Ninth Edition

THE COSMIC PERSPECTIVE

Bennett

Donahue

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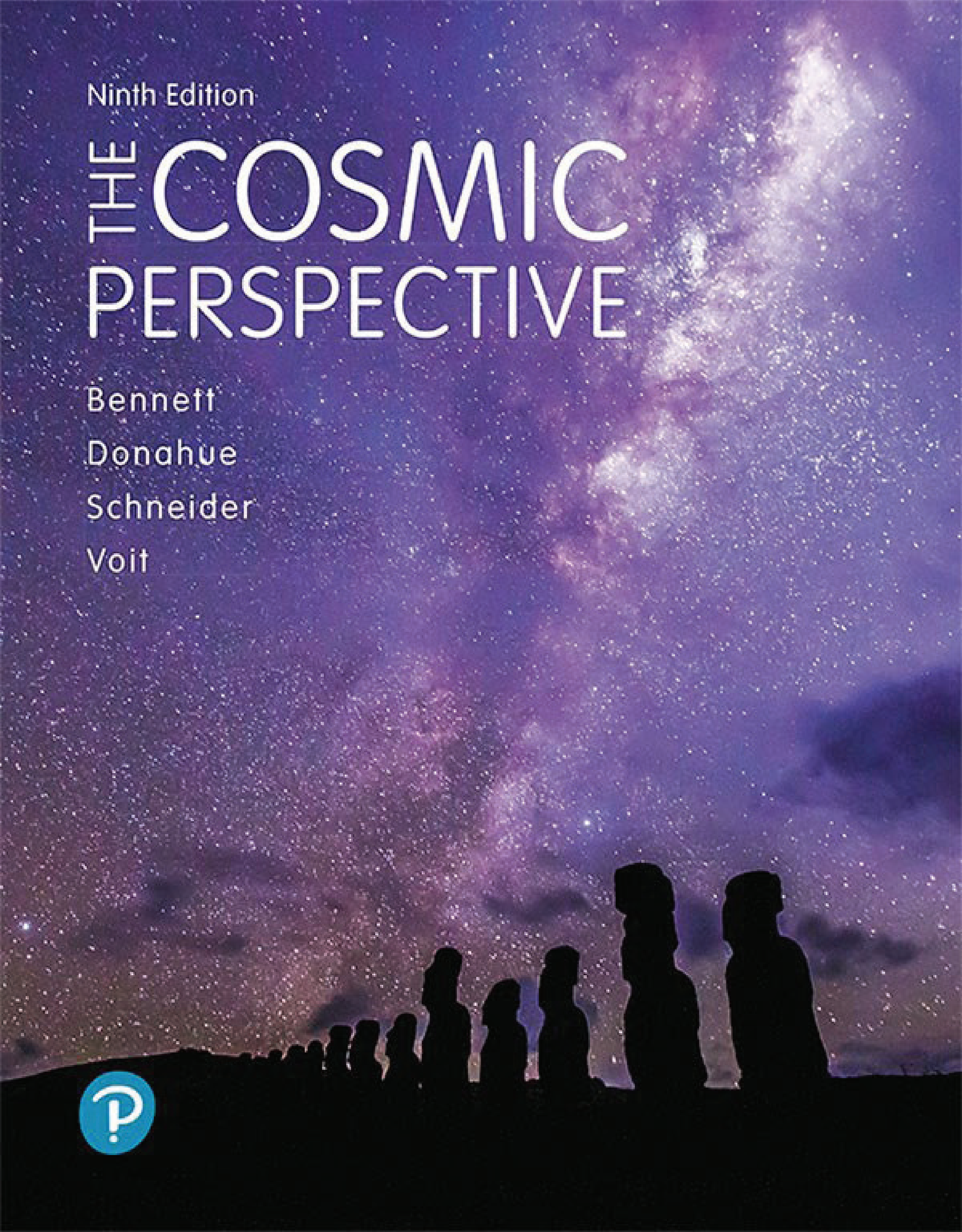
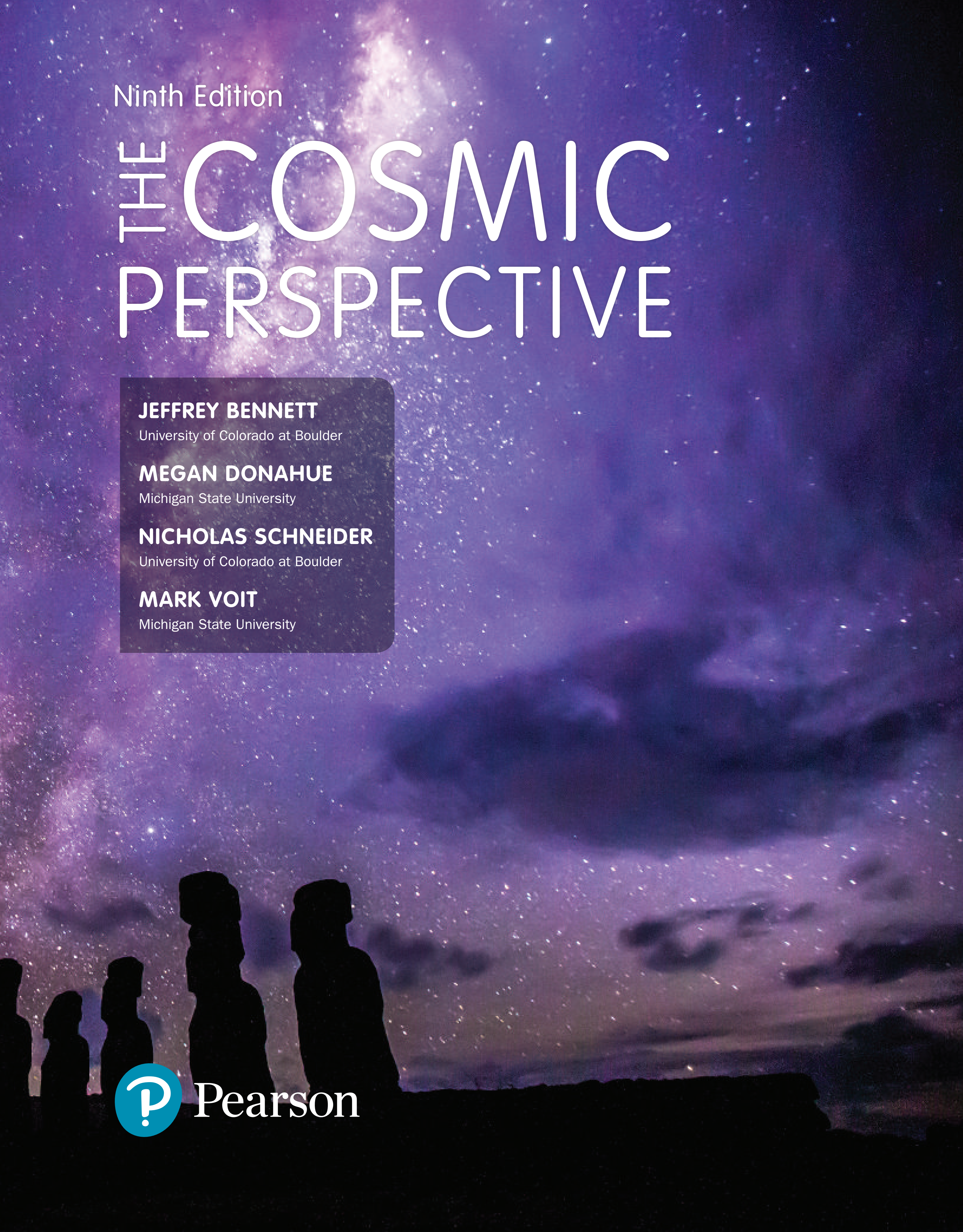


THE COSMIC PERSPECTIVE

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 he orbits Earth during the Space Shuttle's final servicing mission to the Hubble Space Telescope (May 2009).



Ninth Edition

THE COSMIC PERSPECTIVE

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

Pearson

ISBN 10: 0-134-87436-6; ISBN 13: 978-0-134-87436-4 (Student edition)
ISBN 10: 0-134-99077-3; ISBN 13: 978-0-134-99077-4 (The Solar System)
ISBN 10: 0-134-99078-1; ISBN 13: 978-0-134-99078-1 (Stars, Galaxies, and Cosmology)

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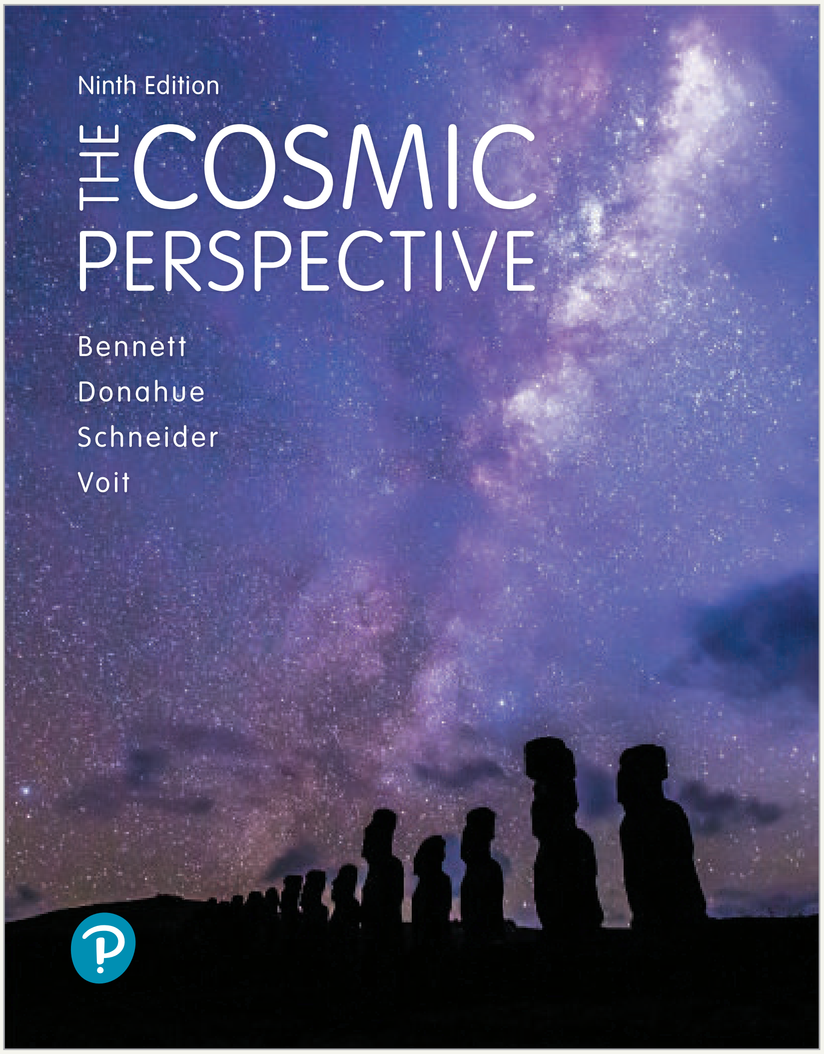
DEDICATION

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

Explore Modern Astronomy and Its Connections to Our Lives

The Cosmic Perspective provides a thoroughly engaging and up-to-date introduction to astronomy for anyone who is curious about the universe. As respected teachers and active researchers, the authors present astronomy using a coherent narrative and a thematic approach that engages students immediately and guides them through connecting ideas. The **Ninth Edition** features major scientific updates, new content that focuses on the possibility of life in the universe and recent discoveries, and an enhanced focus on cultural diversity among scientists and ethics across science and astronomy. **Mastering Astronomy** includes a wealth of author-created resources for students to use before, during, and after class.



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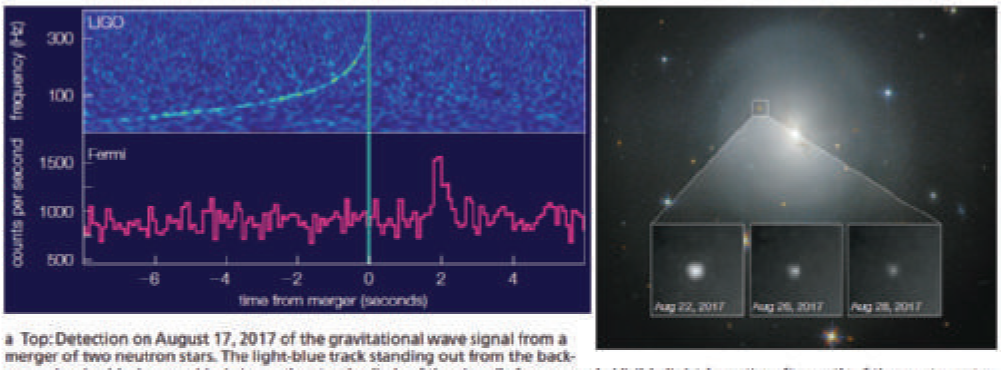
Fully Updated Science Engages Students

P. 311

Chapter 11 has been updated with the latest discoveries from the *Juno* and *Cassini* missions, as well as new understanding of Jupiter's weather, Saturn's rings, and more.

Other updates include new material on the detection of gravitational waves (Chapters S3 and 18), new insights into extrasolar planets (Chapter 13), new discoveries about early life on Earth (Chapter 24), and much more.



a Top: Detection on August 17, 2017 of the gravitational wave signal from a merger of two neutron stars. The light-blue track standing out from the background noise (darker speckles) shows the steady climb of the signal's frequency from below 100 Hz through more than 300 Hz just before the merger. The vertical green line shows the moment of the merger event. The signal's peak frequency shows that the neutron stars were orbiting one another more than 300 times per second just before the merger. Bottom: Detection by the Fermi observatory of a gamma-ray burst from the merger two seconds after the end of the gravitational-wave signal.

b Visible light from the aftermath of the neutron-star merger shown in part a, as seen by the Hubble Space Telescope. Information from the LIGO signal allowed astronomers to find this afterglow in the galaxy NGC 4993, about 130 million light-years away. The inset frames show the afterglow fading during the two weeks following the gravitational-wave detection.

FIGURE 18.18 Observed signals from the first detection of a merger of two neutron stars.

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Revised End-of-Chapter Exercises Deepen Student Understanding

Inclusive Astronomy

Use these questions to reflect on participation in science.

33. *Group Discussion: Ancestral Astronomy.* No matter what your background, you had ancestors who watched the sky and observed how celestial objects move through it.
    a. Working independently, choose a particular branch of your ancestry to explore, then gather historical information dating back as far as possible (ideally at least several centuries) about how and why your ancestors made use of their observations of the sky.
    b. Gather in small groups (two to four students) and take turns sharing what you learned through your research. Be clear about the ancestral group you have chosen and the time period your research covers.
    c. Make a list of the major uses of astronomical knowledge that your group members found, categorizing the uses as practical, ceremonial/religious, or other. Which uses were most common? Do you see any noticeable differences among the cultures?
    d. Discuss how cultural or geographical factors may have influenced the astronomical knowledge of these different ancestral groups.

P. 82

NEW! Each chapter now has **Inclusive Astronomy** exercises designed to spur student discussion about topics such as why astronomy belongs to everyone and the ways in which the astronomical community is working to address historical inequities.

The Process of Science, a major theme integrated throughout the main text, is reinforced with a set of short-answer questions at the end of each chapter, as well as a suite of tutorials available for assignment in Mastering Astronomy.

