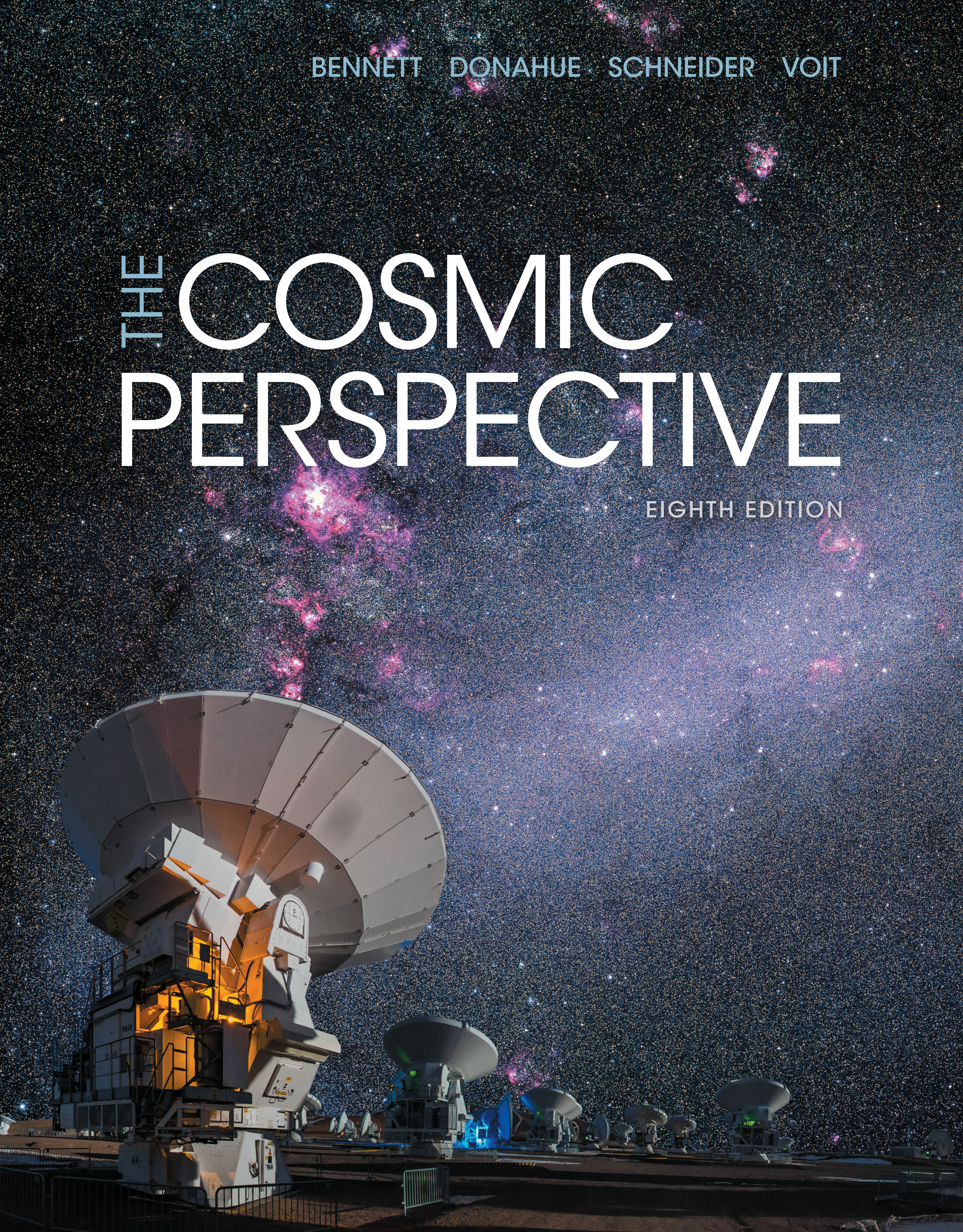
BENNETT DONAHUE SCHNEIDER VOIT

THE COSMIC PERSPECTIVE

EIGHTH EDITION



You Are Here in Space

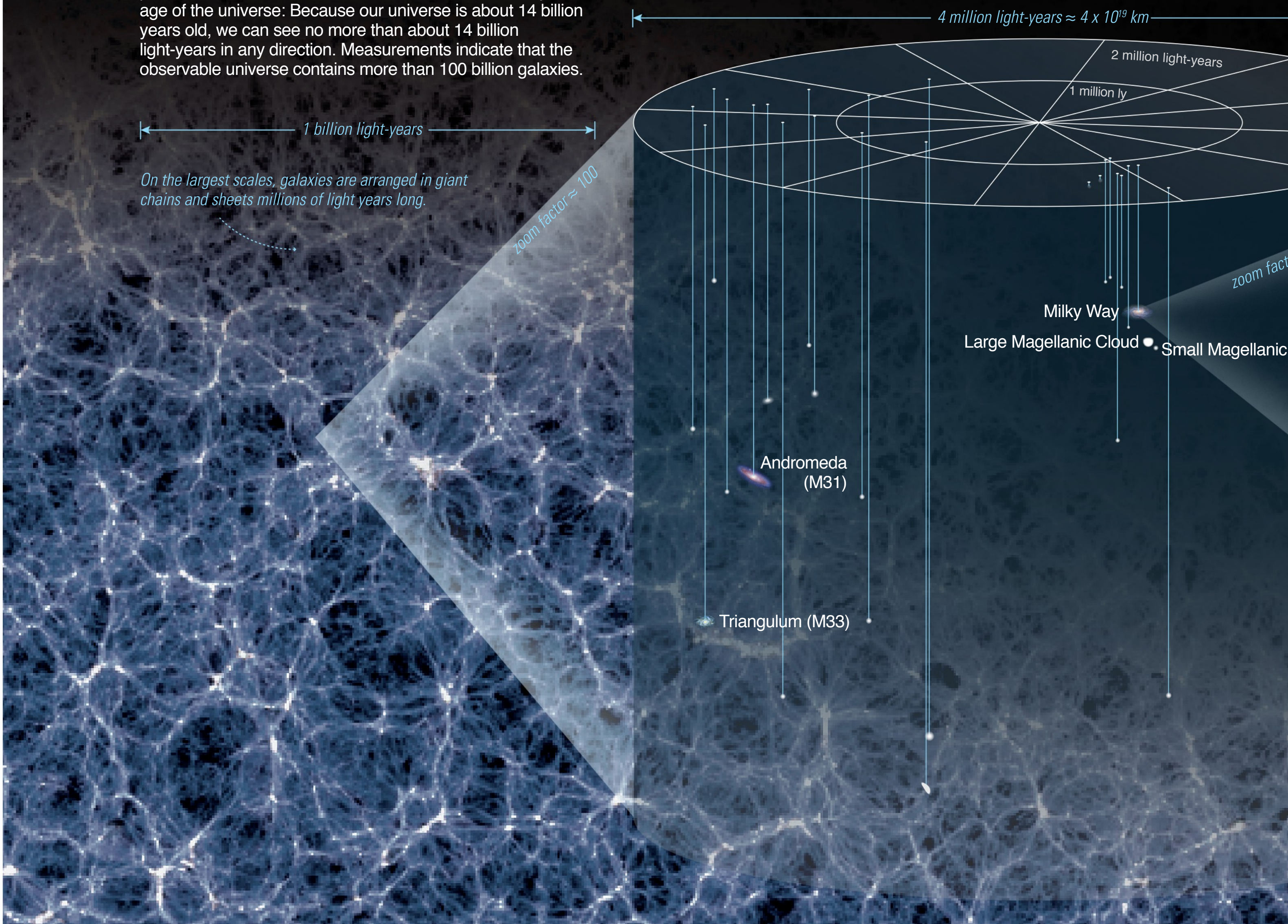
One of the best reasons to study modern astronomy is to learn the universe. This visual will lead you through the basic levels with the universe as a whole and ending with Earth.

The Observable Universe

The background illustration depicts the overall distribution of galaxies in our observable universe; individual galaxies are microscopic on this scale. The portion of the universe that we can observe is limited by the age of the universe: Because our universe is about 14 billion years old, we can see no more than about 14 billion light-years in any direction. Measurements indicate that the observable universe contains more than 100 billion galaxies.

