and plays piano and bass guitar for fun and no profit.

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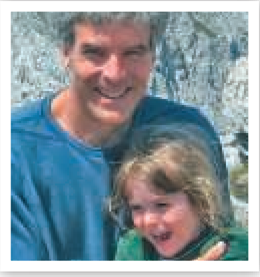
Nicholas Schneider is an associate professor in the Department of Astrophysical and Planetary Sciences at the University of Colorado and a researcher in the Laboratory for Atmospheric and Space Physics. He received his B.A. in physics and astronomy from Dartmouth College in 1979 and his Ph.D. in planetary science from the University of Arizona in 1988. In 1991, he received the National Science Foundation's Presidential Young Investigator Award. 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 hopes 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. In 2010 he received the Boulder Faculty Assembly's Teaching Excellence Award. Off the job, Nick enjoys exploring the outdoors with his family and figuring out how things work.

Mark Voit



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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.

As a rough guideline, your study time might be divided as shown in the table above. 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.
- Visit the MasteringAstronomy® site and make use of resources that will help you further build your understanding. 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

- Study the Review Questions, and rework problems and other assignments; try additional questions to be sure you understand the concepts. Study your performance on assignments, quizzes, or exams from earlier in the term.
- Work through the relevant chapter quizzes and other study resources available at the MasteringAstronomy® site.
- Study your notes from lectures and discussions. Pay attention to what your instructor expects you to know for an exam.
- Reread the relevant sections in the textbook, paying special attention to notes you have made on the pages.
- 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. In particular, research has shown that writing (or typing) and speaking trigger different areas of your brain. Writing something down—even when you think you already understand it—reinforces your learning by involving other areas of your brain.
2. If you make your work clear and self-contained (that is, make 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.
- Make all answers and other writing fully self-contained. A good test 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 × symbol (not with an asterisk), and write 10^5, not 10^5 or 10E5.
    2. *Check that word problems 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*

© Neil deGrasse Tyson

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. He contributed this essay about the meaning of "The Cosmic Perspective," abridged from his 100th essay written for* Natural History *magazine.*

> 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 **[pp. xxii–xxiii]**
2. Powers of 10 **[Appendixes C.1, 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.

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.