The Process of Science

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

34. *What Makes It Science?* Choose a single idea in the modern view of the cosmos as discussed in Chapter 1, such as "The universe is expanding," "The universe began with a Big Bang," "We are made from elements manufactured by stars," or "The Sun orbits the center of the Milky Way Galaxy once every 230 million years."
    a. Describe how this idea reflects each of the three hallmarks of science, discussing how it is based on observations, how our understanding of it depends on a model, and how that model is testable.
    b. Describe a hypothetical observation that, if it were actually made, might cause us to call the idea into question. Then briefly discuss whether you think that, overall, the idea is likely or unlikely to hold up to future observations.
35. *The Importance of Ancient Astronomy.* Why was astronomy important to people in ancient times? Discuss both the practical importance of astronomy and the importance it may have had for religious, ceremonial, or philosophical traditions. Which of those roles (practical or religious/ceremonial/philosophical) do you think was more important in leading to the development of modern astronomy? Defend your opinion.
36. *The Impact of Science.* The modern world is filled with ideas, knowledge, and technology that developed through science and application of the scientific method. Discuss some of these things and how they affect our lives. Which of these impacts do you think are positive? Which are negative? Overall, do you think science has benefited the human race? Defend your opinion.

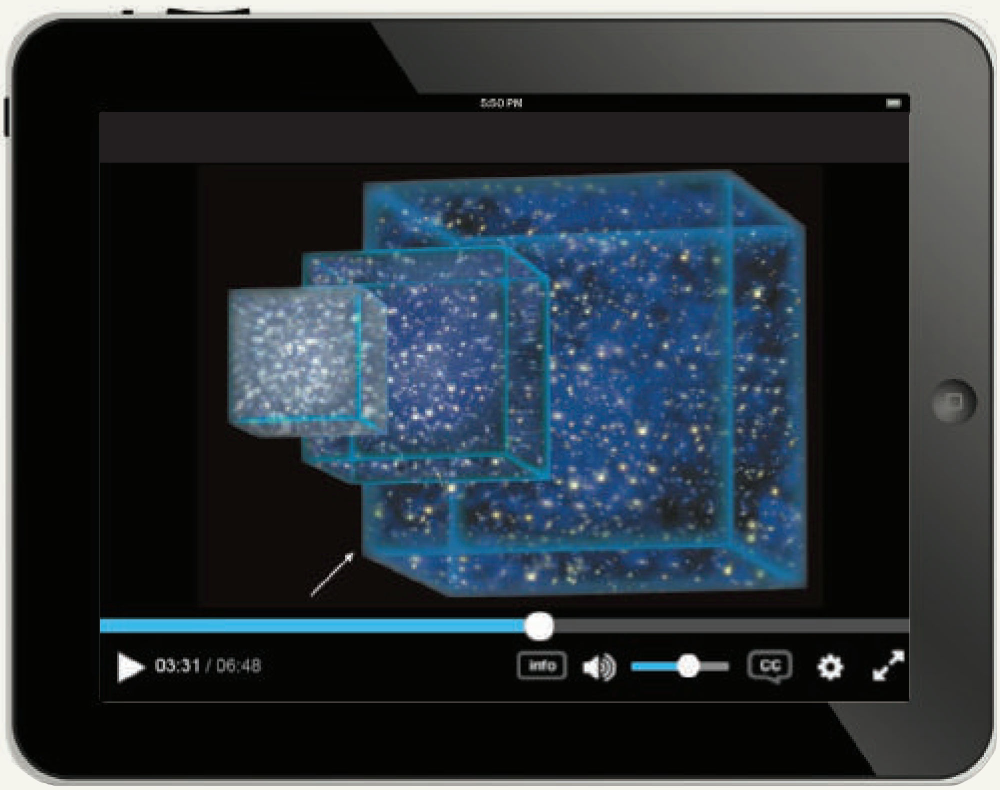
P. 82

See the newly reorganized end-of-chapter exercise sets for additional problem types designed to help your students review key concepts, check their understanding, and learn to think critically. All exercises are also assignable through Mastering Astronomy.

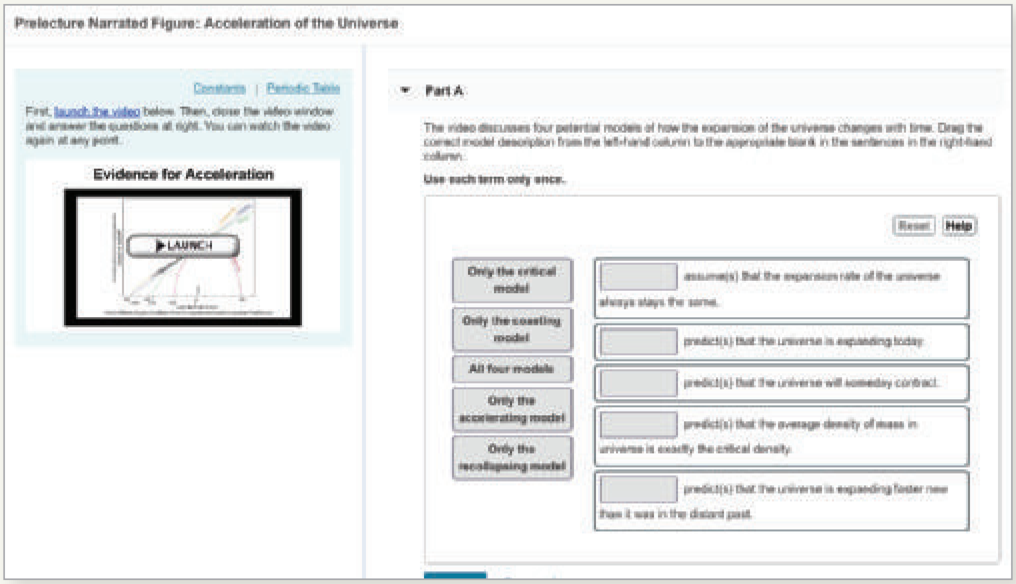
Mastering Astronomy's Study Area Helps Students Come Prepared to Class . . .

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

NEW! Nearly 100 new videos about key concepts and figures in the text, all written and most narrated by the authors to ensure consistency of terminology and pedagogy. Most videos include embedded pause-and-predict questions that allow students to check their understanding as they watch. Students can use these videos to help prepare for lectures, while instructors will find the same videos with assignable tutorials in the instructor-accessible Item Library.

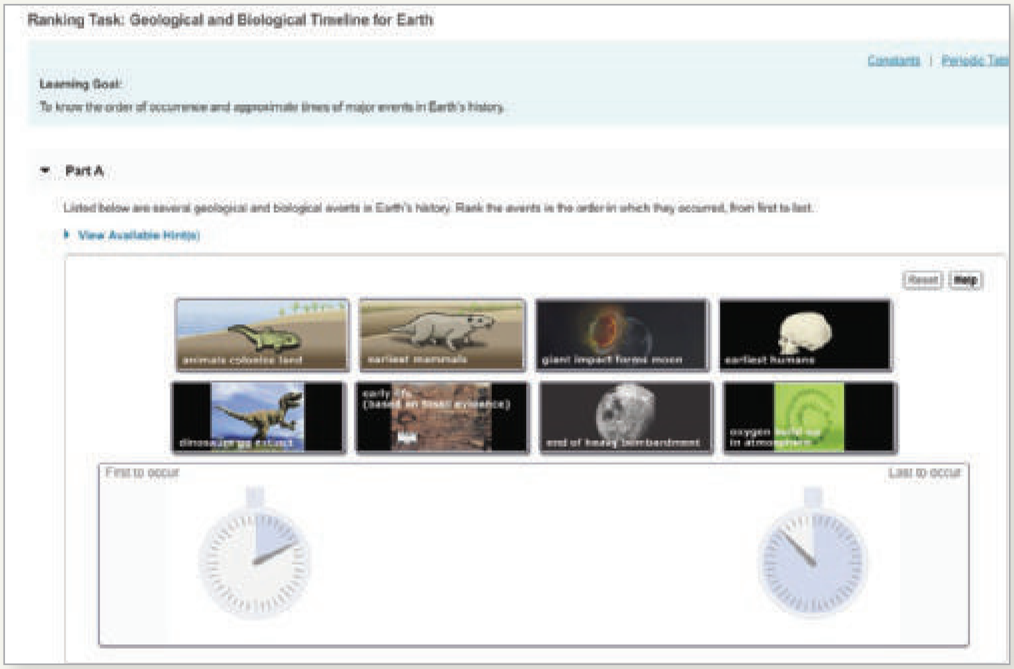


. . . While Instructors Can Access a Large Library of Homework and Test Questions



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

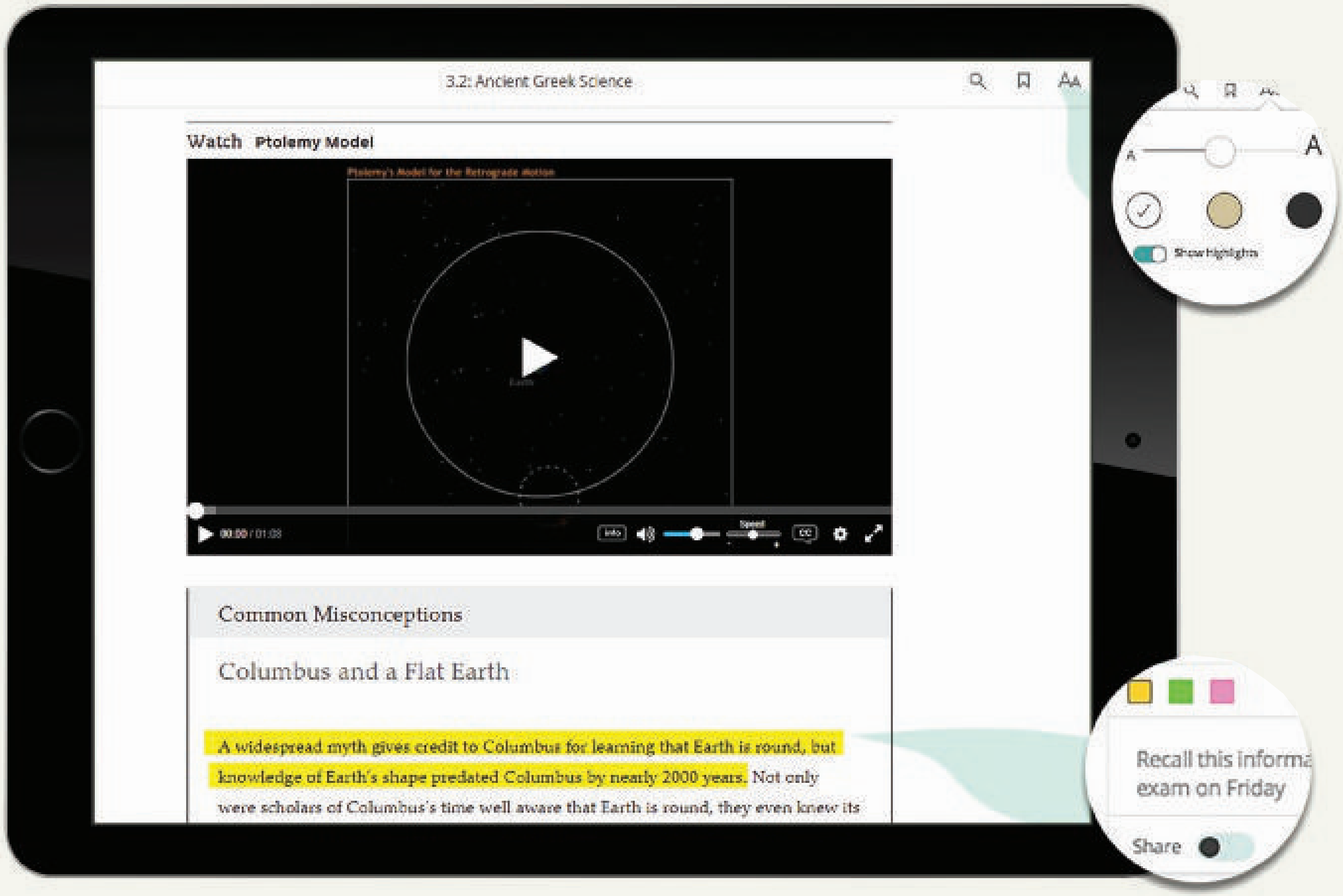
Many of the **assignable tutorials** use ranking or sorting tasks, which research shows to be particularly effective in building conceptual understanding.



The Item Library also includes all end-of-chapter exercises from the book, individual questions from the three self-study quizzes (Reading, Concept, and Visual) for each chapter, and a large test bank.