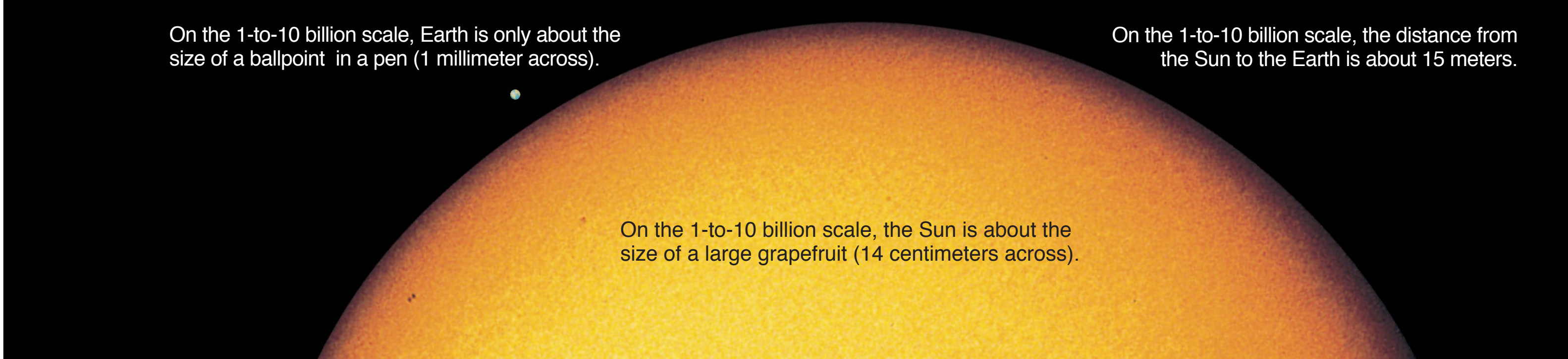
The Local Group

This image shows the largest galaxies in our Local Group. Most galaxies are member up to a few dozen galaxies, such as our own Local Group, or larger clusters containing up galaxies.



Putting Space in Perspective

One good way to put the vast sizes and distances of astronomical objects into perspective is with a scale model. In this book, we'll build perspective using a model that shows our solar system at *one-ten-billionth* its actual size.



about your place in of structure, starting

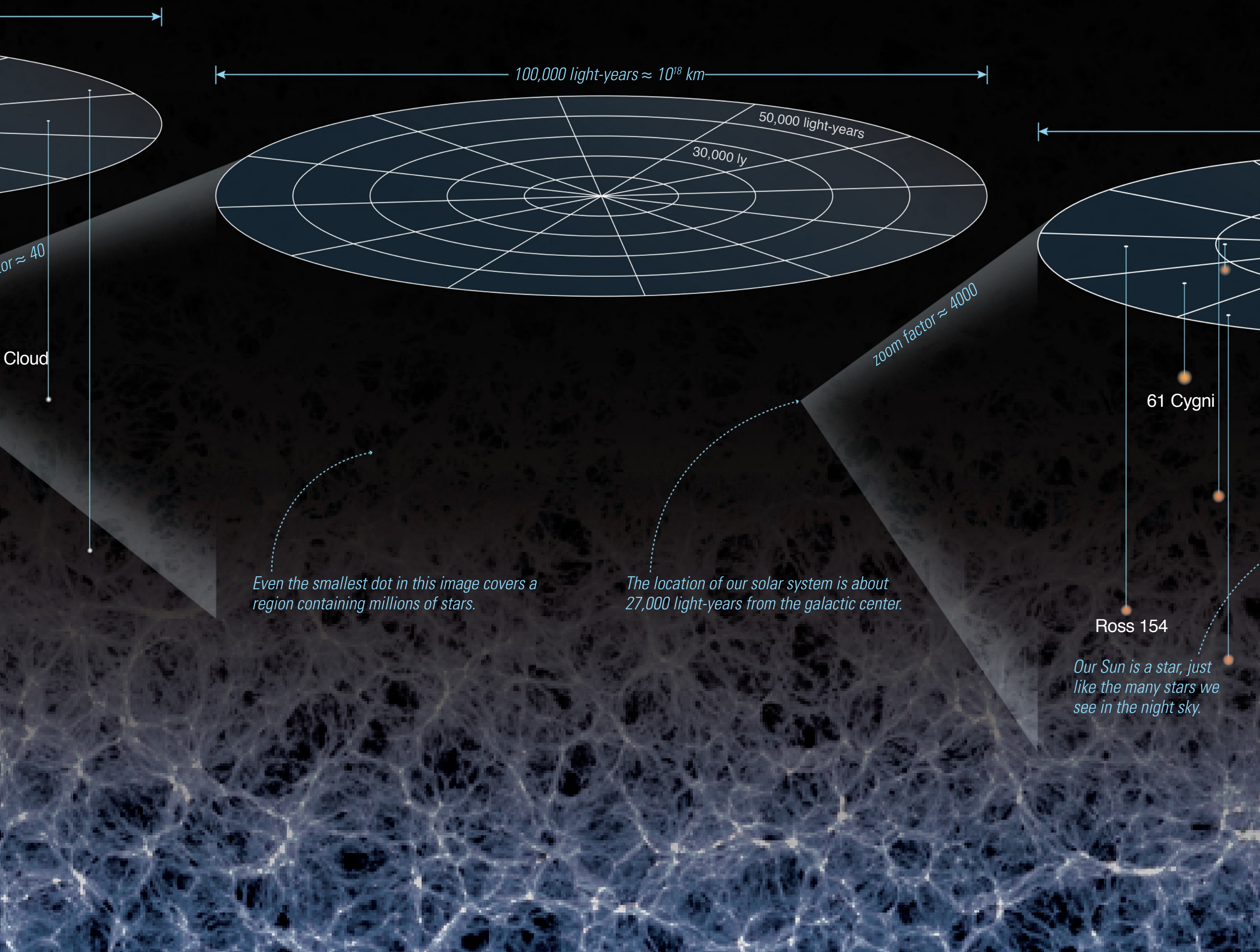
s of small groups of to a few thousand

The Milky Way Galaxy

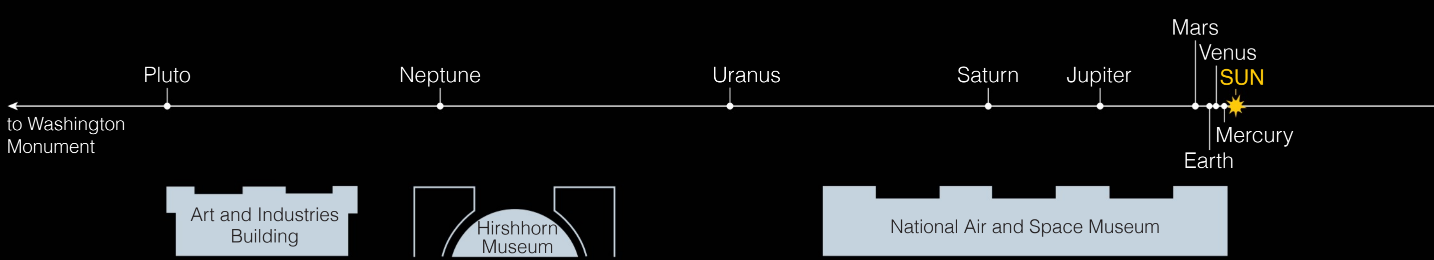
This illustration shows what the Milky Way Galaxy would look like from the outside. Our galaxy is one of the three largest members of the Local Group. The Milky Way contains more than 100 billion stars — so many stars that it would take thousands of years just to count them out loud.

The Nearest Stars

This image shows the loca scale, so their sizes have b piece of the Milky Way brings we *see* only stars, we now kr



The Voyage scale model solar system in Washington, D.C. uses this 1-to-10 billion scale, making it possible to walk to the outermost planets in just a few minutes.



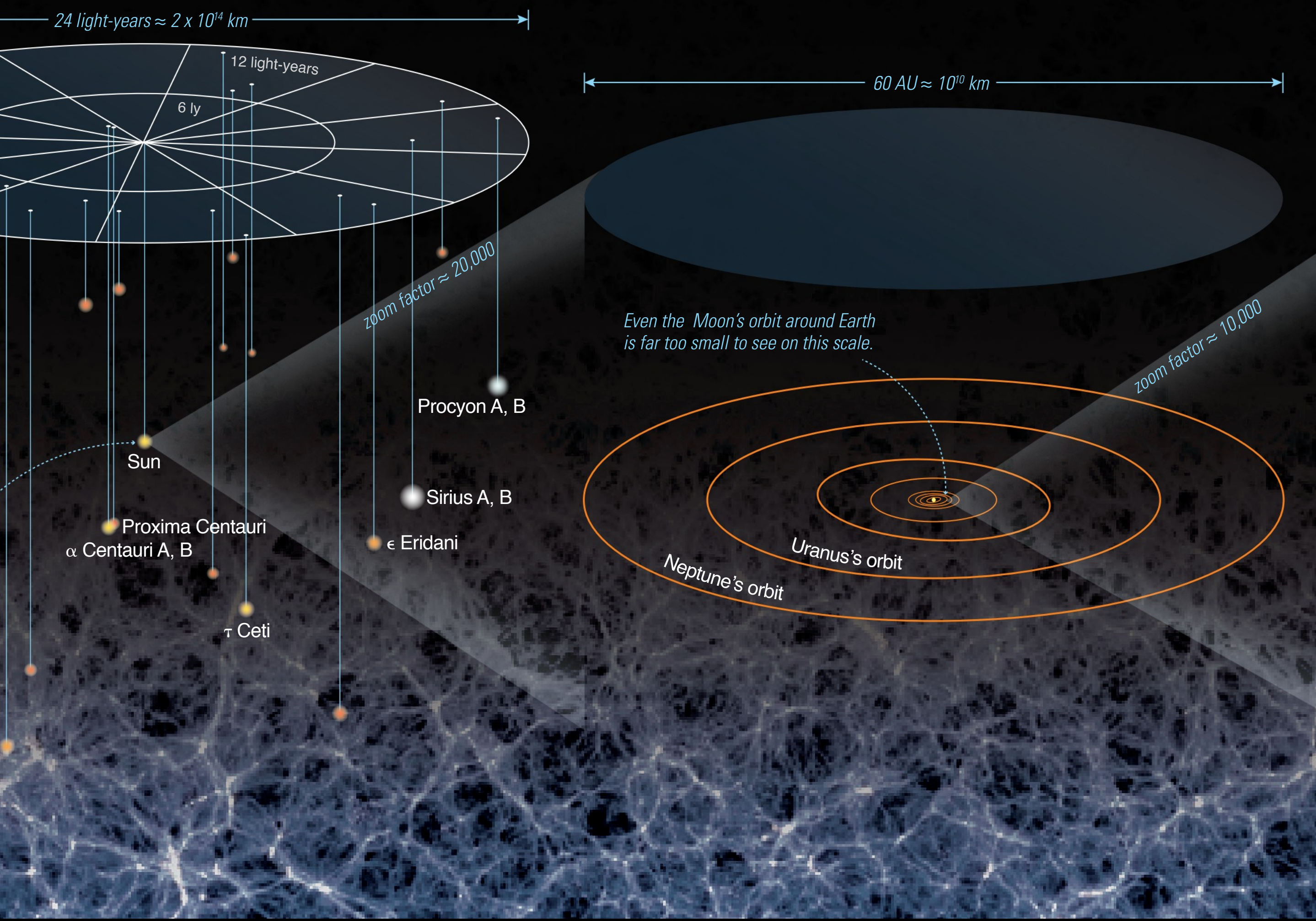
This map shows planet locations in the Voyage model. Keep in mind that planets actually follow orbits that go all the way around the Sun.