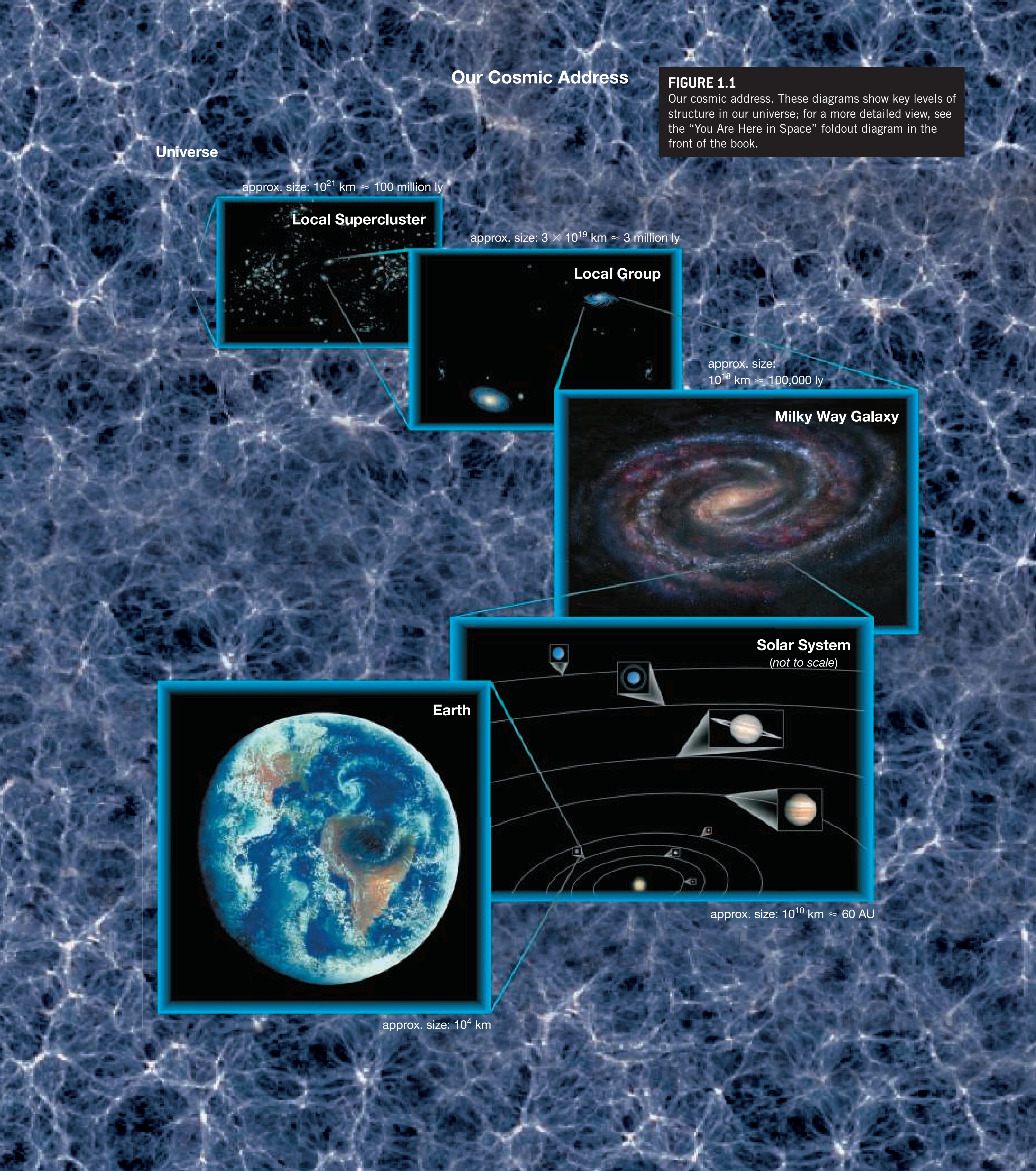


FIGURE 1.1
Our cosmic address. These diagrams show key levels of structure in our universe; for a more detailed view, see the "You Are Here in Space" foldout diagram in the front of the book.

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

$$\begin{aligned}
1\ \text{light-year} &= (\text{speed of light}) \times (1\ \text{yr}) \\
&= \left(300{,}00\ \frac{\text{km}}{\cancel{\text{s}}}\right) \times (1\ \cancel{\text{yr}}) \times \frac{365\ \cancel{\text{days}}}{1\ \cancel{\text{yr}}} \\
&\quad \times \frac{24\ \cancel{\text{hr}}}{1\ \cancel{\text{day}}} \times \frac{60\ \cancel{\text{min}}}{1\ \cancel{\text{hr}}} \times \frac{60\ \cancel{\text{s}}}{1\ \cancel{\text{min}}} \\
&= 9{,}460{,}000{,}000{,}000\ \text{km} \\
&= 9.46\ \text{trillion km}
\end{aligned}$$

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}.

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

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

Billions of other galaxies are scattered throughout space. Some galaxies are fairly isolated, but most are found in groups. Our Milky Way, for example, is one of the two largest among more than 70 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 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 (which was recently named *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.

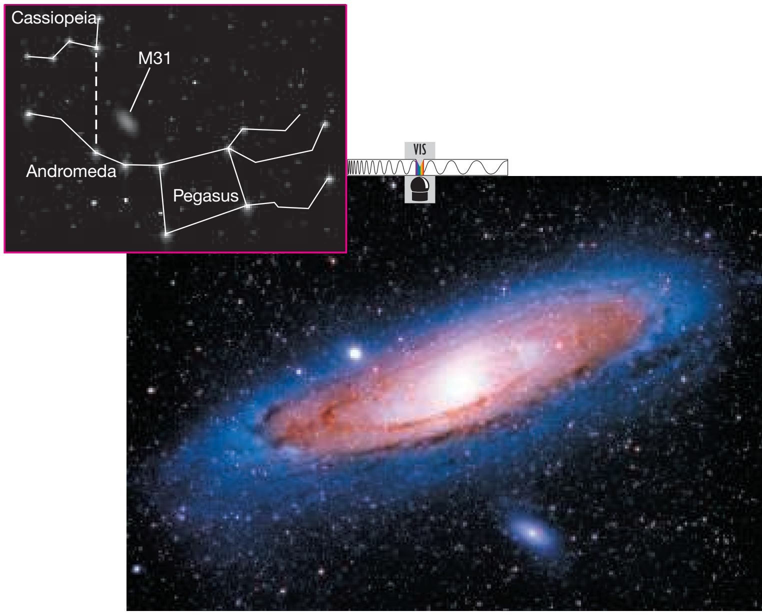
Looking Back in Time The speed of light is extremely fast by earthly standards. It is so fast that if you could make light go in circles, it could circle Earth nearly eight times in a single second. Nevertheless, even light takes time to travel the vast distances in space. Light takes a little more than 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