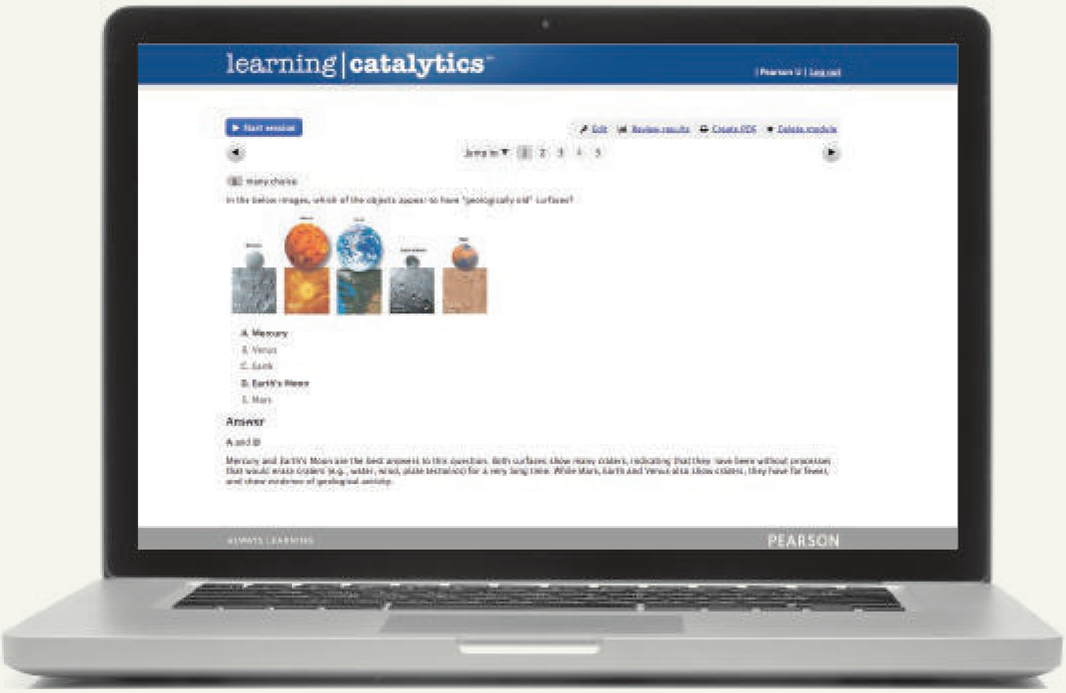
Reach Every Student with Pearson eText

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



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

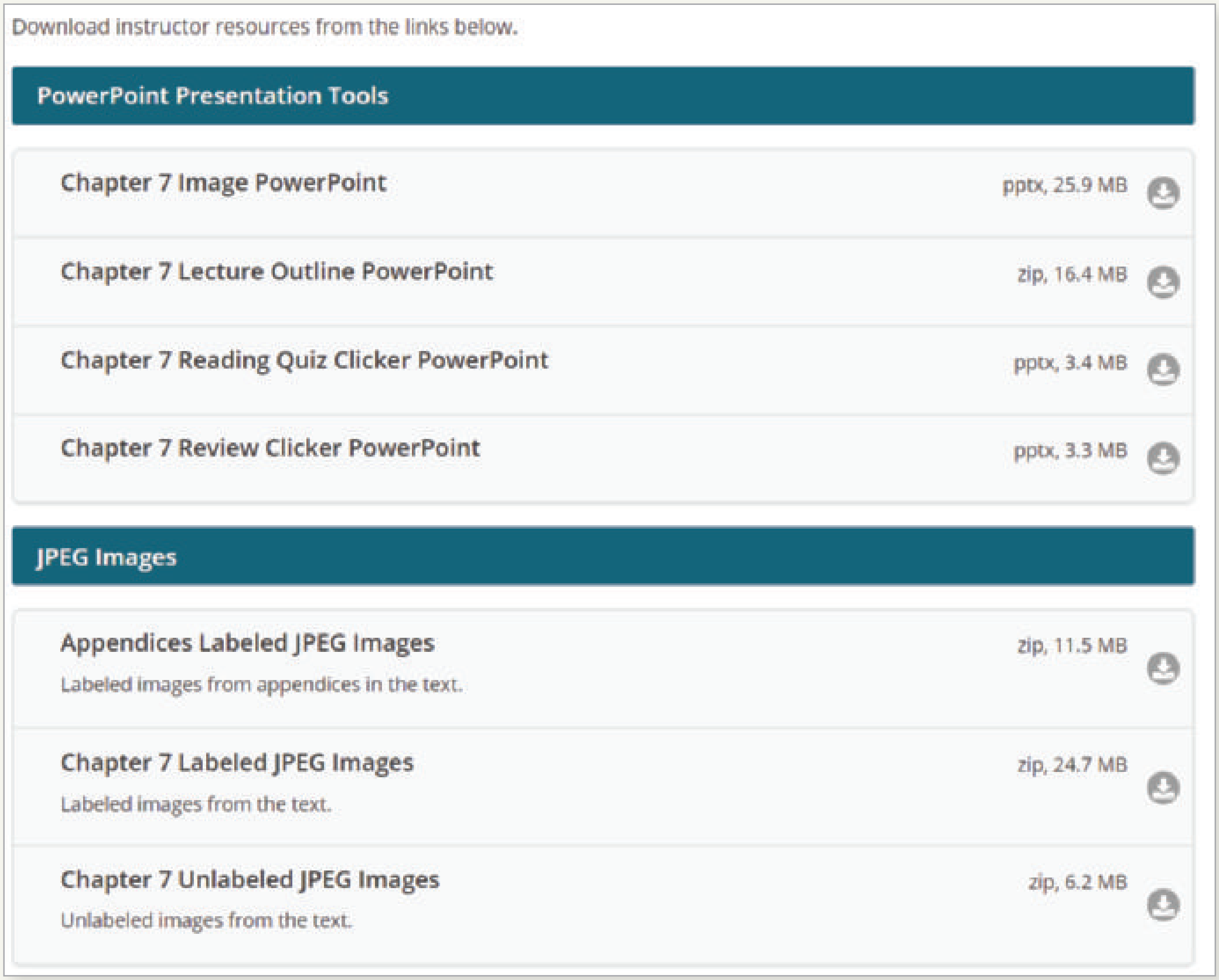
NEW! Dynamic Study Modules in Mastering Astronomy help students study effectively—and at their own pace—by keeping them motivated and engaged. The assignable modules rely on the latest research in cognitive science, using methods—such as adaptivity, gamification, and intermittent rewards—to stimulate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



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

Instructor Support You Can Rely on

The Cosmic Perspective includes a full suite of instructor support materials in the Instructor Resources area in Mastering Astronomy. Resources include lecture presentations, images, reading quizzes, and clicker questions in PowerPoint; labeled and unlabeled JPEGs of all images from the text; an instructor's guide for each chapter; and a test bank.



Detailed Contents

PART II
KEY CONCEPTS FOR ASTRONOMY

PART III
LEARNING FROM OTHER WORLDS

PART V STARS

PART VI GALAXIES AND BEYOND

Preface

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

Who Is This Book For?

The Cosmic Perspective provides a comprehensive survey of modern astronomy suitable for anyone who is curious about the universe, regardless of prior background in astronomy or physics. However, it is designed primarily to serve as a textbook for college courses in introductory astronomy. *The Cosmic Perspective* contains enough material for a full-year introductory astronomy sequence but can be flexibly used for shorter courses as well.

Instructors of shorter courses may also wish to consider several available variations of this textbook. We offer two volumes containing selected chapters from this book: *The Solar System*, which consists of Chapters 1–14 (including S1) and 24, and *Stars, Galaxies, and Cosmology*, which consists of Chapters 1–6 (including S1), S2–S4, and 14–24. Those teaching one-term general survey courses may wish to consider *The Essential Cosmic Perspective*, which covers a smaller set of topics and is tailored to meet the needs of comprehensive one-term survey courses in astronomy, and *The Cosmic Perspective Fundamentals*, which is even shorter and covers only the most fundamental topics in astronomy. All of these options are also available with Mastering™ Astronomy.

New to This Edition

The underlying philosophy, goals, and structure of *The 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 the ninth edition:

- **Major Chapter-Level Changes:** We have made numerous significant changes to both update the science and improve the pedagogical flow in this edition. The full list is too long to put here, but major changes include the following:
    - In **Chapter 2**, we have reworked the section on eclipses with a new set of art pieces and revised pedagogy to reflect the fact that many students heard about or witnessed the 2017 eclipse.
    - **Chapter 5** has a new Common Misconception box on "Light Paths, Lasers, and Shadows."
    - In **Chapter 6**, we have made three significant updates: a focus on major new and planned observatories, including the James Webb Space Telescope; a new subsection on the role of "big data" in astronomy, using LSST as an example; and an expanded discussion of multi-messenger astronomy, such as the gravitational-wave observatory LIGO.
    - **Chapter 9** has numerous scientific updates based on recent planetary missions, especially in Section 9.4 on Mars, where we discuss how recent evidence from the *Curiosity* rover is providing a new view of past periods of liquid water on Mars. We also discuss recent reanalysis of the cause of dark streaks and gullies on crater walls.
    - **Chapter 10** has similar updates for new data, including the addition of a new Learning Goal in Section 10.4 on Mars, to reflect a deeper discussion of the history of the Martian climate. Section 10.6 on global warming has also been significantly updated, with greater emphasis on expected consequences of the warming.
    - In **Chapter 11**, we have revamped the discussion of Jupiter's weather to include new results from the *Juno* mission. We have also made important scientific updates to the information on Saturn's moons and rings based on results from the final stages of the *Cassini* mission.
    - **Chapter 12** includes updated data and images from the *Dawn*, *Rosetta*, and *New Horizons* missions, along with discussion of the possibility of an undiscovered "Planet 9" and a new Special Topic box on 'Oumuamua, the first confirmed object with origin beyond our solar system to pass through our solar system.
    - **Chapter 13** covers the fast-evolving topic of extrasolar planets and hence has numerous scientific updates and new figures.
    - In **Chapter S3**, we have rewritten the section on gravitational waves to include their recent direct detection.
    - **Chapter 14** includes new discussion and a new figure about the Sun's influence on Earth's climate, and how we can rule out a changing Sun as a cause of recent global warming.
    - In **Chapter 18**, we have almost completely rewritten Section 18.4—changing from the two learning goals in the prior edition to three learning goals—to include the detection of gravitational waves from neutron star and black hole mergers.

- **Chapters 20 and 21** have been updated in light of new research on galactic evolution, some of which is based on the work of two of the authors of this book (Donahue and Voit). Chapter 20 also incorporates updates in describing the cosmic distance scale, including honoring Henrietta Levitt by referring to her period-luminosity relation as *Leavitt's law*.
- In **Chapter 24**, the first section has significant changes to incorporate newly discovered evidence for early life on Earth. The second section has been reworked to update the discussion of searching for life on Mars, and its second learning goal has been reworked to cover more than just the moons of Jupiter and Saturn.

- **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 described above, we have made many other scientific updates to reflect the latest results from both ground-based and space-based observatories and from spacecraft missions within the solar system.
- **Revamped Exercise Sets:** We have reorganized the end-of-chapter exercise sets in order to place greater emphasis on questions designed to promote discussion and group work.
- **New Feature—Inclusive Astronomy:** The astronomical community is engaged in broad and wide-ranging conversations about inclusion and the persistent lack of diversity in the fields of astronomy and other sciences. To provide sample openings for discussions of inclusion in the classroom, we have (1) added a new set of exercises in every chapter under the heading "Inclusive Astronomy," written to initiate student discussions about topics centered on inclusiveness in astronomy; (2) added a similar set of additional exercises that you can find in the set of Group Activities available in the Study Area of Mastering Astronomy; and (3) replaced many of the chapter-opening epigraphs in order to include a more diverse group of individuals.
- **New Content in Mastering Astronomy:** *The Cosmic Perspective* is much more than a textbook; it is a complete "learning package" that combines the textbook with deeply integrated, interactive media developed to support every chapter of our book. We continually update the material on the Mastering Astronomy website, and for this edition we call your attention to nearly 100 new "prelecture videos," all written by (and most narrated by) the authors, designed to help students understand key concepts. Students can watch the videos at any time in the Study Area, while instructors can find assignable tutorials based on the videos in the instructor-accessible Item Library. In addition to the new videos and their corresponding tutorials, you will find many other new tutorials in the Item Library, as well as a fully updated set of reading, concept, and visual quizzes for each chapter, available in both the Study Area and the assignable Item Library. These resources should be especially valuable to instructors who wish to offer assignments designed to ensure that students are prepared before class and to those using "flipped classroom" strategies.

The Pedagogical Approach of *The Cosmic Perspective*

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

Themes

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

Theme 1: We are a part of the universe and can therefore learn about our origins by studying the universe. This is the overarching theme of *The Cosmic Perspective*, as we continually emphasize that learning about the universe helps us understand ourselves. Studying the intimate connections between human life and the cosmos gives students a reason to care about astronomy and also deepens their appreciation of the unique and fragile nature of our planet and its life.

Theme 2: The universe is comprehensible through scientific principles that anyone can understand. The universe is comprehensible because the same physical laws appear to be at work in every aspect, on every scale, and in every age of the universe. Moreover, while professional scientists generally have discovered the laws, anyone can understand their fundamental features. Students can learn enough in one or two terms of astronomy to comprehend the basic reasons for many phenomena that they see around them—phenomena ranging from seasonal changes and phases of the Moon to the most esoteric astronomical images that appear in the news.

Theme 3: Science is not a body of facts but rather a process through which we seek to understand the world around us. Many students assume that science is just a laundry list of facts. The long history of astronomy can show them that science is a process through which we learn about our universe—a process that is not always a straight line to the truth. That is why our ideas about the cosmos sometimes change as we learn more, as they did dramatically when we first recognized that Earth is a planet going around the Sun rather than the center of the universe. In this book, we continually emphasize the nature of science so that students can understand how and why modern theories have gained acceptance and why these theories may change in the future.

Theme 4: Astronomy belongs to everyone. Astronomy has played a significant role throughout history in virtually every culture, and the modern science of astronomy owes a debt to these early and largely unsung astronomers. We therefore strive throughout the book to make sure that students understand that astronomical knowledge belongs to everyone, that people of all backgrounds have made and continue to make contributions to astronomical understanding, and that everyone should have the opportunity to study astronomy. Moreover, we seek to motivate students enough to ensure that they will remain engaged in the ongoing human adventure of astronomical discovery throughout their lives, no matter whether they choose to do that only by following the news media or by entering careers relating to astronomy.

Theme 5: Astronomy affects each of us personally with the new perspectives it offers. We all conduct the daily business of our lives with reference to some "world view"—a set of personal beliefs about our place and purpose in the universe, which we have developed through a combination of schooling, religious training, and personal thought. This world view shapes our beliefs and many of our actions. Although astronomy does not mandate a particular set of beliefs, it does provide perspectives on the architecture of the universe that can influence how we view ourselves and our world, and these perspectives can potentially affect our behavior. For example, someone who believes Earth to be at the center of the universe might treat our planet quite differently from someone who views it as a tiny and fragile world in the vast cosmos. In many respects, the role of astronomy in shaping world views may represent the deepest connection between the universe and the everyday lives of humans.

Pedagogical Principles

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

- *Stay focused on the big picture.* Astronomy is filled with interesting facts and details, but they are meaningless unless they fit into a big-picture view of the universe. We therefore take care to stay focused on the big picture (essentially the themes discussed above) at all times. A major benefit of this approach is that although students may forget individual facts and details after the course is over, the big-picture framework should stay with them for life.
- *Always provide context first.* We all learn new material more easily when we understand why we are learning it. In essence, this is simply the idea that it is easier to get somewhere when you know where you are going. We therefore begin the book (Chapter 1) with a broad overview of modern understanding of the cosmos, so that students know what they will be studying in the rest of the book. We maintain this "context first" approach throughout the book by always telling students what they will be learning, and why, before diving into the details.
- *Make the material relevant.* It's human nature to be more interested in subjects that seem relevant to our lives. Fortunately, astronomy is filled with ideas that touch each of us personally. For example, the study of our solar system helps us better understand and appreciate our planet Earth, and the study of stars and galaxies helps us learn how we have come to exist. By emphasizing our personal connections to the cosmos, we make the material more meaningful, inspiring students to put in the effort necessary to learn it.
- *Emphasize conceptual understanding over "stamp collecting" of facts.* If we are not careful, astronomy can appear to be an overwhelming collection of facts that are easily forgotten when the course ends. We therefore emphasize a few key conceptual ideas, which we use over and over again. For example, the laws of conservation of energy and conservation of angular momentum (introduced in Section 4.3) reappear throughout the book, and the wide variety of features found on the terrestrial planets are described in terms of just a few basic geological processes. Research shows that, long after the course is over, students are far more likely to retain such conceptual learning than individual facts or details.
- *Proceed from the more familiar and concrete to the less familiar and abstract.* It's well known that children learn best by starting with concrete ideas and then generalizing to abstractions later. The same is true for many adults. We therefore always try to "build bridges to the familiar"— that is, to begin with concrete or familiar ideas and then gradually draw more general principles from them.
- *Use plain language.* Surveys have found that the number of new terms in many introductory astronomy books is larger than the number of words taught in many first-year courses on a foreign language. In essence, this means the books are teaching astronomy in what looks to students like a foreign language! Clearly, it is much easier for students to understand key astronomical concepts if they are explained in plain English without resorting to unnecessary jargon. We have gone to great lengths to eliminate jargon or, at minimum, to replace 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 also holding misconceptions about astronomical ideas. Therefore, to teach correct ideas, we must help students recognize the paradoxes in their prior misconceptions. We address this issue in a number of ways, the most obvious being the presence of many Common Misconceptions boxes. These

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

summarize commonly held misconceptions and explain why they cannot be correct.

The Organizational Structure of *The Cosmic Perspective*

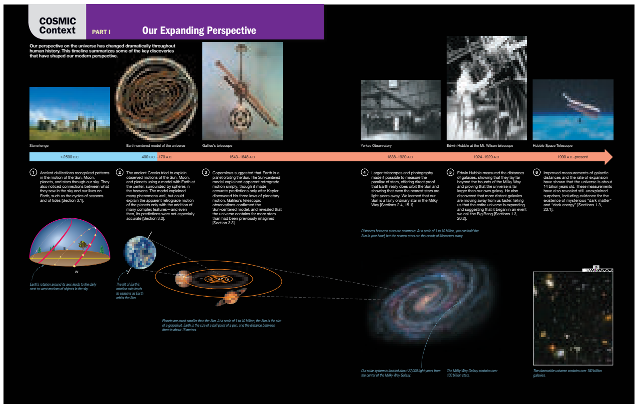
The Cosmic Perspective is organized into seven broad topical areas (the seven parts in the table of contents), each corresponding to a set of chapters along with related content in Mastering Astronomy. Note that the above themes and pedagogical principles are woven into this structure at every level.