s

tions of nearby stars; stars would be atom-sized on this een greatly exaggerated for visibility. Zooming in on a tiny s us to the nearby stars of our *local solar neighborhood.* While how that many (perhaps most) stars are orbited by planets.

The Solar System

This diagram shows the orbits of the planets around the Sun; the planets themselves are microscopic on this scale. Our solar system consists of the Sun and all the objects that orbit it, including the planets and their moons, and countless smaller objects such as asteroids and comets.



On the 1-to-10 billion scale, you'd have to cross the United States to reach the nearest stars.

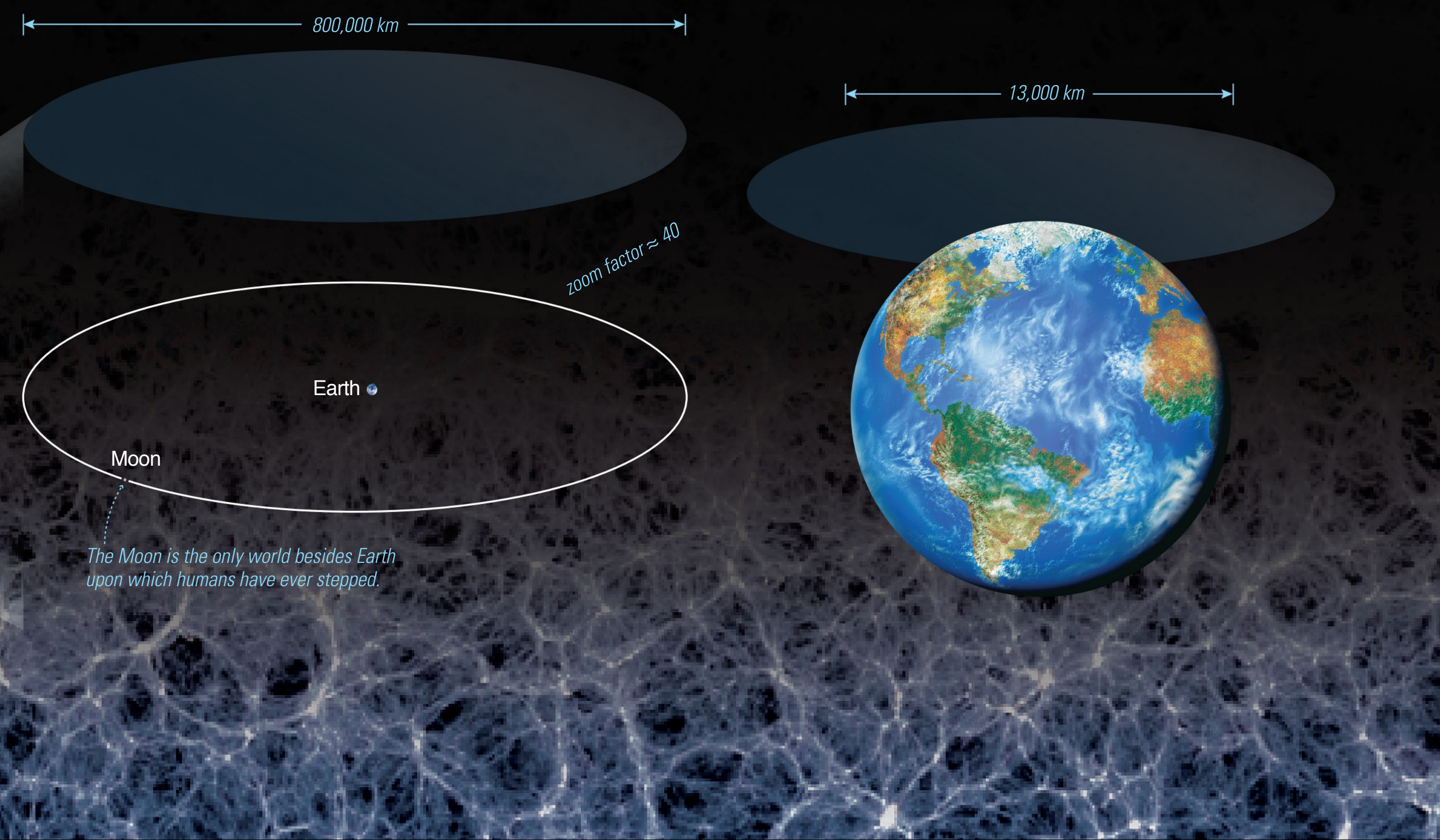
One light-year becomes 1000 kilometers on the Voyage scale, so even the nearest stars are more than 4000 kilometers away, equivalent to the distance across the United States.

The Earth–Moon System

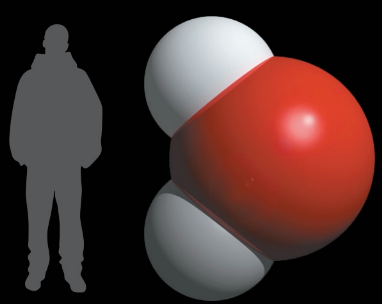
This diagram shows Earth, the Moon, and the Moon's orbit to scale. We must magnify the image of our solar system another 10,000 times to get a clear view of our home planet and its constant companion, our Moon.

Earth

You are here. The physical sizes of human beings and even the planet on which we live are almost unimaginably small compared to the vastness of space. Yet in spite of this fact, we have managed to measure the size of the observable universe and to discover how our lives are related to the stars.



A water molecule is a million times smaller than a grain of sand. On the 1-to-10 billion scale, *you* would be slightly smaller than a water molecule.



These comparisons show how tiny we are compared to the solar system in which we live, but we've only just begun to cover the range of scales in the universe.

- To appreciate the size of our galaxy, consider that the stars on this scale are like grapefruits thousands of kilometers apart, yet there are so many that it would take you thousands of years to count them one-by-one.
- And with more than 100 billion galaxies, the observable universe contains a total number of stars comparable to the number of grains of dry sand on *all the beaches on Earth* combined.

This photo of the Hubble Ultra Deep Field shows galaxies visible in a patch of sky that you could cover with a grain of sand held at arm's length.

You Are Here in Time

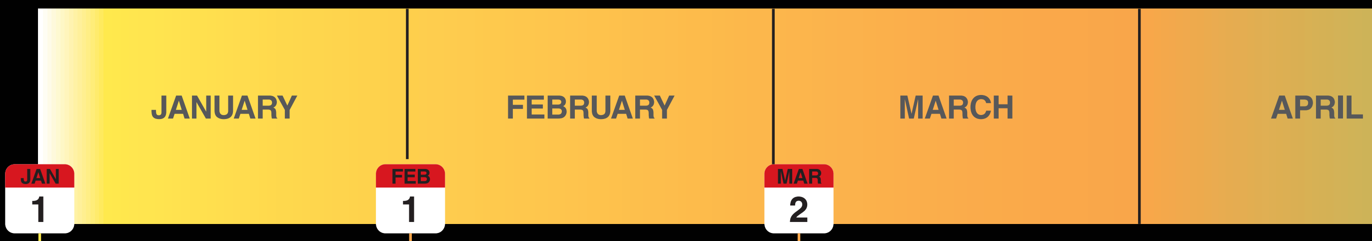
How does your life fit into the scale of time? We can gain perspective on this question with a *cosmic calendar* on which the 14-billion-year history of the universe is scaled down using a single calendar year. The Big Bang occurs at the stroke of midnight on January 1, and the present is the last instant of December 31.