▲ **FIGURE 1.2**
The Andromeda Galaxy (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 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.

before the light from the near side. Figure 1.2 therefore shows different parts of the galaxy spread over a time period of 100,000 years. When we study the universe, it is impossible to separate space and time.

see it for yourself The 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 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.

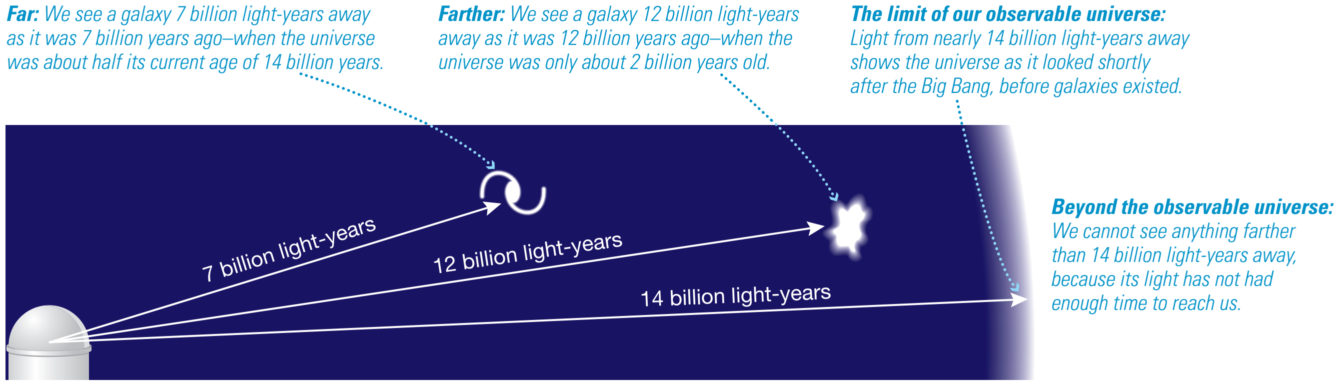
common misconceptions

The Meaning of a Light-Year

You've probably heard people say things like "It will take me light-years to finish this homework!" But a statement like this one 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.

▼ **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.



Far: *We see a galaxy 7 billion light-years away as it was 7 billion years ago–when the universe was about half its current age of 14 billion years.*

Farther: *We see a galaxy 12 billion light-years away as it was 12 billion years ago–when the universe was only about 2 billion years old.*

The limit of our observable universe: *Light from nearly 14 billion light-years away shows the universe as it looked shortly after the Big Bang, before galaxies existed.*

Beyond the observable universe: *We cannot see anything farther than 14 billion light-years away, because its light has not had enough time to reach us.*

---

*As we'll see in Chapter 16, distances to faraway galaxies must be defined carefully in an expanding universe; in this book, we use distances based on the light-travel time from a distant object (called the *lookback time*).

◆ How big is the universe?

Figure 1.1 put numbers on the sizes of different structures in the universe, but these numbers have little meaning for most people—after all, they are literally astronomical. 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 the Sun, the planets, and the distances between them at *one ten-billionth* of their actual sizes and distances.