Part Structure

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

Part I: Developing Perspective (Chapters 1–3, S1)

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

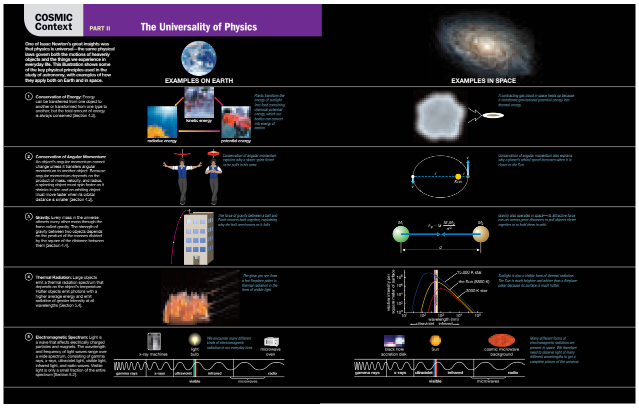


The Cosmic Context figure for Part I appears on pp. 108–109.

The basic goal of these chapters is to give students a big-picture overview and context for the rest of the book, as well as to help them develop an appreciation for the process of science and how science has developed through history. Chapter 1 outlines our modern understanding of the cosmos, including the scale of space and time, 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 supplementary (optional) Chapter S1 goes into more detail about the sky, including celestial timekeeping and navigation.

Part II: Key Concepts for Astronomy (Chapters 4–6)

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



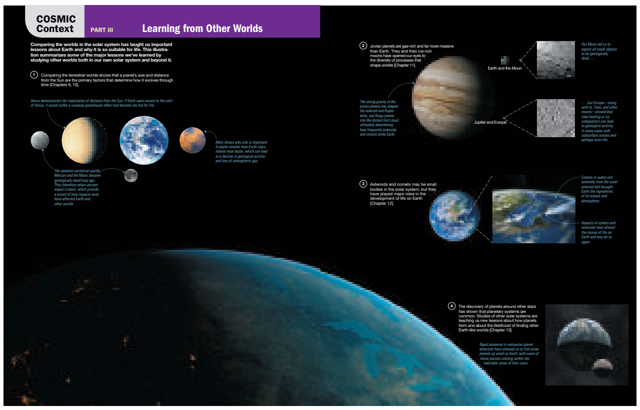
The Cosmic Context figure for Part II appears on pp. 188–189.

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. Each chapter begins with a section on science in everyday life in which we remind students how much they already know about scientific phenomena from their everyday experiences. We then build on this everyday knowledge to help students learn the formal principles of physics needed for the rest of their study of astronomy. Chapter 4 covers the laws of motion, the crucial conservation laws of angular momentum and energy, and the universal law of gravitation. Chapter 5 deals with the nature of light and matter, the formation of spectra, and the Doppler effect. Chapter 6 covers telescopes and astronomical observing techniques.

Part III: Learning from Other Worlds (Chapters 7–13)

Guiding Philosophy: We learn about our own world and existence by studying about other planets in our solar system and beyond.

Note: Part III is essentially independent of Parts IV through VII and can be covered either before or after them.



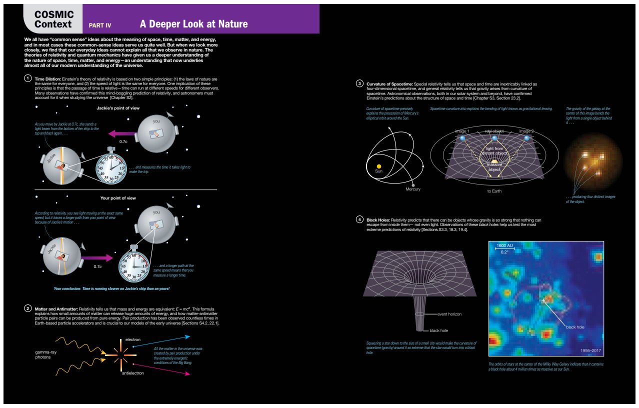
The Cosmic Context figure for Part III appears on pp. 400–401.

This set of chapters begins in Chapter 7 with a broad overview of the solar system, including an 11-page tour that highlights some of the most important and interesting features of the Sun and each of the planets in our solar system. In the remaining chapters of this part, we seek to explain these features through a true *comparative planetology* approach, in which the discussion emphasizes the *processes* that shape the planets rather than the "stamp collecting" of facts about them. Chapter 8 uses the concrete features of the solar system presented in Chapter 7 to build student understanding of the current theory of solar system formation. Chapters 9 and 10 focus on the terrestrial planets, covering key ideas of geology and atmospheres, respectively. In both chapters, we start with examples from our own planet Earth to help students understand the types of features that are found throughout the terrestrial worlds and the fundamental processes that explain how these features came to be. We then complete each of these chapters by summarizing how the various processes have played out on each individual world. Chapter 11 covers the jovian planets and their moons and rings. Chapter 12 discusses small bodies in the solar system, including asteroids, comets, and dwarf planets. It also covers cosmic collisions, including the impact linked to the extinction of the dinosaurs and views on how seriously we should take the ongoing impact threat. Finally, Chapter 13 turns to the exciting topic of other planetary systems.

Part IV: A Deeper Look at Nature (Chapters S2–S4)

Guiding Philosophy: Ideas of relativity and quantum mechanics are accessible to anyone.

Note: These chapters are labeled "supplementary" because coverage of them is optional. Covering them will give your students a deeper understanding of the topics that follow on stars, galaxies, and cosmology, but the later chapters are self-contained so that they may be studied without having read Part IV at all.

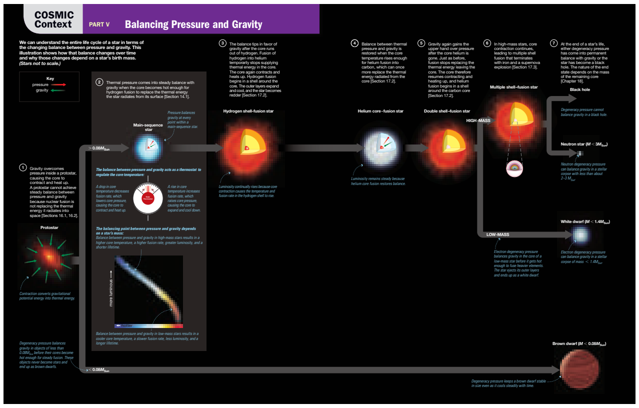


The Cosmic Context figure for Part IV appears on pp. 466–467.

Nearly all students have at least heard of things like the prohibition on faster-than-light travel, curvature of spacetime, and the uncertainty principle. But few (if any) students enter an introductory astronomy course with any idea of what these things mean, and they are naturally curious about them. Moreover, a basic understanding of the ideas of relativity and quantum mechanics makes it possible to gain a much deeper appreciation of many of the most important and interesting topics in modern astronomy, including black holes, gravitational lensing, and the overall geometry of the universe. The three chapters of Part IV cover special relativity (Chapter S2), general relativity (Chapter S3), and key astronomical ideas of quantum mechanics (Chapter S4). The main thrust throughout is to demystify relativity and quantum mechanics by convincing students that they are capable of understanding the key ideas despite the reputation of these subjects for being hard or counterintuitive.

Part V: Stars (Chapters 14–18)

Guiding Philosophy: We are intimately connected to the stars.

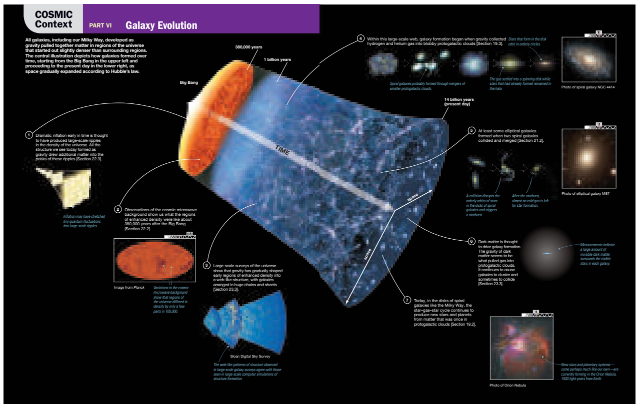


The Cosmic Context figure for Part V appears on pp. 578–579.

These are our chapters on stars and stellar life cycles. Chapter 14 covers the Sun in depth so that it can serve as a concrete model for building an understanding of other stars. Chapter 15 describes the general properties of other stars, how we measure these properties, and how we classify stars with the H-R diagram. Chapter 16 covers star birth, and the rest of stellar evolution is discussed in Chapter 17. Chapter 18 focuses on the end points of stellar evolution: white dwarfs, neutron stars, and black holes.

Part VI: Galaxies and Beyond (Chapters 19–23)

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

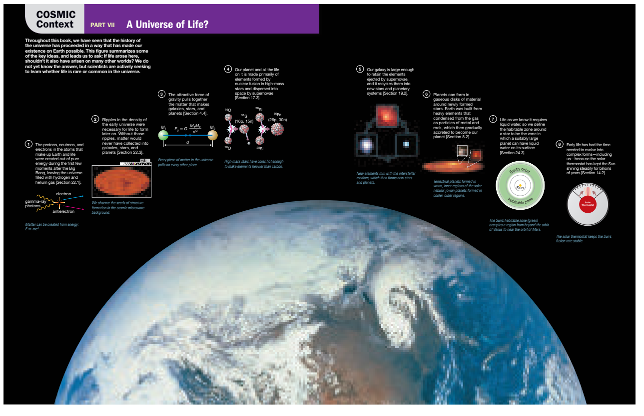


The Cosmic Context figure for Part VI appears on pp. 696–697.

These chapters cover galaxies and cosmology. Chapter 19 presents the Milky Way as a paradigm for galaxies in much the same way that Chapter 14 uses the Sun as a paradigm for stars. Chapter 20 describes the properties of galaxies and shows how the quest to measure galactic distances led to Hubble's law and laid the foundation for modern cosmology. Chapter 21 discusses how the current state of knowledge regarding galaxy evolution has emerged from our ability to look back through time. Chapter 22 then presents the Big Bang theory and the evidence supporting it, setting the stage for Chapter 23, which explores dark matter and its role in galaxy formation, as well as dark energy and its implications for the fate of the universe.

Part VII: Life on Earth and Beyond (Chapter 24)

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



The Cosmic Context figure for Part VII appears on pp. 728–729.

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 wish to consider the text *Life in the Universe*, by Bennett and Shostak.

Chapter Structure

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

- **Chapter Learning Goals:** Each chapter opens with a page offering an enticing image and a brief overview of the chapter, including a list of the section titles and associated learning goals. The learning goals are presented as key questions designed to help students both to understand what they will be learning about and to stay focused on these key goals as they work through the chapter.
- **Introduction and Epigraph:** The main chapter text begins with a one- to three-paragraph introduction to the chapter material and an inspirational quotation relevant to the chapter.
- **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 have learned in the chapter into the context of the overall goal of gaining a broader perspective on ourselves, our planet, and prospects for life beyond Earth. The final entry in this section is always entitled "My Cosmic Perspective"; it aims to help students see a personal connection between themselves and the chapter content, with the goal of encouraging them to think more critically about the meaning of all that they learn in their astronomy course.
- **Chapter Summary:** The end-of-chapter summary offers a concise review of the learning goal questions, helping 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:** This set of questions is designed to help students build their skills at interpreting the many types of visual information used in astronomy.
    - **Chapter Review Questions:** These questions are ones that students should be able to answer from the reading alone.
    - **Does It Make Sense?** (or similar title): Each of these short statements is to be critically evaluated by students, to explain why it does or does not make sense. These exercises are generally easy once students understand a particular concept, but difficult otherwise; this makes these questions an excellent probe of comprehension.
    - **Quick Quiz:** The short multiple-choice quiz allows students to check their basic understanding. Note that, for further self-testing, every chapter also has a Reading, Concept, and Visual quiz available on the Mastering Astronomy website.
    - **Inclusive Astronomy:** These questions are designed to stimulate discussion about participation in science, and in particular about the ideas that (1) astronomy belongs to everyone; (2) all cultures have made contributions to astronomical understanding; (3) opportunities for women and minorities have historically been limited; and (4) the scientific community can take active steps to provide more equitable opportunities for the future.
    - **Process of Science Questions:** These questions, which can be used for discussion or essays, are intended to help students think about how science progresses over time. This set always concludes with an activity designed for group work, in order to promote collaborative learning in class.
    - **Investigate Further:** The remaining questions are designed for home assignment and are intended

to go beyond the earlier review questions. These questions are separated into two groups: Short-Answer/Essay questions, which focus on conceptual interpretation and sometimes on outside research or experiment, and Quantitative Problems, which require some mathematics and are usually based on topics covered in the Mathematical Insight boxes.

Additional Pedagogical Features

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

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

Mastering Astronomy

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

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

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

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

Supplements for *The Cosmic Perspective*

The 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 Mastering Astronomy (described above), the following supplements are available with this book:

Name of Supplement	Instructor or Student Supplement	Description
SkyGazer 5.0 (Access code card ISBN 0-321-76518-5, CD ISBN 0-321-89843-2)	Student Supplement	Based on Voyager IV, one of the world's most popular planetarium programs, SkyGazer 5.0 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. Both SkyGazer and LoPresto's workbook are available for download.
Starry Night™ College (ISBN 0-321-71295-1)	Student Supplement	Now available as an additional option with *The Cosmic Perspective*, Starry Night™ College 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 Mastering Astronomy Study Area or with a Starry Night College access code.
Astronomy Active Learning In-Class Tutorials (ISBN 0-805-38296-8) by Marvin L. De Jong	Student Supplement	This workbook provides fifty 20-minute in-class tutorial activities to choose from. Designed for use in large lecture classes, these activities are also suitable for labs. The short, structured activities are designed for students to complete on their own or in peer-learning groups. Each activity targets specific learning objectives such as understanding Newton's laws, understanding Mars's retrograde motion, tracking stars on the H-R diagram, or comparing the properties of planets.
Lecture Tutorials for Introductory Astronomy (ISBN 0-321-82046-0) by Ed Prather, Tim Slater, Jeff Adams, and Gina Brissenden	Student Supplement	These forty-four lecture tutorials are designed to engage students in critical reasoning and spark classroom discussion.
Sky and Telescope (ISBN 0-321-70620-X)	Student Supplement	This supplement, which includes nine articles with an assessment insert covering general review, Process of Science, Scale of the Universe, and Our Place in the Universe, is available for bundling.
Observation Exercises in Astronomy (ISBN 0-321-63812-3) by Lauren Jones	Student Supplement	This workbook includes fifteen observation activities that can be used with a number of different planetarium software packages.
Astronomy Lab: A Concept Oriented Approach (ISBN 0-321-86177-9) by Nate McCrady and Emily Rice	Student Supplement	This modular collection of forty conceptually oriented introductory astronomy labs, housed in the Pearson Custom Library, allows for easy creation of a customized lab manual.
Instructor Resources (ISBN 0-135-17325-1)	Instructor Supplement	This comprehensive collection of instructor resources includes high-resolution JPEGs of all images from the book; Interactive Figures and Photos™ based on figures in the text; additional applets and animations to illustrate key concepts; PowerPoint® Lecture Outlines that incorporate figures, photos, checkpoint questions, and multimedia; and PRS-enabled clicker quizzes based on the book and book-specific interactive media, to make preparing for lectures quick and easy. These resources are located in the Mastering Astronomy Instructor Resource Area.
Instructor Guide (ISBN 0-135-17324-4)	Instructor Supplement	The Instructor Guide contains a detailed overview of the text, sample syllabi for courses of different emphasis and duration, suggested teaching strategies, answers or discussion points for all Think About It and See It for Yourself questions in the text, solutions to all end-of-chapter problems, and a detailed reference guide summarizing media resources available for every chapter and section of the book.
Test Bank (ISBN 0-135-17326-4)	Instructor Supplement	Available in both Word and TestGen formats in the Instructor Resource Center and Mastering Astronomy, the Test Bank contains a broad set of multiple-choice, true/false, and free-response questions for each chapter. The Test Bank is also assignable through Mastering Astronomy.