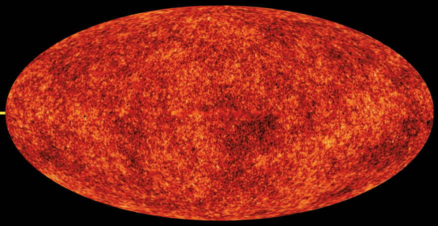
The Early Universe

Observations indicate that the universe began about 14 billion years ago in what we call the *Big Bang*. All matter and energy in the universe came into being at that time. The expansion of the universe also began at that time, and continues to this day.

Galaxy Formation

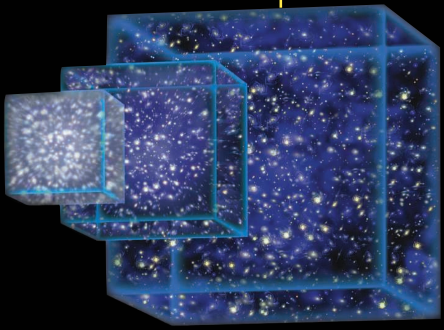
Galaxies like our Milky Way gradually grew over the next few billion years. Small collections of stars and gas formed first, and these smaller objects merged to form larger galaxies.



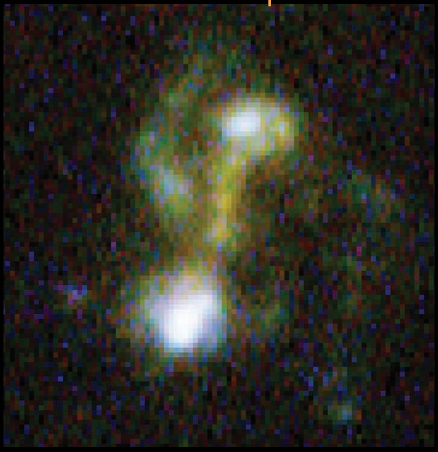


This image shows the cosmic microwave background, which comes to us from all directions in space and represents radiation leftover from the Big Bang—January 1 on the cosmic calendar.

Globular clusters containing up to a million stars were among the first objects to form in the universe. This cluster (M80) formed more than 12 billion years ago, about February 1 on the cosmic calendar.



These cubes represent the first billion years of expansion for a small portion of the universe. During this time, gravity began to clump matter into stars and galaxies. The universe is still expanding today and continues to form new stars.

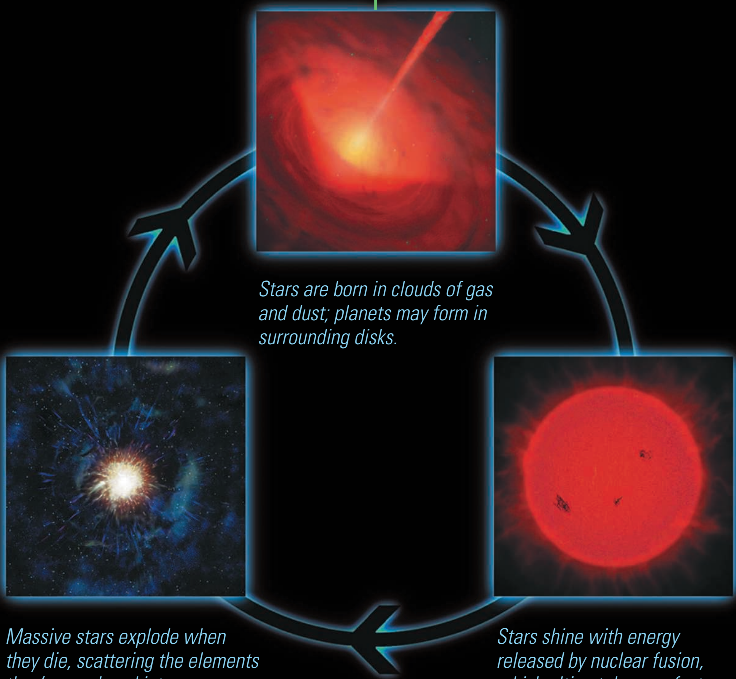


Many young galaxies grew by colliding and merging with other galaxies. This image shows a collision that occurred about 11.4 billion years ago, around March 2 on the cosmic calendar, but the collision is so far away that the light from it is just reaching us now.

Element Production by Stars

The early universe contained just three chemical elements: hydrogen, helium, and a tiny amount of lithium. Essentially all of the other elements were manufactured by nuclear fusion in stars, or by the explosions that end stellar lives. The elements that now make up Earth — and life — were created by stars that lived before our solar system was born.

MAY | JUNE | JULY | AUGUST

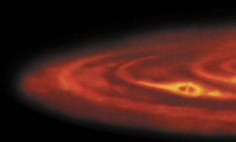


Stars are born in clouds of gas and dust; planets may form in surrounding disks.

Stars shine with energy released by nuclear fusion, which ultimately manufactures all elements heavier than hydrogen and helium.

Massive stars explode when they die, scattering the elements they've produced into space.

Each new generation of stars is born from gas that has been recycled and enriched with new elements from prior generations of stars. This cycle started with the first generation of stars and continues to this day.



This illustration shows what t
the Sun and planets finished

Birth of Our Solar System

Our solar system was born from the gravitational collapse of an interstellar cloud of gas about $4\frac{1}{2}$ billion years ago, or about September 3 on the cosmic calendar. The Sun formed at the center of the cloud while the planets, including Earth, formed in a disk surrounding it.

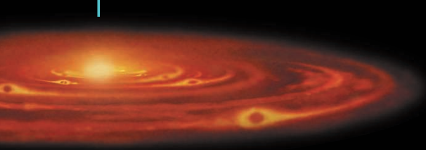
Life on Earth

We do not know exactly when life arose on Earth, but fossil evidence indicates that it was within a few hundred million years after Earth's formation. Nearly three billion more years passed before complex plant and animal life evolved.

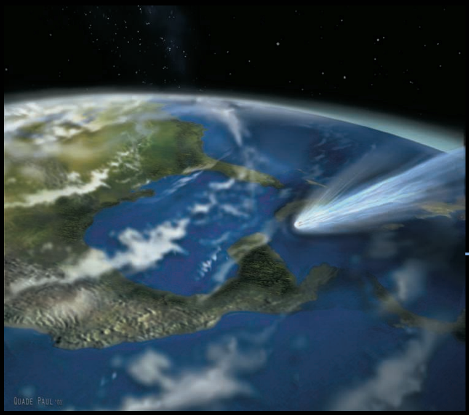
This rock formation in West Greenland holds the oldest known evidence of life on Earth, dating to more than 3.85 billion years ago, or September 22 on the cosmic calendar.

Fossil evidence shows a remarkable increase in animal diversity beginning about 540 million years ago — December 17 on the cosmic calendar. We call this the Cambrian explosion.

Dinosaurs arose about 225 million years ago — December 26 on the cosmic calendar. Mammals arose around the same time.



he solar system may have looked like shortly before forming.



Dinosaurs went extinct, probably due to an asteroid or comet impact, about 65 million years ago, which was only yesterday (December 30) on the cosmic calendar.

Human History

On the cosmic calendar, our hominid ancestors arose only a few hours ago, and all of recorded human history has occurred in just the last 15 seconds before midnight.

You

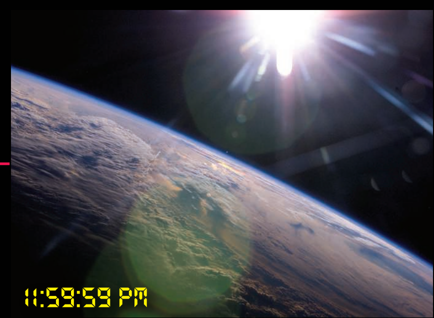
The average human life span is only about two-tenths of a second on the cosmic calendar.

Our early ancestors had smaller brains, but probably were walking upright by about 5 million years ago—December 31, 9 PM on the cosmic calendar.

Modern humans arose about 40,000 years ago, which is only about two minutes ago (December 31, 11:58 PM) on the cosmic calendar.

On the cosmic calendar, our ancestors began to master agriculture only 25 seconds ago ...

...the Egyptians built the pyramids only 11 seconds ago ...