Figure 1.5a shows the Sun and planets at their correct 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 a ballpoint from 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 (16.5 yards) 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,

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

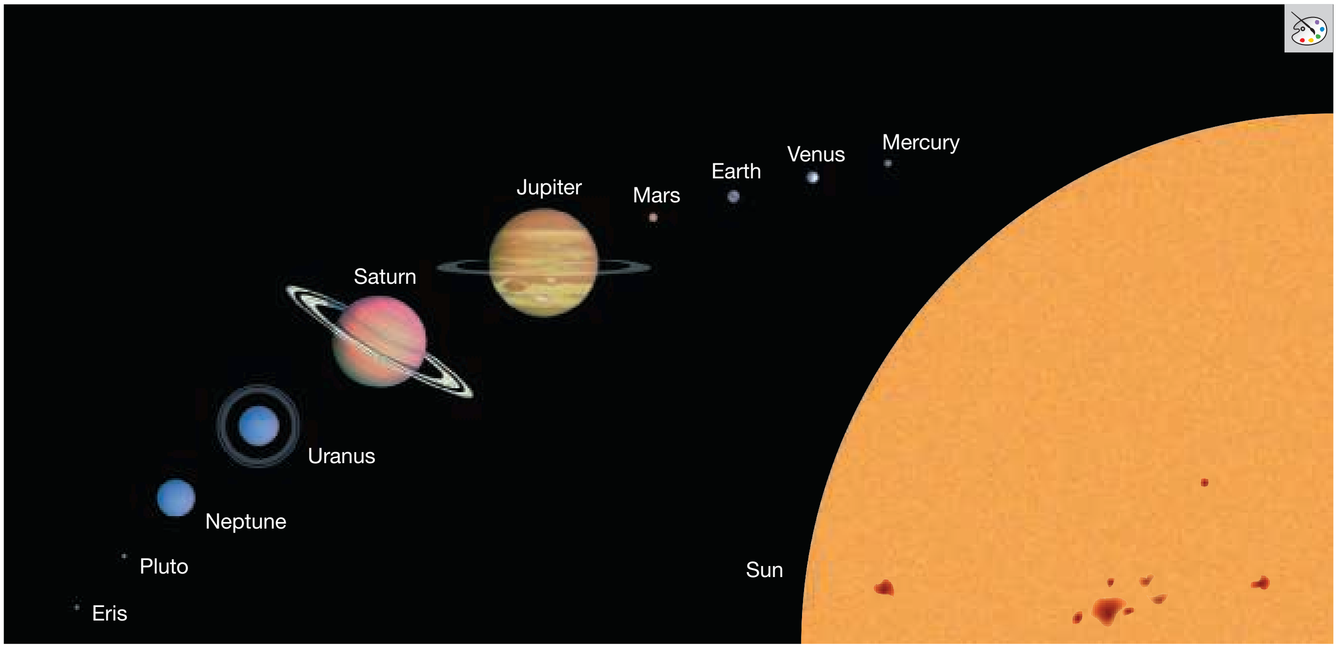
special topic How Many Planets Are in Our Solar System?

Until recently, children were taught that our solar system had nine planets. However, in 2006 astronomers voted to demote Pluto to a *dwarf planet*, leaving our solar system with only eight official planets. Why the change?

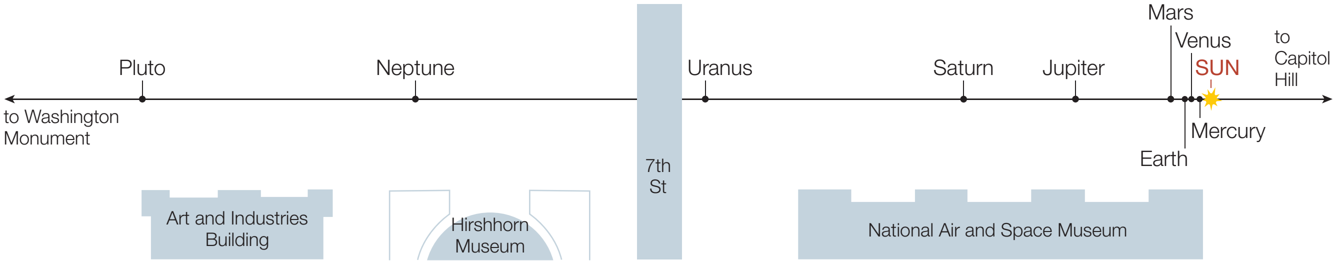
When Pluto was discovered in 1930, it was assumed to be similar to other planets. But as we'll discuss in Chapter 9, we now know that Pluto is much smaller than any of the first eight planets and that it shares the outer solar system with thousands of other icy objects. Still, as long as Pluto was the 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. Three smaller solar system objects are also now considered dwarf planets (the asteroid Ceres and the Kuiper belt objects Makemake and Haumea). More than a half dozen other objects are still being studied to determine if they meet the dwarf planet definition.