Acknowledgments

Our textbook carries only four author names, but in fact it is the result of hard work by a long list of committed individuals. We could not possibly list everyone who has helped, but we would like to call attention to a few people who have played particularly important roles. First, we thank our past and present editors at Addison-Wesley and Pearson, including Bill Poole, Robin Heyden, Sami Iwata, Ben Roberts, Adam Black, Nancy Whilton, and Jeanne Zalesky, along with many others at Pearson who have contributed to making our books possible. Special thanks to our production teams, especially Sally Lifland, and our art and design team.

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

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

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

Jeff Bennett, *Megan Donahue*,
Nick Schneider, *Mark Voit*

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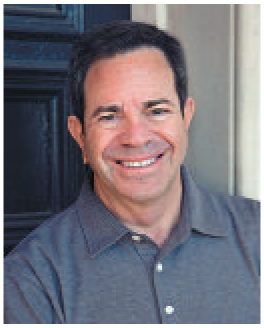


Jeffrey Bennett

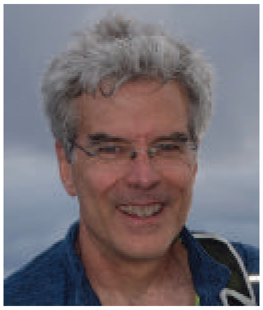
Jeffrey Bennett, a recipient of the American Institute of Physics Science Communication Award, holds a B.A. in biophysics (UC San Diego) and an M.S. and Ph.D. in astrophysics (University of Colorado). He specializes in science and math education and has taught at every level from preschool through graduate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

Megan Donahue

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

Nicholas Schneider

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



Mark Voit

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

How to Succeed in Your Astronomy Course

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

The Key to Success: Study Time

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

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

Using This Book

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

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

General Strategies for Studying

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

class lectures and discussions are designed to reinforce key ideas from the reading.

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

Preparing for Exams

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

Presenting Homework and Writing Assignments

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

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

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

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

Foreword
The Meaning of *The Cosmic Perspective*

by Neil deGrasse Tyson

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

1

A Modern View of the Universe

▲ **About the photo:** 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?

1.4 The Human Adventure of Astronomy
- How has the study of astronomy affected human history?

It suddenly struck me that that tiny pea, pretty and blue, was the Earth. I put up my thumb and shut one eye, and my thumb blotted out the planet Earth. I didn't feel like a giant. I felt very, very small.

—Neil Armstrong on looking back at the Earth from the Moon, July 1969

Chapter 1 Overview

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, 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 encompasses an almost unimaginable expanse of both space and time. Nearly every object within it is a *galaxy* filled with 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 are just one of several key levels of structure in our universe, all illustrated as our "cosmic address" in **FIGURE 1.1**.

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

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

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

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

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 an approximate size for each structure in kilometers (recall that 1 kilometer $\approx$ 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 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 one second. Similarly, one

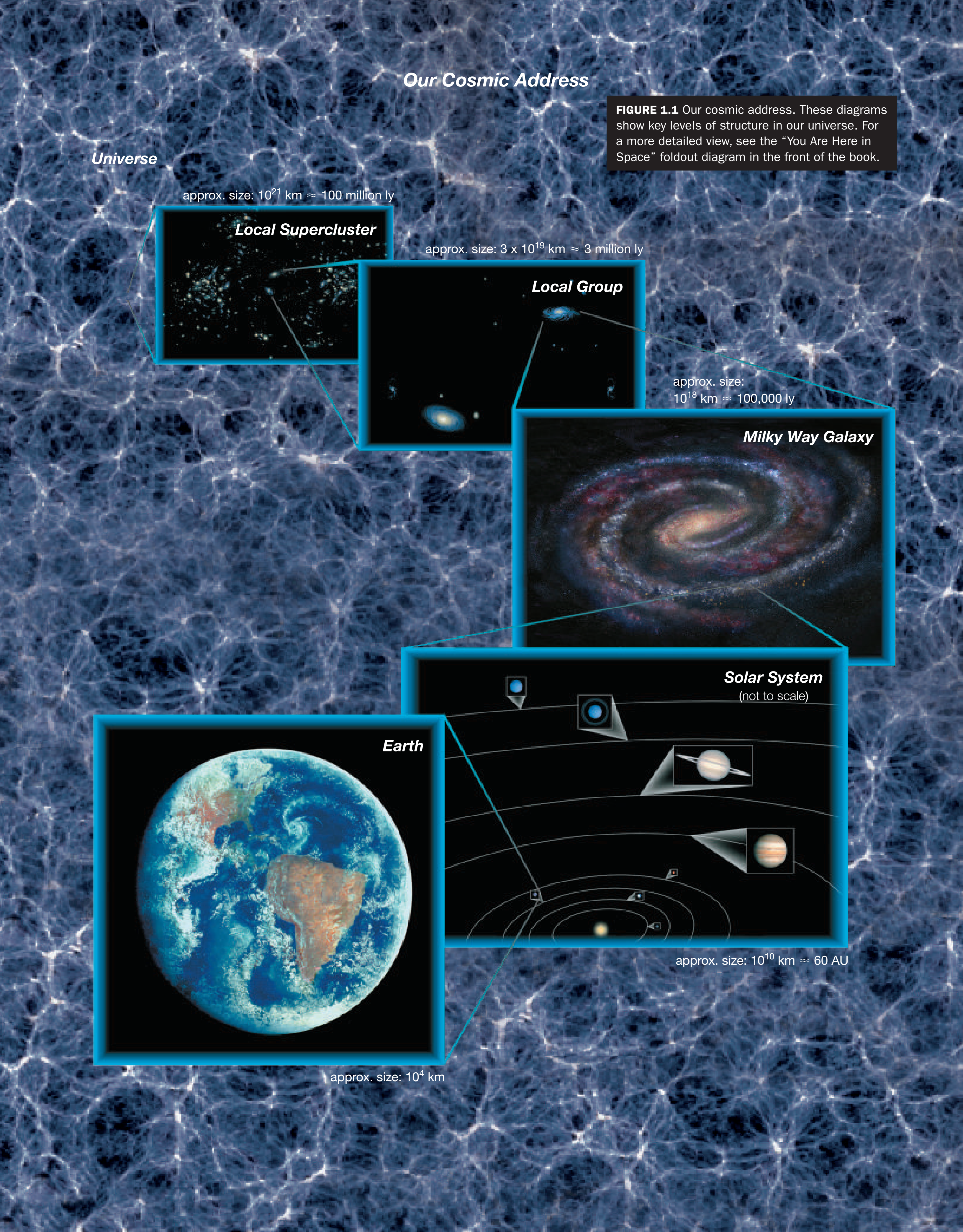


FIGURE 1.1 Our cosmic address. These diagrams show key levels of structure in our universe. For a more detailed view, see the "You Are Here in Space" foldout diagram in the front of the book.

light-minute is the distance that light travels in one minute, one light-hour is the distance that light travels in one hour, and so on. Mathematical Insight 1.1 (page 6) shows that light travels about 10 trillion kilometers in one 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.

Consider Sirius, the brightest star in the night sky, which is located about 8 light-years away. Because it takes light 8 years to travel this distance, we see Sirius not as it is today, but rather as it was 8 years ago. The effect is more dramatic at greater distances. The Orion Nebula (**FIGURE 1.2**) is a giant cloud in which stars and planets are forming. It is located about 1350 light-years from Earth, which means we see it as it looked about 1350 years ago. If any major events have occurred in the Orion Nebula since that time, we cannot yet know about them because the light from these events has not yet reached us.

The general idea that light takes time to travel through space leads to a remarkable fact:

> **The farther away we look in distance, the further back we look in time.**

The Andromeda Galaxy (**FIGURE 1.3**) is about 2.5 million light-years away, which means we see it as it looked about 2.5 million years ago. We see more distant galaxies as they were even further in the past. 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.

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?

It's also amazing to realize that any "snapshot" of a distant galaxy is a picture of both space and time. For

BASIC ASTRONOMICAL DEFINITIONS

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 millions, billions, or even trillions of stars.

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

supercluster A gigantic region of space 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 (or **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.

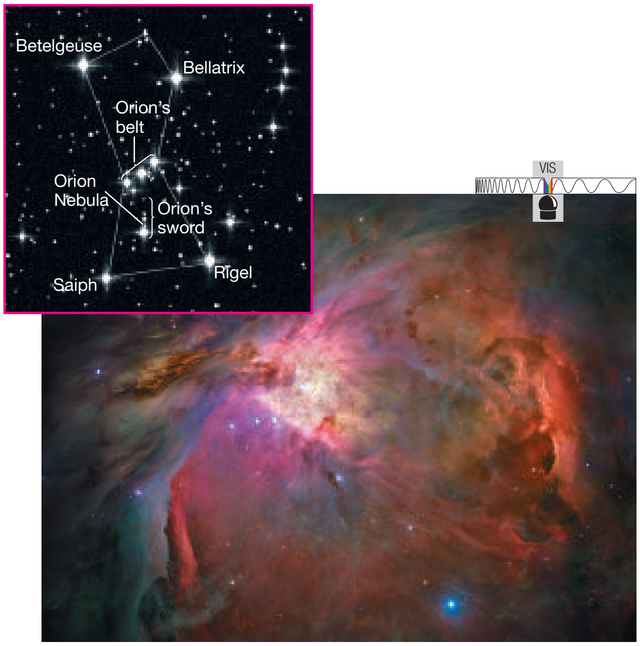


FIGURE 1.2 The Orion Nebula, located about 1350 light-years away. The inset shows its location in the constellation Orion.

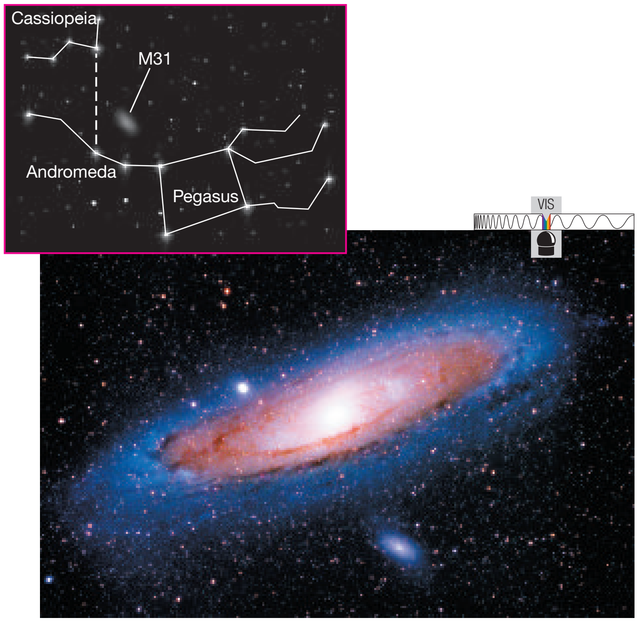


FIGURE 1.3 The Andromeda Galaxy (also known as M31). When we look at this galaxy, we see light that has been traveling through space for 2.5 million years. The inset shows the galaxy's location in the constellation Andromeda.

example, because the Andromeda Galaxy is about 100,000 light-years in diameter, the light we currently see from the far side of the galaxy must have left on its journey to us some 100,000 years before the light we see from the near side. Figure 1.3 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.

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

FIGURE 1.4 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. And if we tried to look beyond 14 billion light-years, we'd be looking to a time more than 14 billion years ago—which is before the universe existed and therefore means that there is nothing to see. This distance of 14 billion light-years therefore marks the boundary (or *horizon*) of our **observable universe**—the portion of the entire universe that we can potentially observe. Note that this fact does not put any limit on the size of the *entire* universe, which 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.

*As we'll discuss in Chapter 20, distances to faraway galaxies in an expanding universe can be described in more than one way; distances like those given here are based on the time it has taken a galaxy's light to reach us (called the *lookback time*).

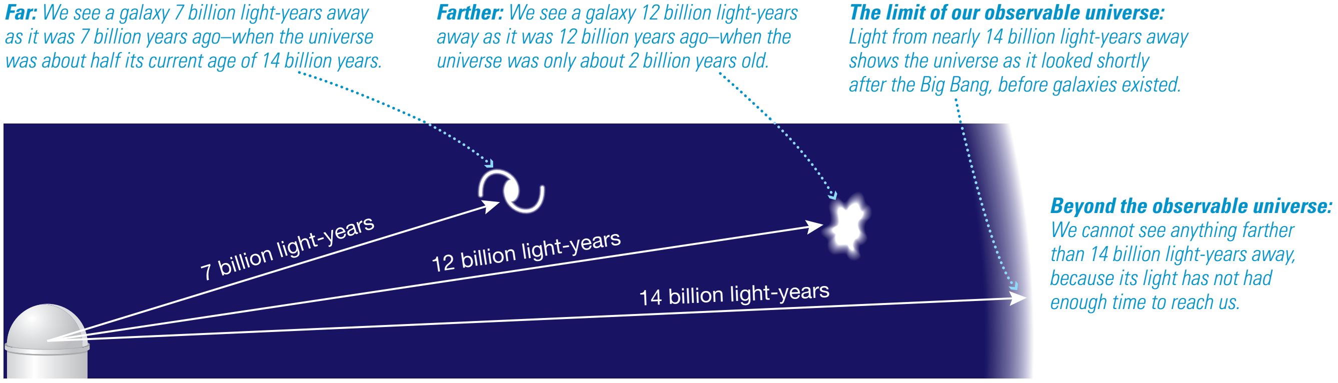


FIGURE 1.4 The farther away we look in space, the further back we look in time. The age of the universe therefore puts a limit on the size of the *observable* universe—the portion of the entire universe that we can observe, at least in principle.

COMMON MISCONCEPTIONS

The Meaning of a Light-Year

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

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 1.5**) makes such a walk possible by showing sizes and distances in the solar system at *one ten-billionth* of their actual values.

FIGURE 1.6a shows the Sun and planets at their actual sizes (but not distances) on the Voyage scale. The model Sun is about the size of a large grapefruit, Jupiter is about the size of a marble, and Earth is about the size of the ball point in a pen. You can immediately see some key facts about our solar system. For example, the Sun is far larger than any of the planets; in mass, the Sun outweighs all the planets combined by a factor of nearly 1000. The planets also vary considerably in size: The storm on Jupiter known as the Great Red Spot (visible near Jupiter's lower left in the painting) could swallow up the entire Earth.

The scale of the solar system is even more remarkable when you combine the sizes shown in Figure 1.6a with the distances illustrated by the map of the Voyage model in **FIGURE 1.6b**. For example, the ball-point-size Earth is located about 15 meters (49 feet) from the grapefruit-size Sun, which means you can picture Earth's orbit as a circle of radius 15 meters around a grapefruit.

Perhaps the most striking feature of our solar system when we view it to scale is its emptiness. The Voyage model shows the planets along a straight path, so we'd need to draw each planet's orbit around the model Sun to show the full extent of our planetary system. Fitting all these orbits would require an area measuring more than a

MATHEMATICAL INSIGHT 1.1

Problem Solving Part 1

How Far Is a Light-Year? An Introduction to Astronomical Problem Solving

We can develop greater insight into astronomical ideas by applying mathematics. The key to using mathematics is to approach problems in a clear and organized way. One simple approach uses the following three steps:

Step 1 Understand the problem: Ask yourself what the solution will look like (for example, what units will it have? will it be big or small?) and what information you need to solve the problem. Draw a diagram or think of a simpler analogous problem to help you decide how to solve it.

Step 2 Solve the problem: Carry out the necessary calculations.

Step 3 Explain your result: Be sure that your answer makes sense, and consider what you've learned by solving the problem.

You can remember this process as "Understand, Solve, and Explain," or U-S-E for short. You may not always need to write out the three steps explicitly, but they may help if you are stuck.

EXAMPLE: How far is a light-year?

SOLUTION: Let's use the three-step process.