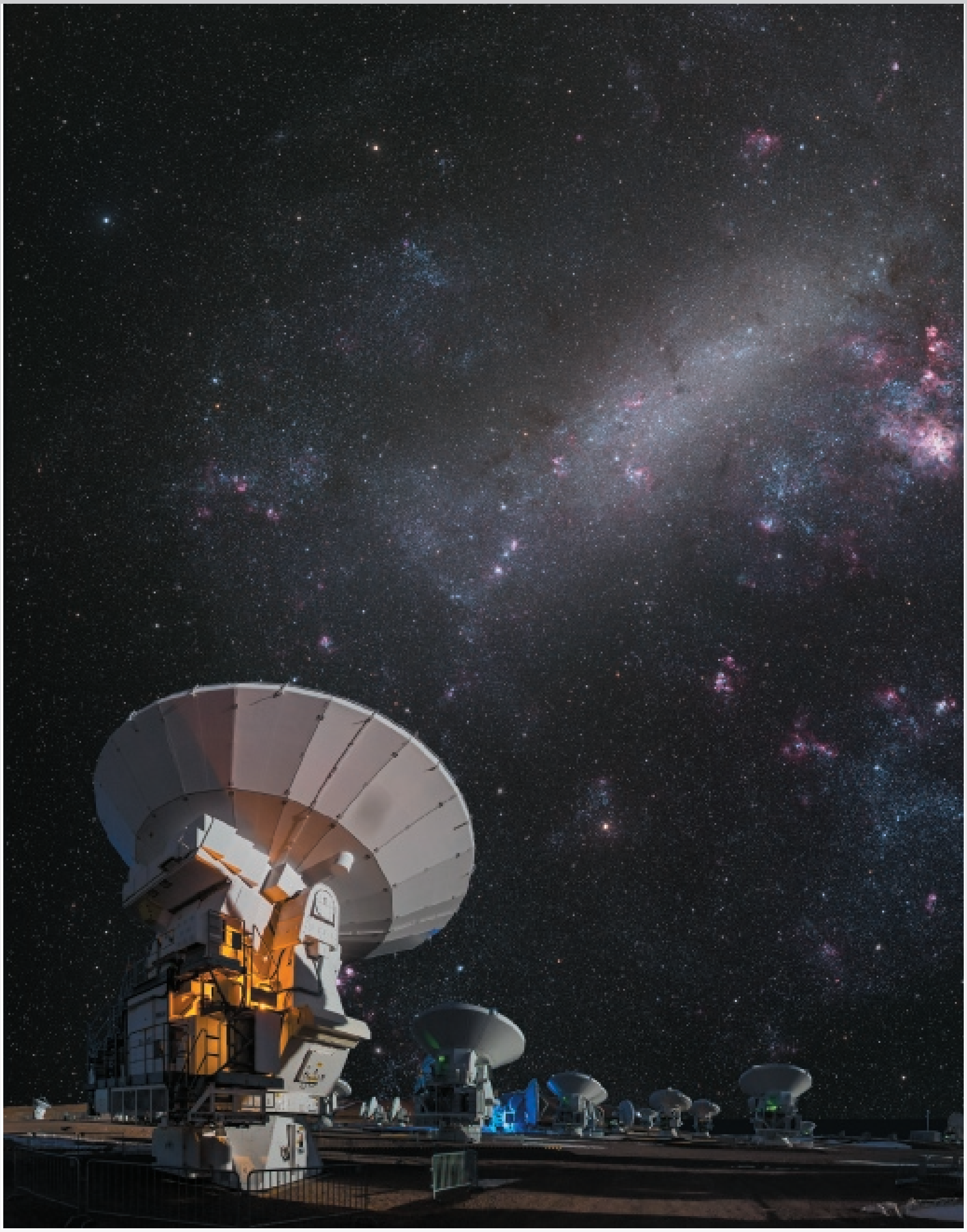


...we learned that Earth is a planet orbiting the Sun only 1 second ago ...

11:59:59.95 PM

...and a typical college student was born only 0.05 second ago.

THE COSMIC PERSPECTIVE



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

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EIGHTH EDITION

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DEDICATION

To all who have ever wondered about the mysteries of the universe. We hope this book will answer some of your questions—and that it will also raise new questions in your mind that will keep you curious and interested in the ongoing human adventure of astronomy. And, especially, to Michaela, Emily, Sebastian, Grant, Nathan, Brooke, and Angela. The study of the universe begins at birth, and we hope that you will grow up in a world with far less poverty, hatred, and war so that all people will have the opportunity to contemplate the mysteries of the universe into which they are born.

Brief Contents

Detailed Contents

PART II
KEY CONCEPTS FOR ASTRONOMY

PART III
LEARNING FROM OTHER WORLDS

PART IV
A DEEPER LOOK AT NATURE

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 of ourselves and our planet.

This book grew out of our experience teaching astronomy to both college students and the general public over more than 30 years. During this time, a flood of new discoveries fueled a revolution in our understanding of the cosmos but had little impact on the basic organization and approach of most astronomy textbooks. We felt the time had come to rethink how to organize and teach the major concepts in astronomy to reflect this revolution in scientific understanding. This book is the result.

Who Is This Book For?

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

The Cosmic Perspective provides a comprehensive survey of modern astronomy, and it contains enough material for a two-semester introductory astronomy sequence. It may also be used for one-semester survey courses if professors choose their areas of emphasis. However, instructors of one-term courses may also wish to consider our two shorter versions of this book: *The Essential Cosmic Perspective*, which covers a smaller set of topics and is tailored to meet the needs of comprehensive one-semester survey courses in astronomy, and *The Cosmic Perspective Fundamentals*, which covers only the most fundamental topics in astronomy and is designed for courses that address a more limited set of topics.

New to This Edition

The underlying philosophy, goals, and structure of *The 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 eighth 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 made a number of small changes to make sure the discussion works for students in the Southern Hemisphere in addition to working for those in the Northern Hemisphere.
  - In **Chapter 3**, we have enhanced the discussion of the nature of science with the new Table 3.2, which summarizes how the same terms often have different meanings in science than in everyday usage.
  - **Chapters 9 and 10** have been significantly rewritten to reflect new results from *MESSENGER* at Mercury, *Curiosity* and *MAVEN* at Mars, and the latest data on global warming.
  - **Chapter 12** has been significantly reorganized and rewritten to reflect recent developments in the study of small bodies, particularly the revolutionary new views provided by recent spacecraft including *Dawn*, *Rosetta*, and *New Horizons*.
  - **Chapter 13** has been heavily revised in light of thousands of new discoveries of extrasolar planets since the prior edition.
  - In **Chapter 14**, we have updated the discussion of solar neutrinos and reorganized Section 14.3 into two (rather than the former three) learning goals.
  - In **Chapter 18**, we have almost completely rewritten Section 18.4 to focus on events in which black holes can form and neutron stars merge.
  - **Chapter 19** has been revised to reduce jargon and to include a new full-page figure showing the Milky Way in different wavelengths. In addition, Section 19.4 on the galactic center has been rewritten and features a new two-page Cosmic Context spread.
  - **Chapters 20 and 21** have been significantly revised in light of new research into galactic evolution, some of which is based on the work of two of the authors of this book (Donahue and Voit).
  - **Chapter 23** has been updated to reflect the latest results about dark energy and the expansion of the universe.
  - **Chapter 24** has been significantly rewritten, particularly Sections 24.2 and 24.3 (which has also been completely reorganized), thanks to new understanding of the potential habitability of Mars, Titan, and extrasolar planets.
- **Fully Updated Science:** Astronomy is a fast-moving field, and numerous new developments have occurred since the prior edition was published. In addition to the major chapter-level changes above, other scientific updates in this edition include

- New results and images from spacecraft exploring our solar system, including *Curiosity* and *MAVEN* at Mars, *Cassini* at Saturn, *MESSENGER* at Mercury, *Dawn* at Ceres, *New Horizons* at Pluto, and more
- Recent results from major space observatories, including Hubble and Kepler, and from powerful ground-based observatories such as ALMA
- Updated data and models on topics including the formation of planetary systems, global warming, and galaxy formation and evolution
- Major new discoveries and statistics relating to the study of extrasolar planets, new research on the timing and possible origin of life on Earth, and much more

- **New Feature — *Extraordinary Claims* boxes:** Carl Sagan made famous the statement "extraordinary claims require extraordinary evidence." With this new feature, we provide students with examples of extraordinary claims about the universe and how they were either supported or debunked as scientists collected more evidence. The first of these features appears in Chapter 3, where the context of Sagan's dictum is also explained. Another nine Extraordinary Claims boxes are sprinkled throughout the rest of the text.
- **New Content in MasteringAstronomy®**: *The Cosmic Perspective* is no longer just a textbook; rather, it is a "learning package" that combines a printed book with deeply integrated, interactive media developed to support every chapter of our book. For students, the MasteringAstronomy Study Area provides a wealth of tutorials and activities to build understanding, while quizzes and exercises allow them to test what they've learned. For instructors, the MasteringAstronomy Item Library provides the unprecedented ability to quickly build, post, and automatically grade pre- and post-lecture diagnostic tests, weekly homework assignments, and exams of appropriate difficulty, duration, and content coverage. It also provides the ability to record detailed information on the step-by-step work of every student directly into a powerful and easy-to-use gradebook, and to evaluate results with a sophisticated suite of diagnostics. Among the changes you'll find to the MasteringAstronomy site for this edition are numerous new and revised interactive figures, including many narrated video tours; numerous new tutorials in the Item Library; and a fully updated set of reading, concept, and visual quizzes in both the Study Area and the Item Library.