Some astronomers object to these definitions, which may yet be revisited. Pluto and other objects will remain the same either way. Indeed, much as there are no well-defined distinctions between the flowing waterways that we call creeks, streams, or rivers, this case offers a good example of the difference between the fuzzy boundaries of nature and the human preference for categories.



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



b Locations of the major objects in the Voyage model (Washington, D.C.); the distance from the Sun to Pluto is about 600 meters (1/3 mile). Planets are lined up in the model, but in reality each planet orbits the Sun independently and a perfect alignment never occurs.

▲ **FIGURE 1.5**
The Voyage scale model represents the solar system at one *ten-billionth* of its actual size. Pluto is included in the Voyage model for context.

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!*).

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 can walk the roughly 600-meter distance from the Sun to Pluto in just a few minutes. 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

common misconceptions

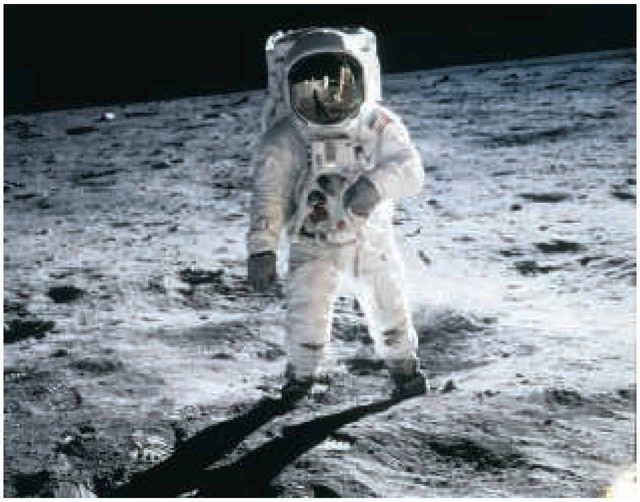
Confusing Very Different Things

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!

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.

system to our own, a three-star system called Alpha Centauri (Figure 1.7), is about 4.4 light-years away. That distance is about 4400 kilometers (2700 miles) on the 1-to-10-billion scale, 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.



▲ **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."

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.

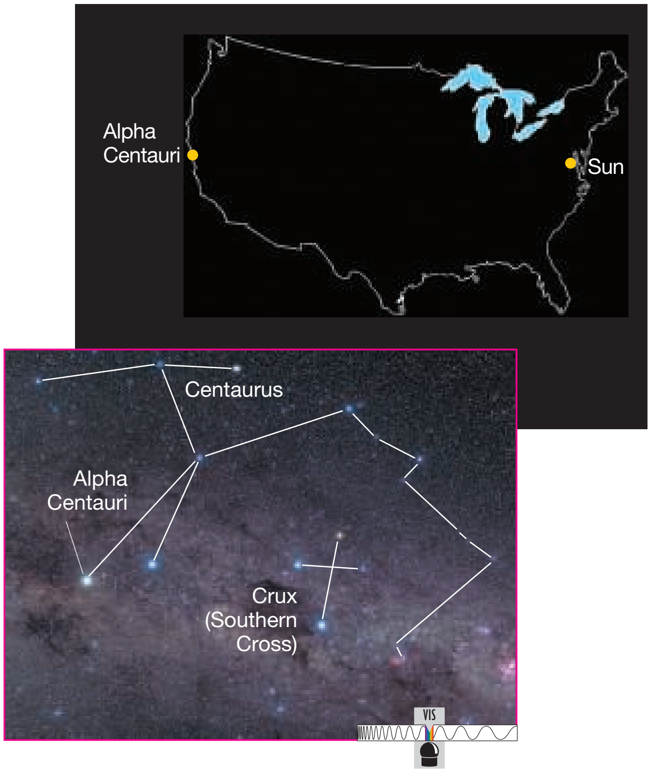
The Size of the Milky Way Galaxy

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. 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



▲ **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 in the night sky.