Step 1 Understand the problem: The question asks how *far*, so we are looking for a *distance*. In this case, the definition of a light-year tells us that we are looking for the *distance that light can travel in 1 year*. We know that light travels at the speed of light, so we are looking for an equation that gives us distance from speed. If you don't remember this equation, just think of a simpler but analogous problem, such as "If you drive at 50 kilometers per hour, how far will you travel in 2 hours?" You'll realize that you simply multiply the speed by the time: distance = speed × time. In this case, the speed is the speed of light, or 300,000 km/s, and the time is 1 year.

Step 2 Solve the problem: From Step 1, our equation is that 1 light-year is the speed of light times 1 year. To make the units consistent, we convert 1 year to seconds by remembering that there are 60 seconds in 1 minute, 60 minutes in 1 hour, 24 hours in 1 day, and 365 days in 1 year. (See Appendix C.3 to review unit conversions.) We now carry out the calculations:

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

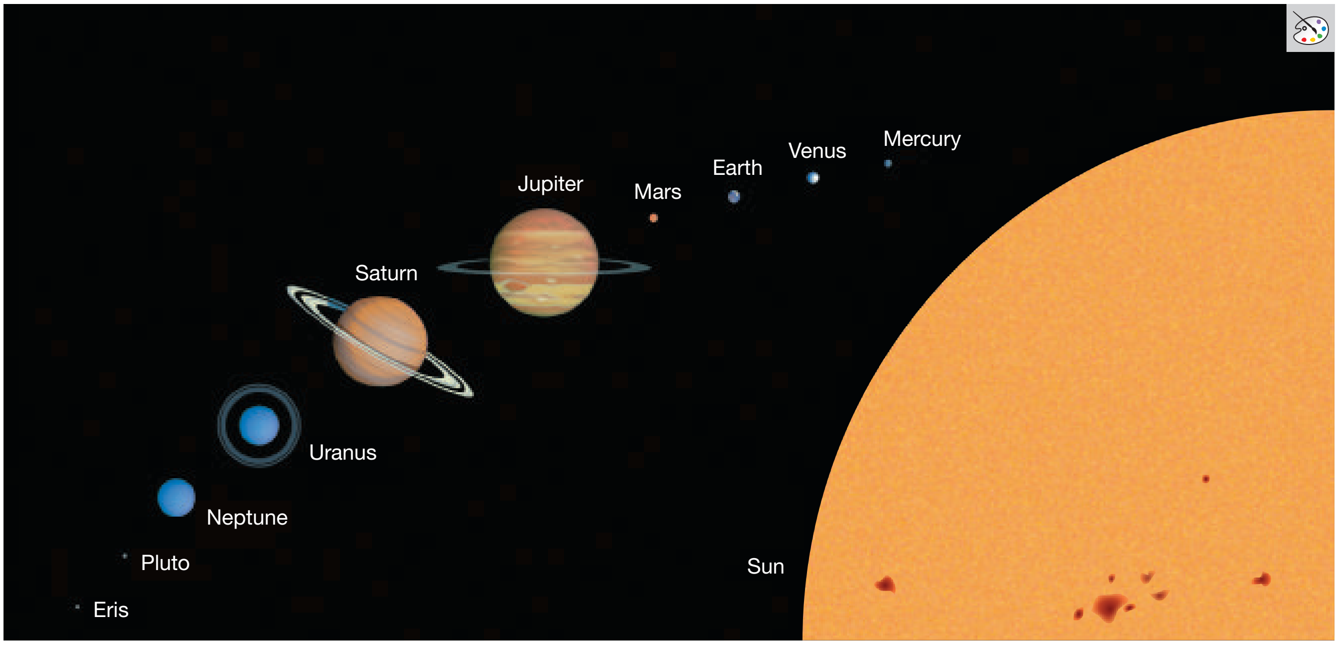
Step 3 Explain your result: In sentence form, our answer is "One light-year is about 9.46 trillion kilometers." This answer makes sense: It has the expected units of distance (kilometers) and it is a long way, which we expect for the distance that light can travel in a year. We say "about" in the answer because we know it is not exact. For example, a year is not exactly 365 days long. In fact, for most purposes, we can approximate the answer further as "One light-year is about 10 trillion kilometers."

FIGURE 1.5 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.

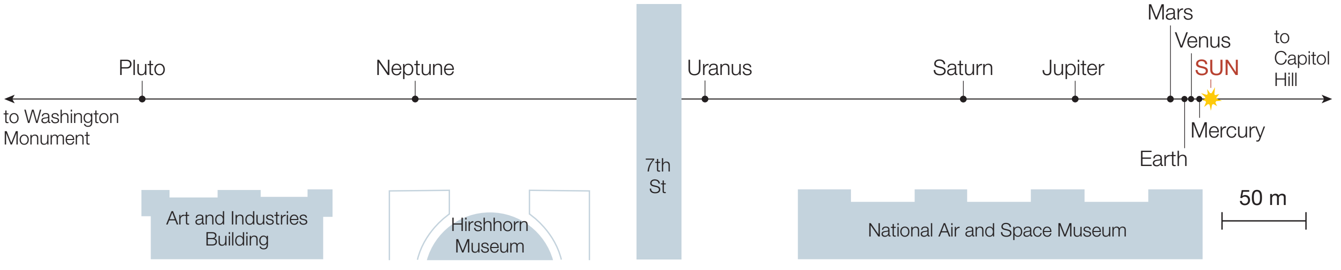
kilometer on a side—an area equivalent to more than 300 football fields arranged in a grid. Spread over this large area, only the grapefruit-size Sun, the planets, and a few moons would be big enough to see. The rest of it would look virtually empty (that's why we call it *space!*).

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

Distances to the Stars If you visit the Voyage model in Washington, D.C., you need to walk only about 600 meters



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



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

FIGURE 1.6 The Voyage scale model represents sizes and distances in the solar system at *one ten-billionth* of their actual values. Planets are lined up in the model, but in reality each planet orbits the Sun independently and a perfect alignment never occurs.

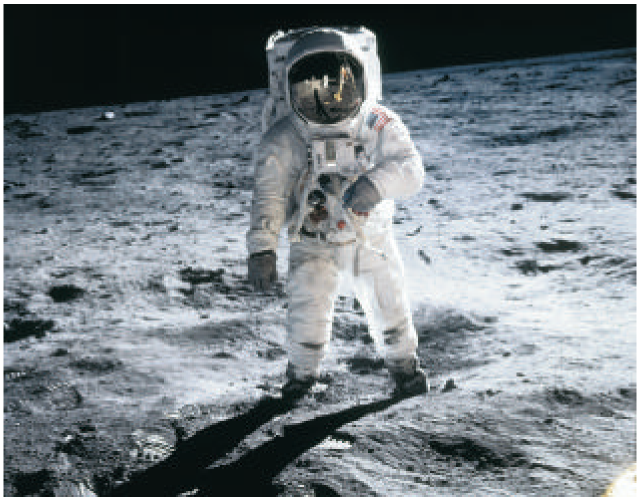


FIGURE 1.7 This famous photograph from the first Moon landing (*Apollo 11* in July 1969) shows astronaut Buzz Aldrin, with Neil Armstrong reflected in his visor. Armstrong was the first to step onto the Moon's surface, saying, "That's one small step for a man, one giant leap for mankind." (When asked why this photo became so iconic, Aldrin replied, "Location, location, location!")

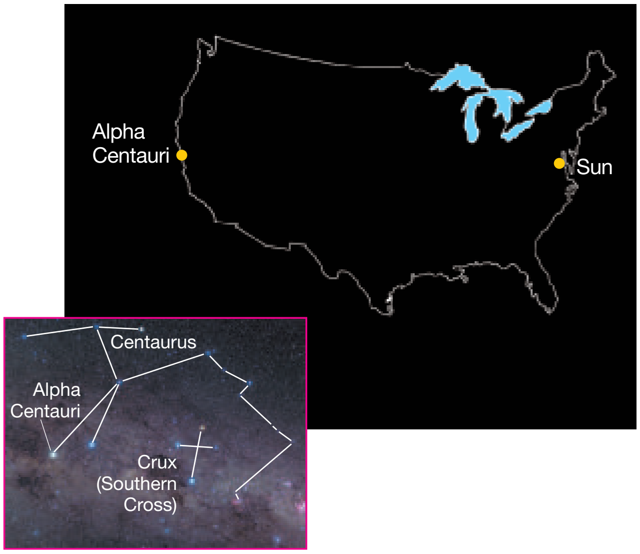


FIGURE 1.8 On the same 1-to-10 billion scale on which you can walk from the Sun to Pluto in just a few minutes, you'd need to cross the United States to reach Alpha Centauri, the nearest other star system. The inset shows the location and appearance of Alpha Centauri among the constellations.

to go from the Sun to Pluto. How much farther would you have to walk to reach the next star on this scale?

Amazingly, you would need to walk to California. If this answer seems hard to believe, you can check it for yourself. A light-year is about 10 trillion kilometers, which becomes 1000 kilometers on the 1-to-10-billion scale (because 10 trillion ÷ 10 billion = 1000). The nearest star system to our own, a three-star system called Alpha Centauri (**FIGURE 1.8**), is about 4.4 light-years away. That distance is about 4400 kilometers (2700 miles) on the 1-to-10-billion scale, or roughly equivalent to the distance across the United States.

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

Now, consider the difficulty of detecting *planets* orbiting nearby stars, which is equivalent to looking from Washington, D.C., and trying to find ball points 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 13.1**].

SPECIAL TOPIC How Many Planets Are There in Our Solar System?

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

When Pluto was discovered in 1930, it was assumed to be similar to other planets. But by the mid-1990s, it had become clear that Pluto is part of a large group of ice-rich objects that share its region of the solar system (called the *Kuiper belt*, which we'll discuss in Chapter 12). 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 4), but added the "dwarf planet" category to accommodate them. These definitions still spark some controversy, but perhaps are best thought of as an example of the difference between the fuzzy boundaries of nature and the human preference for categories. After all, the argument about whether Pluto is a planet or a dwarf planet is not so different from the argument you may hear over whether a particular waterway is a creek, stream, or river.

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

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 (**FIGURE 1.9**). Our entire solar system is a microscopic dot located around the 20-yard line. The 4.4-light-year separation between our solar system and Alpha Centauri becomes just 4.4 millimeters on this scale—smaller than the width of your little finger. If you stood at the position of our solar system in this model, millions of star systems would lie within reach of your arms.

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

MATHEMATICAL INSIGHT 1.2

Scientific Notation, Parts 1 to 3

The Scale of Space and Time

Making a scale model usually requires nothing more than division. For example, in a 1-to-20 architectural scale model, a building that is actually 6 meters tall will be only $6 \div 20 = 0.3$ meter tall. The idea is the same for astronomical scaling, except that we usually divide by such large numbers that it's easier to work in *scientific notation*—that is, with the aid of powers of 10. (See Appendixes C.1 and C.2 to review these concepts.)

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

SOLUTION:

Step 1 Understand: We are looking for the scaled *size* of the Sun, so we simply need to divide its actual radius by 10 billion, or 10^{10}. Appendix E.1 gives the Sun's radius as 695,000 km, or 6.95×10^5 km in scientific notation.

Step 2 Solve: We carry out the division:

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

Notice that we used the rule that dividing powers of 10 means subtracting their exponents [**Appendix C.1**].

Step 3 Explain: We have found an answer, but because most of us don't have a good sense of what 10^{-5} kilometer looks like, the answer will be more meaningful if we convert it to centimeters (recalling that $1 \text{ km} = 10^3$ m and $1 \text{ m} = 10^2$ cm):

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

On the 1-to-10-billion scale, the Sun's radius is about 7 centimeters, which is a diameter of about 14 centimeters—about the size of a large grapefruit.

EXAMPLE 2: What scale allows the 100,000-light-year diameter of the Milky Way Galaxy to fit on a 100-meter-long football field?

SOLUTION:

Step 1 Understand: We want to know *how many times larger* the actual diameter of the galaxy is than 100 meters, so we'll divide the actual diameter by 100 meters. To carry out the division, we'll need both numbers in the same units. We can put the galaxy's diameter in meters by using the fact that a light-year is about 10^{13} kilometers (see Mathematical Insight 1.1) and a kilometer is 10^3 meters; because we are working with powers of 10, we'll write the galaxy's 100,000-light-year diameter as 10^5 ly.

Step 2 Solve: We now convert the units and carry out the division:

$$\frac{\text{galaxy diameter}}{\text{football field diameter}} = \frac{10^5 \cancel{\text{ly}} \times \frac{10^{13} \cancel{\text{km}}}{1 \cancel{\text{ly}}} \times \frac{10^3 \cancel{\text{m}}}{1 \cancel{\text{km}}}}{10^2 \cancel{\text{m}}} = 10^{(5+13+3-2)} = 10^{19}$$

Note that the answer has no units, because it simply tells us how many times larger one thing is than the other.

Step 3 Explain: We've found that we need a scale of 1 to 10^{19} to make the galaxy fit on a football field.

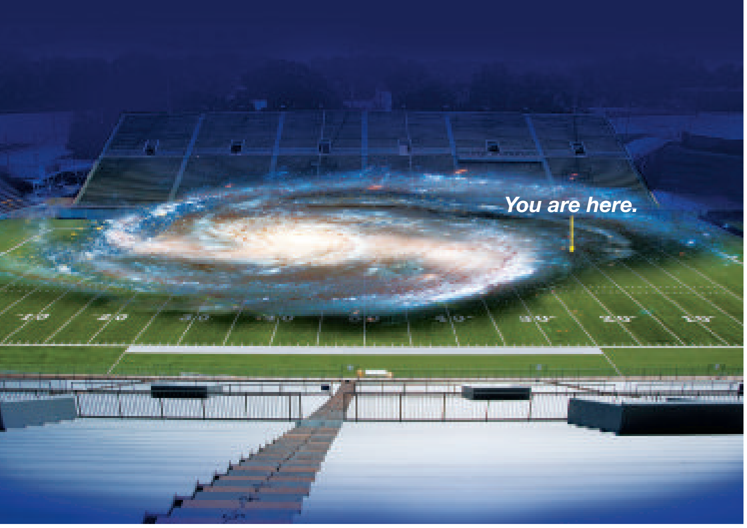


FIGURE 1.9 This painting shows the Milky Way Galaxy on a scale where its diameter is the length of a football field. On this scale, stars are microscopic and the distance between our solar system and Alpha Centauri is only 4.4 millimeters. There are so many stars in our galaxy that it would take thousands of years just to count them out loud.

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

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

Think for a moment about the total number of stars in all these galaxies. If we assume 100 billion galaxies and 100 billion stars per galaxy, the total number of stars in the observable universe is roughly $100 \text{ billion} \times 100 \text{ billion}$, or 10,000,000,000,000,000,000,000 $\left(10^{22}\right)$. How big is this number? Visit a beach. Run your hands through the fine-grained sand. Imagine counting each tiny grain of sand as it slips through your fingers. Then imagine counting every grain of sand on the beach and continuing to count *every* grain of dry sand on *every* beach on Earth (see Mathematical Insight 1.3). If you could actually complete this task, you would find that the number of grains of sand is comparable to the number of stars in the observable universe (**FIGURE 1.10**).

Think about it Study the foldout in the front of this book, which illustrates the ideas covered in this section in greater detail. Overall, how does visualizing Earth to scale affect your perspective on our planet and on human existence? Explain.

MATHEMATICAL INSIGHT 1.3 Order of Magnitude Estimation

In astronomy, numbers are often so large that an estimate can be useful even if it's good only to about the nearest power of 10. For example, when we multiplied 100 billion stars per galaxy by 100 billion galaxies to estimate that there are about 10^{22} stars in the observable universe, we knew that the "ballpark" nature of these numbers means the actual number of stars could easily be anywhere from about 10^{21} to 10^{23}. Estimates good to about the nearest power of 10 are called **order of magnitude estimates**.

EXAMPLE: Verify the claim that the number of grains of (dry) sand on all the beaches on Earth is comparable to the number of stars in the observable universe.