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

- *Theme 1: We are a part of the universe and thus can learn about our origins by studying the universe*. This is the overarching theme of *The 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 still change in the future.
- *Theme 4: A course in astronomy is the beginning of a lifelong learning experience*. Building upon the prior themes, we emphasize that what students learn in their astronomy course is not an end but a beginning. By remembering a few key physical principles and understanding the nature of science, students can follow astronomical developments for the rest of their lives. We therefore seek to motivate students enough that they will continue to participate in the ongoing human adventure of astronomical discovery.
- *Theme 5: Astronomy affects each of us personally with the new perspectives it offers*. We all conduct the daily business of our lives with reference to some "world view"—a set of personal beliefs about our place and purpose in the universe that we have developed through a combination of schooling, religious training, and personal thought. This world view shapes our beliefs and many of our actions.

Although astronomy does not mandate a particular set of beliefs, it does provide perspectives on the architecture of the universe that can influence how we view ourselves and our world, 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 be to represent the deepest connection between the universe and the everyday lives of humans.

Pedagogical Principles of *The Cosmic Perspective*

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

- *Stay focused on the big picture*. Astronomy is filled with interesting facts and details, but they are meaningless unless they fit into a big picture view of the universe. We therefore take care to stay focused on the big picture (essentially the themes discussed above) at all times. A major benefit of this approach is that although students may forget individual facts and details after the course is over, the big picture framework should stay with them for life.
- *Always provide context first*. We all learn new material more easily when we understand why we are learning it. 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 can 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 that we use over and over again. For example, the laws of conservation of energy and conservation of angular momentum (introduced in Section 4.3) reappear throughout the book, and we find that the wide variety of features found on the terrestrial planets can be understood through just a few basic geological processes. Research shows that, long after the course is over, students are far more likely to retain such conceptual 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 as much as possible or, at minimum, to replace standard jargon with terms that are easier to remember in the context of the subject matter.
- *Recognize and address student misconceptions*. Students do not arrive as blank slates. Most students enter our courses not only lacking the knowledge we hope to teach but often holding misconceptions about astronomical ideas. Therefore, to teach correct ideas, we must also help students recognize the paradoxes in their prior misconceptions. We address this issue in a number of ways, the most obvious being the presence of many Common Misconceptions boxes. These summarize commonly held misconceptions and explain why they cannot be correct.

The Topical (Part) Structure of *The Cosmic Perspective*

The Cosmic Perspective is organized into seven broad topical areas (the seven Parts in the table of contents), each approached in a distinctive way designed to help maintain the focus on the themes discussed earlier. Here, we summarize the guiding philosophy through which we have approached each topic. Every Part concludes with one of our two-page Cosmic Context spreads, which tie together into a coherent whole the diverse ideas covered in the individual chapters.

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 basic goal of these chapters is to give students a big picture overview and context for the rest of the book, and to help them develop an appreciation for the process of science and how science has developed through history. Chapter 1 outlines our modern understanding of the cosmos, 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.

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

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

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

These chapters lay the groundwork for understanding astronomy through what is sometimes called the "universality of physics"—the idea that a few key principles governing matter, energy, light, and motion explain both the phenomena of our daily lives and the mysteries of the cosmos. 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 covers the nature of light and matter, the formation of spectra, and the Doppler effect. Chapter 6 covers telescopes and astronomical observing techniques.

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

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.

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 covers 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 a discussion of how seriously we should take the ongoing impact threat. Finally, Chapter 13 turns to the exciting topic of other planetary systems that have been discovered in recent years. Note that Part III is essentially independent of Parts IV through VII, and can be covered either before or after them.

The *Cosmic Context* figure for Part III appears on pp. 398–399.

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

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

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. 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 covered without having covered Part IV at all.

The *Cosmic Context* figure for Part IV appears on pp. 464–465.

Part V: Stars (Chapters 14–18)

Guiding Philosophy: We are intimately connected to the stars.

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

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

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

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

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 presents 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.

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

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.

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.

The *Cosmic Context* figure for Part VII appears on pp. 726–727.

Pedagogical Features of *The Cosmic Perspective*

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

- **Basic Chapter Structure:** Each chapter is carefully structured to ensure that students understand the goals up front, learn the details, and pull together all the ideas at the end. In particular, note the following key structural elements:
  - **Chapter Learning Goals:** Each chapter opens with a page offering an enticing image and a brief overview of the chapter, including a list of the section titles and associated learning goals. The learning goals are presented as key questions designed to help students both 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've learned in the chapter into the context of the overall goal of gaining a broader perspective on ourselves, our planet, and prospects for life beyond Earth.
  - **Chapter Summary:** The end-of-chapter summary offers a concise review of the learning goal questions, helping reinforce student understanding of key concepts from the chapter. Thumbnail figures are included to remind students of key illustrations and photos in the chapter.
- **End-of-Chapter Exercises:** Each chapter includes an extensive set of exercises that can be used for study, discussion, or assignment. All of the end-of-chapter exercises are organized into the following subsets:
  - **Visual Skills Check:** A set of questions designed to help students build their skills at interpreting the many types of visual information used in astronomy
  - **Review Questions:** Questions that students should be able to answer from the reading alone
  - **Does It Make Sense?** (or similar title): A set of short statements that students are expected to evaluate, determining whether each statement makes sense and explaining why or why not. These exercises are generally easy once students understand a particular concept, but very difficult otherwise; thus, they are an excellent probe of comprehension.
  - **Quick Quiz:** A short multiple-choice quiz that allows students to check their progress
  - **Process of Science Questions:** Essay or discussion questions that help students focus on how science progresses over time
  - **Group Work Exercise:** A suggested activity designed for collaborative learning in class
  - **Short-Answer/Essay Questions:** Questions that go beyond the Review Questions in asking for conceptual interpretation
  - **Quantitative Problems:** Problems that require some mathematics, usually based on topics covered in the Mathematical Insight boxes
  - **Discussion Questions:** Open-ended questions for class discussions
  - **Web Projects:** A few suggestions for additional web-based research

- **Additional Features:** You'll find a number of other features designed to increase student understanding, both within individual chapters and at the end of the book, including the following:
  - **Annotated Figures:** Key figures in each chapter use the research-proven technique of annotation—the placement on the figure of carefully crafted text (in blue) to guide students through interpreting graphs, following process figures, and translating between different representations.
  - **Cosmic Context Two-Page Figures:** These two-page spreads provide visual summaries of key processes and concepts.
  - **Wavelength/Observatory Icons:** For astronomical images, simple icons indicate whether the image is a photo, artist's impression, or computer simulation; whether a photo came from ground-based or space-based observations; and the wavelength band used to take the photo.
  - **MasteringAstronomy® Resources:** Specific resources from the MasteringAstronomy site, such as Interactive Figures or Photos and Self-Guided Tutorials, are referenced alongside specific figure and section titles to direct students to help when they need it.
  - **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.
  - **Cross-References:** When a concept is covered in greater detail elsewhere in the book, we include a cross-reference in brackets to the relevant section (e.g., [**Section 5.2**]).
  - **Glossary:** A detailed glossary makes it easy for students to look up important terms.
  - **Appendixes:** The appendixes contain a number of useful references and tables including key constants (Appendix A), key formulas (Appendix B), key mathematical skills (Appendix C), and numerous data tables and star charts (Appendixes D–I).

MasteringAstronomy®

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

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

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

- MasteringAstronomy specifically supports the structure and pedagogy of *The Cosmic Perspective*. You'll find the same concepts emphasized in the book and on the website, using the same terminology and the same pedagogical approaches. This type of consistency will ensure that students focus on the concepts, without the risk of becoming confused by different presentations.

- Nearly all MasteringAstronomy content has been developed either directly by *The Cosmic Perspective* author team or by this author team in close collaboration with outstanding educators including Jim Dove, Jim Cooney, Jonathan Williams, Richard Gelderman, Lauren Jones, Ed Prather, Tim Slater, and Daniel Loranz. The direct involvement of *The Cosmic Perspective* authors ensures that you can expect the same high level of quality in our website that you have come to expect in our textbook.
- The MasteringAstronomy platform uses the same unique student-driven engine as the highly successful MasteringPhysics® product (the most widely adopted physics homework and tutorial system), developed by a group led by MIT physicist David Pritchard. This robust platform gives instructors unprecedented power not only to tailor content to their own courses but also to evaluate the effectiveness of assignments and exams.

Additional Supplements for *The 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 MasteringAstronomy (described above), the following supplements are available with this book:

- ***SkyGazer 5.0*** (Access code card ISBN 0-321-76518-4, CD ISBN 0-321-89843-5). 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. Ask your Pearson sales representative for details.
- ***Starry Night™ College*** (ISBN 0-321-71295-1). 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 MasteringAstronomy Study Area or with a Starry Night College access code. Ask your Pearson sales representative for details.
- ***Astronomy Active Learning In-Class Tutorials*** (ISBN 0-805-38296-8) by Marvin L. De Jong. 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. These 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*** (0-321-82046-0), by Ed Prather, Tim Slater, Jeff Adams, and Gina Brissenden. These forty-four lecture tutorials are designed to engage students in critical reasoning and spark classroom discussion.
- ***Sky and Telescope: Special Student Supplement*** (0-321-70620-X). 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. Ask your Pearson sales representative for details.
- ***Observation Exercises in Astronomy*** (ISBN 0-321-63812-3). This workbook by Lauren Jones includes fifteen observation activities that can be used with a number of different planetarium software packages.
- ***Astronomy Lab: A Concept Oriented Approach*** (0-321-86177-9) by Nate McCrady and Emily Rice. This modular collection of 40 conceptually oriented introductory astronomy labs, housed in the Pearson Custom Library, allows for easy creation of a customized lab manual.