SOLUTION:

Step 1 Understand: To verify the claim, we need to estimate the number of grains of sand and see if it is close to our estimate of 10^{22} stars. We can estimate the total number of sand grains by dividing the *total volume* of sand on Earth's beaches by the *average volume* of an individual sand grain. Volume is equal to length times width times depth, so the total volume is the total length of sandy beach on Earth multiplied by the typical width and depth of dry sand. That is,

$$\text{total sand grains} = \frac{\text{total volume of beach sand}}{\text{average volume of 1 sand grain}} = \frac{\text{beach length} \times \text{beach width} \times \text{beach depth}}{\text{average volume of 1 sand grain}}$$

We now need numbers to put into the equation. We can estimate the average volume of an individual sand grain by measuring out a small volume of sand, counting the number of grains in this volume, and then dividing the volume by the number of grains. If you do this, you'll find that a reasonable order of magnitude estimate is one-tenth of a cubic millimeter, or $10^{-10}\ \text{m}^3$, per sand grain. We can estimate beach width and depth from experience or photos of beaches. Typical widths are about 20 to 50 meters and typical sand depth is about 2 to 5 meters, so we can make the numbers easy by assuming that the product of beach width times depth is about 100 square meters, or $10^2\ \text{m}^2$. The total length of sandy beach on Earth is more difficult to estimate, but you can look online and find that it is less than about 1 million kilometers, or $10^9\ \text{m}$.

Step 2 Solve: We already have our equation and all the numbers we need, so we just put them in; note that we group beach width and depth together, since we estimated them together in Step 1:

$$\begin{aligned} \text{total sand grains} &= \frac{\text{beach length} \times (\text{beach width} \times \text{beach depth})}{\text{average volume of 1 sand grain}} \\ &= \frac{10^9\ \cancel{\text{m}} \times 10^2\ \cancel{\text{m}^2}}{10^{-10}\ \cancel{\text{m}^3}} \\ &= 10^{[9+2-(-10)]} = 10^{21} \end{aligned}$$

Step 3 Explain: Our order of magnitude estimate for the total number of grains of dry sand on all the beaches on Earth is 10^{21}, which is within a factor of 10 of the estimated 10^{22} stars in the observable universe. Because both numbers could easily be off by a factor of 10 or more, we cannot say with certainty that one is larger than the other, but the numbers are clearly comparable.

FIGURE 1.10 The number of stars in the observable universe is comparable to the number of grains of dry sand on all the beaches on Earth.

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!

1.2 The History of the Universe

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

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

How did we come to be?

FIGURE 1.11 (pages 12–13) summarizes the history of the universe according to modern science. Let's start at the upper left of the figure, and discuss the key events and what they mean.

The Big Bang, Expansion, and the Age of the Universe Telescopic observations of distant galaxies show that the entire universe is *expanding*, meaning that average distances between galaxies are increasing with time. This fact implies that galaxies must have been closer together in the past, and if we go back far enough, we must reach the point at which the expansion began. We call this beginning the **Big Bang**, and scientists use the observed rate of expansion to calculate that it occurred about 14 billion years ago. The three cubes in the upper left portion of Figure 1.11 represent the expansion of a small piece of the universe through time.

The universe as a whole has continued to expand ever since the Big Bang, but on smaller size scales the force of gravity has drawn matter together. Structures such as galaxies and galaxy clusters occupy regions where gravity has won out against the overall expansion. That is, while the universe as a whole continues to expand, individual galaxies and galaxy clusters (and objects within them such as stars and planets) do *not* expand. This idea is also illustrated by the three cubes in Figure 1.11. Notice that as the cube as a whole grew larger, the matter within it clumped into galaxies and galaxy clusters. Most galaxies, including our own Milky Way, formed within a few billion years after the Big Bang.

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

In its final death throes, a star blows much of its contents back out into space. The most massive stars die in titanic explosions called *supernovae*. The returned matter mixes with other matter floating between the stars in the galaxy, eventually becoming part of new clouds of gas and dust from which new generations of stars can be born. Galaxies therefore function as cosmic recycling plants, recycling material expelled from dying stars into new generations of stars and planets. This cycle is illustrated in the lower right of Figure 1.11. Our own solar system is a product of many generations of such recycling.

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

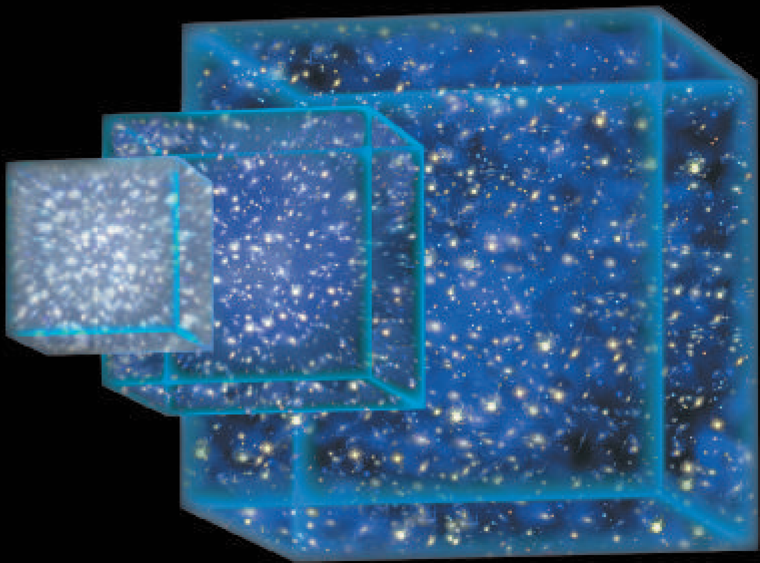
By the time our solar system formed, about $4\frac{1}{2}$ billion years ago, earlier generations of stars had already converted up to 2% of our galaxy's original hydrogen and helium into heavier elements. Therefore, the cloud that gave birth to our

COSMIC Context

FIGURE 1.11 Our Cosmic Origins

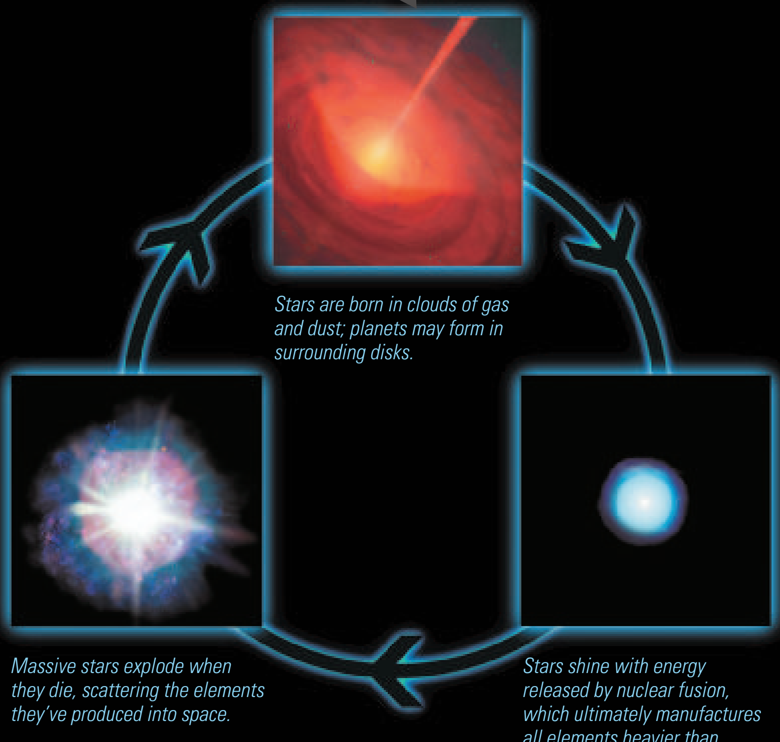
Throughout this book we will see that human life is intimately connected with the development of the universe as a whole. This illustration presents an overview of our cosmic origins, showing some of the crucial steps that made our existence possible.

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



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

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



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

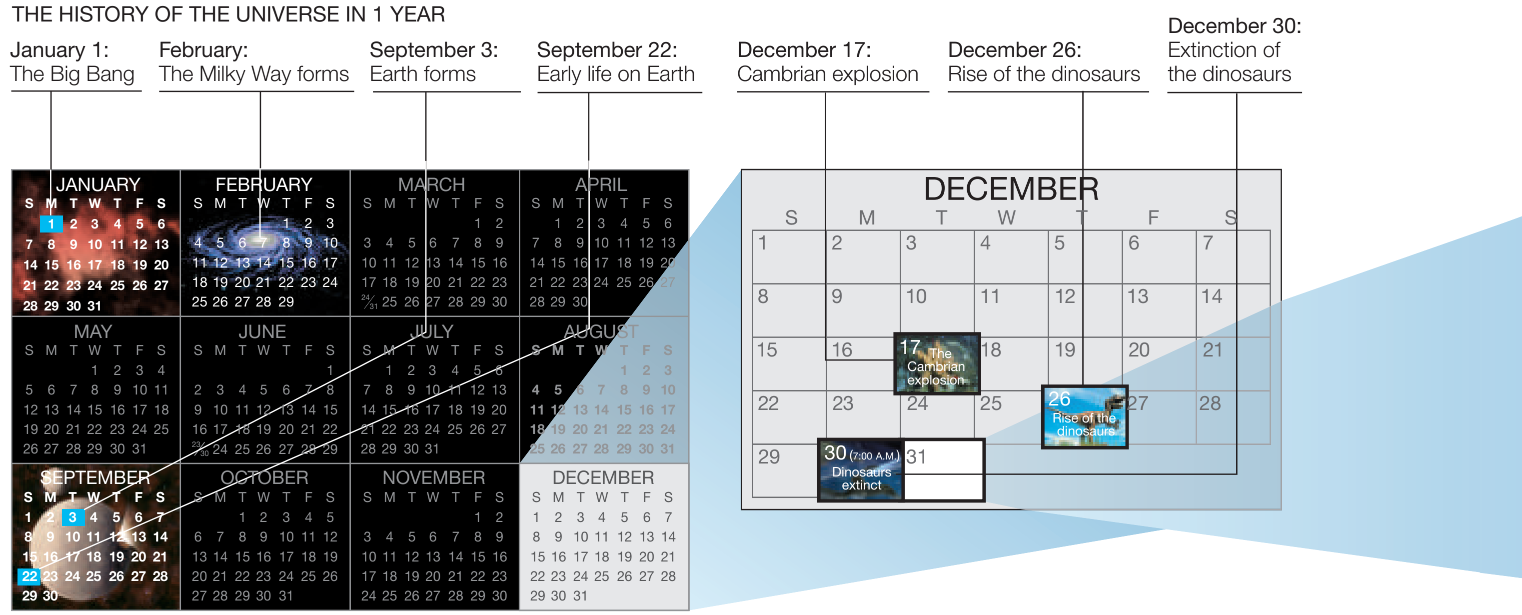


FIGURE 1.12 The cosmic calendar compresses the 14-billion-year history of the universe into 1 year, so each month represents a little more than 1 billion years. Adapted from the cosmic calendar created by Carl Sagan. (For a more detailed version, see the "You Are Here in Time" foldout diagram in the front of the book.)

solar system was made of roughly 98% hydrogen and helium and 2% other elements. This 2% may sound small, but it was more than enough to make the small rocky planets of our solar system, including Earth. On Earth, some of these elements became the raw ingredients of life, which ultimately blossomed into the great diversity of life on Earth today.

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

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

We can put the 14-billion-year age of the universe into perspective by imagining this time compressed into a single year, so each month represents a little more than 1 billion years. On this *cosmic calendar*, the Big Bang occurred at the first instant of January 1 and the present is the stroke of midnight on December 31 (**FIGURE 1.12**).

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

Our solar system and our planet did not form until early September on this scale, or $4\frac{1}{2}$ billion years ago in real time. By late September, life on Earth was flourishing. However, for most of Earth's history, living organisms remained relatively primitive and microscopic. On the scale of the cosmic calendar, recognizable animals became prominent only in mid-December. Early dinosaurs appeared on the day after Christmas. Then, in a cosmic instant, the dinosaurs disappeared forever—probably because of the impact of an asteroid or a comet [**Section 12.5**]. In real time the death of the dinosaurs occurred some 65 million years ago, but on the cosmic calendar it was only yesterday. With the dinosaurs gone, small furry mammals inherited Earth. Some 60 million years later, or around 9 p.m. on December 31 of the cosmic calendar, early hominids (human ancestors) began to walk upright.

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

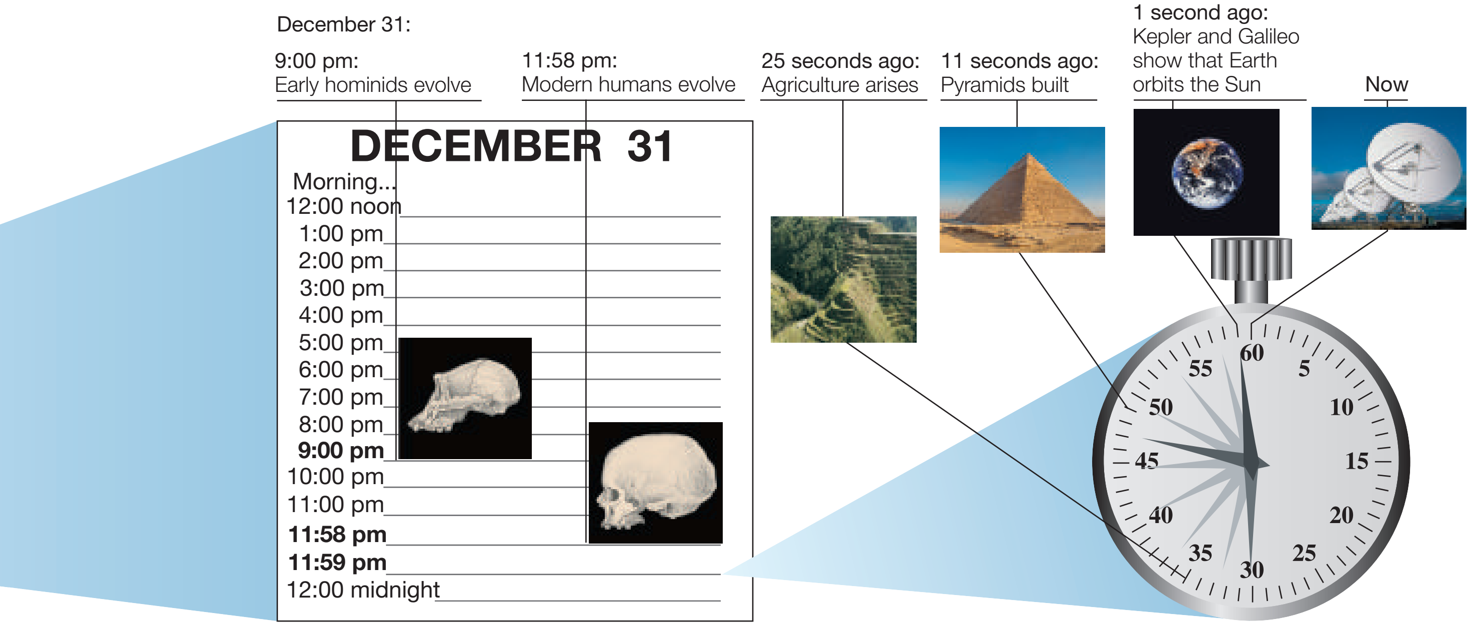
Think about it Study the more detailed cosmic calendar found on the foldout in the front of this book. How does an understanding of the scale of time affect your view of human civilization? Explain.

1.3 Spaceship Earth

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

How is Earth moving through space?

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



Earth's Rotation and Orbit

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

Earth rotates once each day around its axis (**FIGURE 1.13**), which is the imaginary line connecting the North Pole to the South Pole. Earth rotates from west to east—counterclockwise as viewed from above the North Pole—which is why the Sun and stars appear to rise in the east and set in the west each day. Although the physical effects of rotation are so subtle that our ancestors assumed the heavens revolved around us, the rotation speed is substantial: Unless you live quite far north or south, you are whirling around Earth's axis at a speed of more than 1000 kilometers per hour (600 miles per hour)—faster than most airplanes travel.

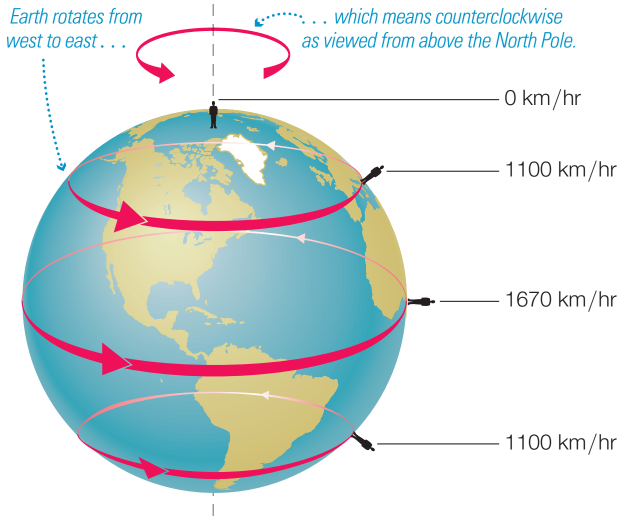


FIGURE 1.13 As Earth rotates, your speed around Earth's axis depends on your location: The closer you are to the equator, the faster you travel with rotation.

At the same time as it is rotating, Earth also orbits the Sun, completing one orbit each year (**FIGURE 1.14**). Earth's orbital distance varies slightly over the course of each year, but as we discussed earlier, the average distance is one astronomical unit (AU), which is about 150 million kilometers. Again, even though we don't feel this motion, the speed is impressive: We are racing around the Sun at a speed in excess of 100,000 kilometers per hour (60,000 miles per hour), which is faster than any spacecraft yet launched.

As you study Figure 1.14, notice that Earth's orbital path defines a flat plane that we call the **ecliptic plane**. Earth's axis is tilted by $23\frac{1}{2}°$ from a line *perpendicular* to the ecliptic plane. This **axis tilt** happens to be oriented so that the axis points almost directly at a star called *Polaris*, or the *North Star*. Keep in mind that the idea of axis tilt makes sense only in relation to the ecliptic plane. That is, the idea of "tilt" by itself has no meaning in space, where there is no absolute up or down. In space, "up" and "down" mean only "away from the center of Earth" (or another planet) and "toward the center of Earth," respectively.

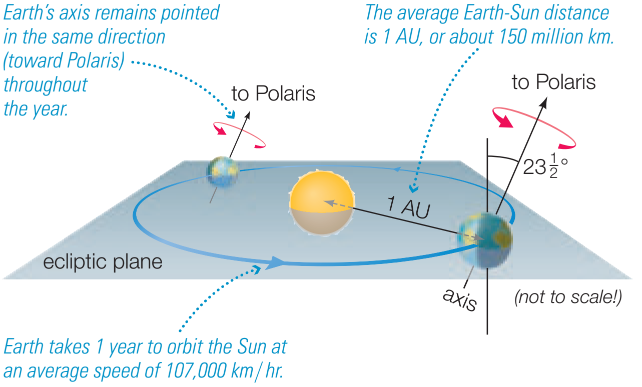


FIGURE 1.14 This diagram shows key characteristics of Earth's daily rotation and yearly orbit, both of which are counterclockwise as viewed from above the North Pole.

Think about it If there is no up or down in space, why do you think that most globes and maps have the North Pole on top? Would it be equally correct to have the South Pole on top or to turn a globe sideways? Explain.

Notice also that Earth orbits the Sun in the same direction that it rotates on its axis: counterclockwise as viewed from above the North Pole. This is not a coincidence but a consequence of the way our planet was born. As we'll discuss in Chapter 8, strong evidence indicates that Earth and the other planets were born in a spinning disk of gas that surrounded our Sun as it formed, and Earth rotates and orbits in the same direction that the disk was spinning.

Motion Within the Milky Way Galaxy Rotation and orbit are only a small part of the travels of spaceship Earth. Our entire solar system is on a great journey within the Milky Way Galaxy. There are two major components to this motion, both shown in **FIGURE 1.15**.

First, our solar system is moving relative to nearby stars in our *local solar neighborhood*, the region of the Sun and nearby stars. The small box in Figure 1.15 shows that stars in our local solar neighborhood (like the stars of any other small region of the galaxy) move essentially at random relative to one another. The speeds are quite fast: On average, our Sun is moving relative to nearby stars at a speed of about 70,000 kilometers per hour (40,000 miles per hour), almost three times as fast as the International Space Station orbits Earth. Given these high speeds, you might wonder why we don't see stars racing around our sky. The answer lies in their vast distances from us. You've probably noticed that a distant airplane appears to move through your sky more slowly than

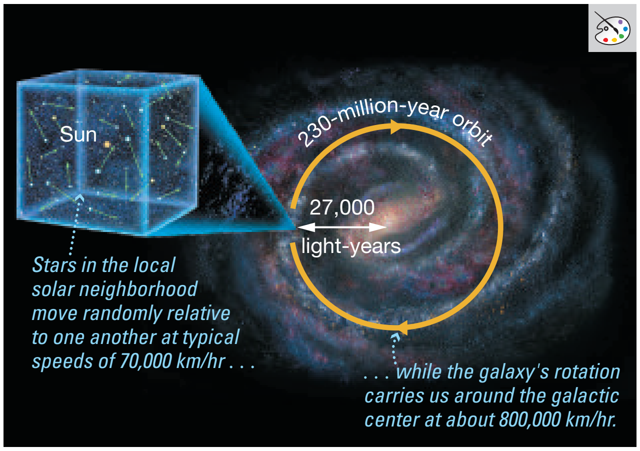


FIGURE 1.15 This painting illustrates the motion of the Sun both within the local solar neighborhood and around the center of the galaxy.

MATHEMATICAL INSIGHT 1.4

Problem Solving Part 3

Speeds of Rotation and Orbit

Building upon prior Mathematical Insights, we will now see how simple formulas—such as the formula for the circumference of a circle—expand the range of astronomical problems we can solve.

EXAMPLE 1: How fast is a person on Earth's equator moving with Earth's rotation?

SOLUTION:

Step 1 Understand: The question *how fast* tells us we are looking for a *speed*. If you remember that highway speeds are posted in miles (or kilometers) per hour, you'll realize that speed is a distance (such as miles) divided by a time (such as hours). In this case, the distance is Earth's equatorial circumference, because that is how far a person at the equator travels with each rotation (see Figure 1.13); we'll therefore use the formula for the circumference of a circle, $C = 2 \times \pi \times \text{radius}$. The time is 24 hours, because that is how long each rotation takes.

Step 2 Solve: From Appendix E.1, Earth's equatorial radius is 6378 km, so its circumference is $2 \times \pi \times 6378\text{ km} = 40{,}074\text{ km}$. We divide this distance by the time of 24 hours:

$$\text{rotation speed at equator} = \frac{\text{equatorial circumference}}{\text{length of day}} = \frac{40{,}074\text{ km}}{24\text{ hr}} = 1670\,\frac{\text{km}}{\text{hr}}$$

Step 3 Explain: A person at the equator is moving with Earth's rotation at a speed of about 1670 kilometers per hour, which is a little over 1000 miles per hour, or about twice the flying speed of a commercial jet.

EXAMPLE 2: How fast is Earth orbiting the Sun?

SOLUTION:

Step 1 Understand: We are again asked *how fast* and therefore need to divide a distance by a time. In this case, the distance is the circumference of Earth's orbit, and the time is the 1 year that Earth takes to complete each orbit.

Step 2 Solve: Earth's average distance from the Sun is 1 AU, or about 150 million (1.5×10^8) km, so the orbit circumference is about $2 \times \pi \times 1.5 \times 10^8\text{ km} \approx 9.40 \times 10^8\text{ km}$. The orbital speed is this distance divided by the time of 1 year, which we convert to hours so that we end up with units of km/hr:

$$\text{orbital speed} = \frac{\text{orbital circumference}}{1\text{ yr}} = \frac{9.40 \times 10^8\text{ km}}{1\,\cancel{\text{yr}} \times \frac{365\,\cancel{\text{days}}}{\cancel{\text{yr}}} \times \frac{24\text{ hr}}{\cancel{\text{day}}}} \approx 107{,}000\,\frac{\text{km}}{\text{hr}}$$

Step 3 Explain: Earth orbits the Sun at an average speed of about 107,000 km/hr (66,000 mi/hr). Most "speeding bullets" travel between about 500 and 1000 km/hr, so Earth's orbital speed is more than 100 times that of a speeding bullet.

FIGURE 1.16 This painting shows an edge-on view of the Milky Way Galaxy. Study of galactic rotation shows that although most visible stars lie in the central bulge or thin disk, most of the mass lies in the halo that surrounds and encompasses the disk. Because this mass emits no light that we have detected, we call it *dark matter*.

one flying close overhead. Stars are so far away that even at speeds of 70,000 kilometers per hour, their motions would be noticeable to the naked eye only if we watched them for thousands of years. That is why the patterns in the constellations seem to remain fixed. Nevertheless, in 10,000 years the constellations will be noticeably different from those we see today. In 500,000 years they will be unrecognizable. If you could watch a time-lapse movie made over millions of years, you *would* see stars racing across our sky.

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

The second motion shown in Figure 1.15 is much more organized. If you look closely at leaves floating in a stream, their motions relative to one another might appear random, just like the motions of stars in the local solar neighborhood. As you widen your view, you see that all the leaves are being carried in the same general direction by the downstream current. In the same way, as we widen our view beyond the local solar neighborhood, the seemingly random motions of its stars give way to a simpler and even faster motion: rotation of the Milky Way Galaxy. Our solar system, located about 27,000 light-years from the galactic center, completes one orbit of the galaxy in about 230 million years. Even if you could watch from outside our galaxy, this motion would be unnoticeable to your naked eye. However, if you calculate the speed of our solar system as we orbit the center of the galaxy, you will find that it is close to 800,000 kilometers (500,000 miles) per hour.

Careful study of the galaxy's rotation reveals one of the greatest mysteries in science. Stars at different distances from the galactic center orbit at different speeds, and we can learn how mass is distributed in the galaxy by measuring these speeds. Such studies indicate that the stars in the disk of the galaxy represent only the "tip of the iceberg" compared to the mass of the entire galaxy (**FIGURE 1.16**). Most of the mass of the galaxy seems to be located outside the visible disk (occupying the galactic *halo* that surrounds the disk), but the matter that makes up this mass is completely invisible to our telescopes. We therefore know very little about the nature of this matter, which we refer to as **dark matter** (because of the lack of light from it). Studies of other galaxies indicate that they also are made mostly of dark matter, which means this mysterious matter significantly outweighs the ordinary matter that makes up planets and stars; this also means that dark matter must be the dominant source of gravity that has led to the formation of galaxies, clusters, and superclusters. We know even less about the mysterious **dark energy** that astronomers first recognized when they discovered that the expansion of the universe is actually getting faster with time, and that scientists have since found to make up the majority of the total energy content of the universe. We'll discuss the mysteries of dark matter and dark energy in Chapter 23.

How do galaxies move within the universe?

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

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

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

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

The Raisin Cake Analogy Imagine that you make a raisin cake in which the distance between adjacent raisins is 1 centimeter. You place the cake into the oven, where it expands as it bakes. After 1 hour, you remove the cake, which has expanded so that the distance between adjacent raisins has increased to 3 centimeters (**FIGURE 1.17**). The expansion of the cake seems fairly obvious. But what would you see if you lived *in* the cake, as we live in the universe?

Pick any raisin (it doesn't matter which one) and call it the Local Raisin. Figure 1.17 shows one possible choice, with three nearby raisins also labeled. The accompanying table summarizes what you would see if you lived within the Local Raisin. Notice, for example, that Raisin 1 starts out at a distance of 1 centimeter before baking and ends up at a distance of 3 centimeters after baking, which means it moves a distance of 2 centimeters farther away from the Local Raisin during the hour of baking. Hence, its speed as seen from the Local Raisin is 2 centimeters per hour. Raisin 2 moves from a distance of 2 centimeters before baking to a distance of 6 centimeters after baking, which means it moves a distance of 4 centimeters farther away from the Local Raisin during the hour. Hence, its speed is 4 centimeters per hour, or twice the speed of Raisin 1. Generalizing, the fact that the cake is expanding means that all the raisins are moving away from the Local Raisin, with more distant raisins moving away faster.

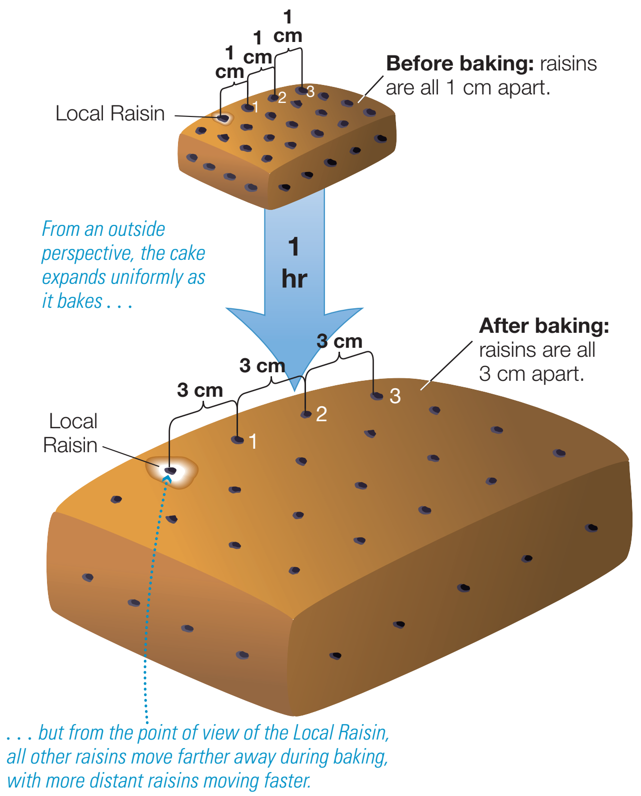
Think about it Suppose a raisin started out 10 centimeters from the Local Raisin. How far away would it be after 1 hour, and how fast would it be moving away from the Local Raisin?

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

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

It's also important to realize that, unlike the case with a raisin cake, we can't actually *see* galaxies moving apart with time—the distances are too vast for any motion to be noticeable on the time scale of a human life. Instead, we measure the speeds of galaxies by spreading their light into spectra and observing what we call *Doppler shifts* [**Section 5.4**]. This illustrates how modern astronomy depends both on careful observations and on using current understanding of the laws of nature to explain what we see.

Motion Summary **FIGURE 1.18** summarizes the motions we have discussed. As we have seen, we are never truly sitting still. We spin around Earth's axis at more than 1000 kilometers per hour, while our planet orbits the Sun at more than 100,000 kilometers per hour. Our solar system moves among the stars of the local solar neighborhood at a typical speed of 70,000 kilometers per hour, while also orbiting the center of the Milky Way Galaxy at a speed of about 800,000 kilometers per hour. Our galaxy moves among the other galaxies of the



Distances and Speeds as Seen from the Local Raisin

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

FIGURE 1.17 An expanding raisin cake offers an analogy to the expanding universe. Someone living in one of the raisins inside the cake could figure out that the cake is expanding by noticing that all other raisins are moving away, with more distant raisins moving away faster. In the same way, we know that we live in an expanding universe because all galaxies outside our Local Group are moving away from us, with more distant ones moving faster.