Instructor-Only Supplements

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

- ***Instructor Resource DVD*** (ISBN 0-134-07427-0). 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 MasteringAstronomy for easy use.
- ***Clickers in the Astronomy Classroom*** (ISBN 0-805-39616-0). This 100-page handbook by Douglas Duncan provides everything you need to know to successfully introduce or enhance your use of CRS (clicker) quizzing in your astronomy class—the research-proven benefits, common pitfalls to avoid, and a wealth of thought-provoking astronomy questions for every week of your course.
- ***Instructor Guide*** (ISBN 0-134-16031-2). 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 0-134-08056-4). Available in both Word and TestGen formats on the Instructor Resource Center and MasteringAstronomy, 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 MasteringAstronomy.

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Geoff Marcy, *University of California, Berkeley, and San Francisco State University*
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Francis Nimmo, *University of California, Santa Cruz*
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Bob Pappalardo, *Jet Propulsion Laboratory*
Bennett Seidenstein, *Arundel High School*
Michael Shara, *American Museum of Natural History*
Evan Skillman, *University of Minnesota*
Brad Snowder, *Western Washington University*
Bob Stein, *Michigan State University*
Glen Stewart, *University of Colorado*
John Stolar, *West Chester University*
Jeff Taylor, *University of Hawaii*
Dave Tholen, *University of Hawaii*
Nick Thomas, *University of Bern*
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Jeff Bennett
Megan Donahue
Nick Schneider
Mark Voit

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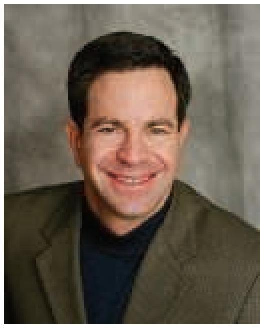

Jeffrey Bennett

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, and proposing and helping to develop the Voyage scale model solar system on the National Mall (Washington, DC). He is the lead author of textbooks in astronomy, astrobiology, mathematics, and statistics, and of critically acclaimed books for the public including *Beyond UFOs* (Princeton University Press, 2008/2011), *Math for Life* (Bid Kid Science, 2014), *What Is Relativity?* (Columbia University Press, 2014), and *On Teaching Science* (Big Kid Science, 2014). He is also the author of six science picture books for children, including *Max Goes to the Moon*, *The Wizard Who Saved the World*, and *I, Humanity*; all six have been launched to the International Space Station and read aloud by astronauts for NASA's Story Time From Space program. Dr. Bennett lives in Boulder, CO with his wife, children, and dog. His personal website is www.jeffreybennett.com.

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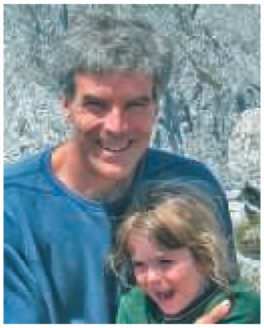
Megan Donahue is a full professor in the Department of Physics and Astronomy at Michigan State University (MSU) and a Fellow of the American Association for the Advancement of Science. Her current research is mainly about using X-ray, UV, infrared, and visible light to study galaxies and clusters of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

Nicholas Schneider

Nicholas Schneider is an associate professor in the Department of Astrophysical and Planetary Sciences at the University of Colorado and a researcher in the Laboratory for Atmospheric and Space Physics. He received his B.A. in physics and astronomy from Dartmouth College in 1979 and his Ph.D. in planetary science from the University of Arizona in 1988. In 1991, he received the National Science Foundation's Presidential Young Investigator Award. His research interests include planetary atmospheres and planetary astronomy. One research focus is the odd case of Jupiter's moon Io. Another is the mystery of Mars's lost atmosphere, which he hopes to answer by leading the Imaging UV Spectrograph team on NASA's *MAVEN* mission now orbiting Mars. Nick enjoys teaching at all levels and is active in efforts to improve undergraduate astronomy education. In 2010 he received the Boulder Faculty Assembly's Teaching Excellence Award. Off the job, Nick enjoys exploring the outdoors with his family and figuring out how things work.



Mark Voit

Mark Voit is a 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 while you attend school, you will need to budget your time carefully.

As a rough guideline, your study time might be divided as shown in the table above. If you find that you are spending fewer hours than these guidelines suggest, you can probably improve your grade by studying longer. If you are spending more hours than these guidelines suggest, you may be studying inefficiently; in that case, you should talk to your instructor about how to study more effectively.

Using This Book

Each chapter in this book is designed to 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.
- Visit the MasteringAstronomy® site and make use of resources that will help you further build your understanding. These resources have been developed specifically to help you learn the most important ideas in your course, and they have been extensively tested to make sure they are effective. They really do work, and the only way you'll gain their benefits is by going to the website and using them.

General Strategies for Studying

- Budget your time effectively. Studying 1 or 2 hours each day is more effective, and far less painful, than studying all night before homework is due or before exams.
- Engage your brain. Learning is an active process, not a passive experience. Whether you are reading, listening to a lecture, or working on assignments, always make sure that your mind is actively engaged. If you find your mind drifting or find yourself falling asleep, make a conscious effort to revive yourself, or take a break if necessary.
- Don't miss class. Listening to lectures and participating in discussions is much more effective than reading someone else's notes. 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 help reinforce key ideas from the reading.

- Take advantage of resources offered by your professor, whether it be email, office hours, review sessions, online chats, or other opportunities to talk to and get to know your professor. Most professors will go out of their way to help you learn in any way that they can.
- Start your homework early. The more time you allow yourself, the easier it is to get help if you need it. If a concept gives you trouble, do additional reading or studying beyond what has been assigned. And if you still have trouble, ask for help: You surely can find friends, peers, or teachers who will be glad to help you learn.
- Working together with friends can be valuable in helping you understand difficult concepts, but be sure that you learn *with* your friends and do not become dependent on them.
- Don't try to multitask. A large body of 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, the same research found that those people who believed they were best at multitasking were actually the worst! So when it is time to study, turn off your electronic devices, find a quiet spot, and concentrate on focusing your efforts.

Preparing for Exams

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

Presenting Homework and Writing Assignments

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

1. The effort you expend in clearly explaining your work solidifies your learning. In particular, research has shown that writing and speaking trigger different areas of your brain. Writing something down—even when you think you already understand it—reinforces your learning by involving other areas of your brain.
2. If you make your work clear and self-contained (that is, make it a document that you can read without referring to the questions in the text), you will have a much more useful study guide when you review for a quiz or exam.

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

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

Foreword

The Meaning of *The Cosmic Perspective*

by Neil deGrasse Tyson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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

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?

▲ **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 at arm's length.

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

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.

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. These ideas 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 many of these stars are orbited by planets. Our solar system is located a little over halfway from the galactic center to the edge of the galactic disk.

Billions of other galaxies are scattered throughout space. Some galaxies are fairly isolated, but most are found in groups. Our Milky Way, for example, is one of the two largest among more than 70 galaxies, most relatively small, that make up 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 (which was recently named *Laniakea*, Hawaiian for "immense heaven").

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

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

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

- One **astronomical unit (AU)** is Earth's average distance from the Sun, which is about 150 million kilometers (93 million miles). We commonly describe distances within our solar system in AU.
- One **light-year (ly)** is the distance that light can travel in 1 year, which is about 10 trillion kilometers (6 trillion miles). We generally use light-years to describe the distances of stars and galaxies.

Be sure to note that a light-year is a unit of *distance*, not of time. Light travels at the speed of light, which is

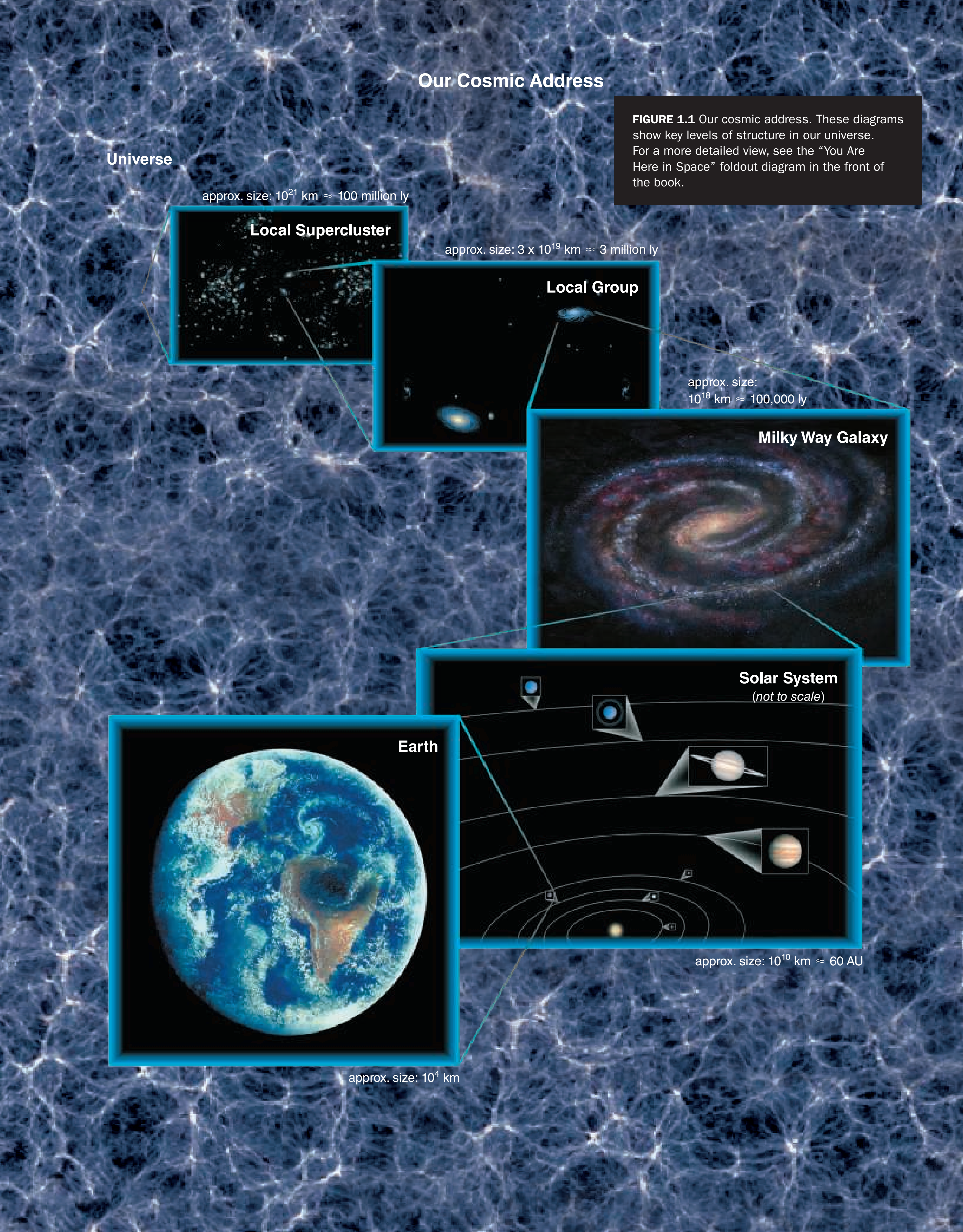


FIGURE 1.1 Our cosmic address. These diagrams show key levels of structure in our universe. For a more detailed view, see the “You Are Here in Space” foldout diagram in the front of the book.

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 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.

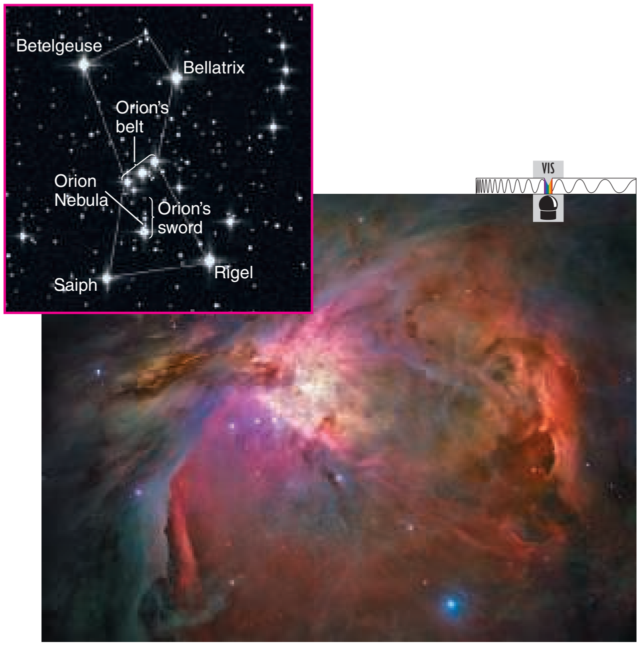


FIGURE 1.2 The Orion Nebula, located about 1350 light-years away. The inset shows its location in the constellation Orion.

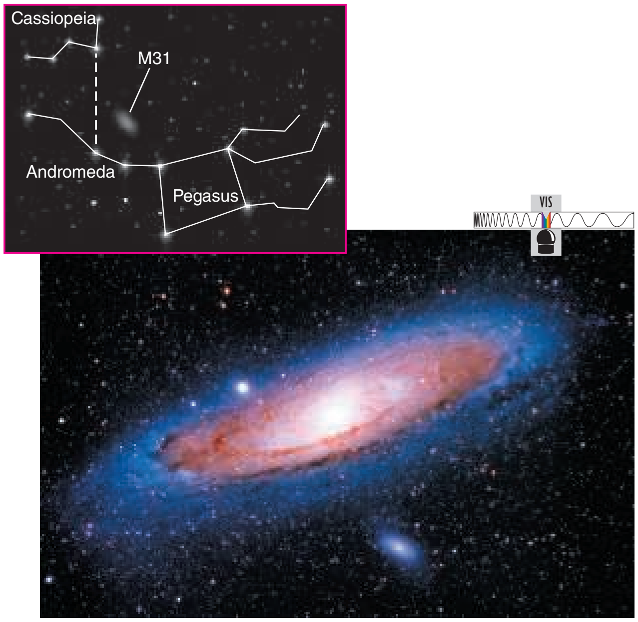


FIGURE 1.3 interactive figure The Andromeda Galaxy (M31). When we look at this galaxy, we see light that has been traveling through space for 2.5 million years.

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 see in Chapter 20, distances to faraway galaxies must be defined carefully in an expanding universe; distances like those given here are based on the time it has taken a galaxy's light to reach us (called the *lookback time*).

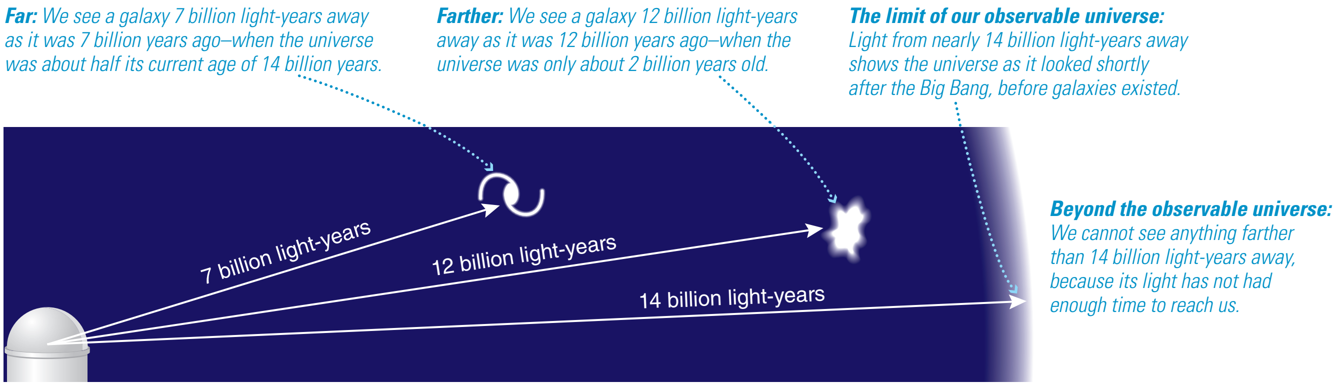


FIGURE 1.4 interactive figure The farther away we look in space, the further back we look in time. The age of the universe therefore puts a limit on the size of the *observable* universe—the portion of the entire universe that we can observe, at least in principle.

COMMON MISCONCEPTIONS

The Meaning of a Light-Year

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

MA Scale of the Universe Tutorial, Lessons 1–3

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 the Sun and planets, and the distances between them, at *one ten-billionth* of their actual sizes and distances.

FIGURE 1.6a shows the Sun and planets at their correct sizes (but not distances) on the Voyage scale. The model Sun is about the size of a large grapefruit, Jupiter is about the size of a marble, and Earth is about the size of the 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 (16.5 yards) from the grapefruit-size Sun, which means you can picture Earth's orbit as a circle of radius 15 meters around a grapefruit.

Perhaps the most striking feature of our solar system when we view it to scale is its emptiness. The Voyage model shows the planets along a straight path, so we'd need to draw each planet's orbit around the model Sun to show the full extent of our planetary system. Fitting all these orbits would require an area measuring more than a kilometer on a side—an area equivalent to more than 300 football fields

MATHEMATICAL INSIGHT 1.1

MA Math Review Video: 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:

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

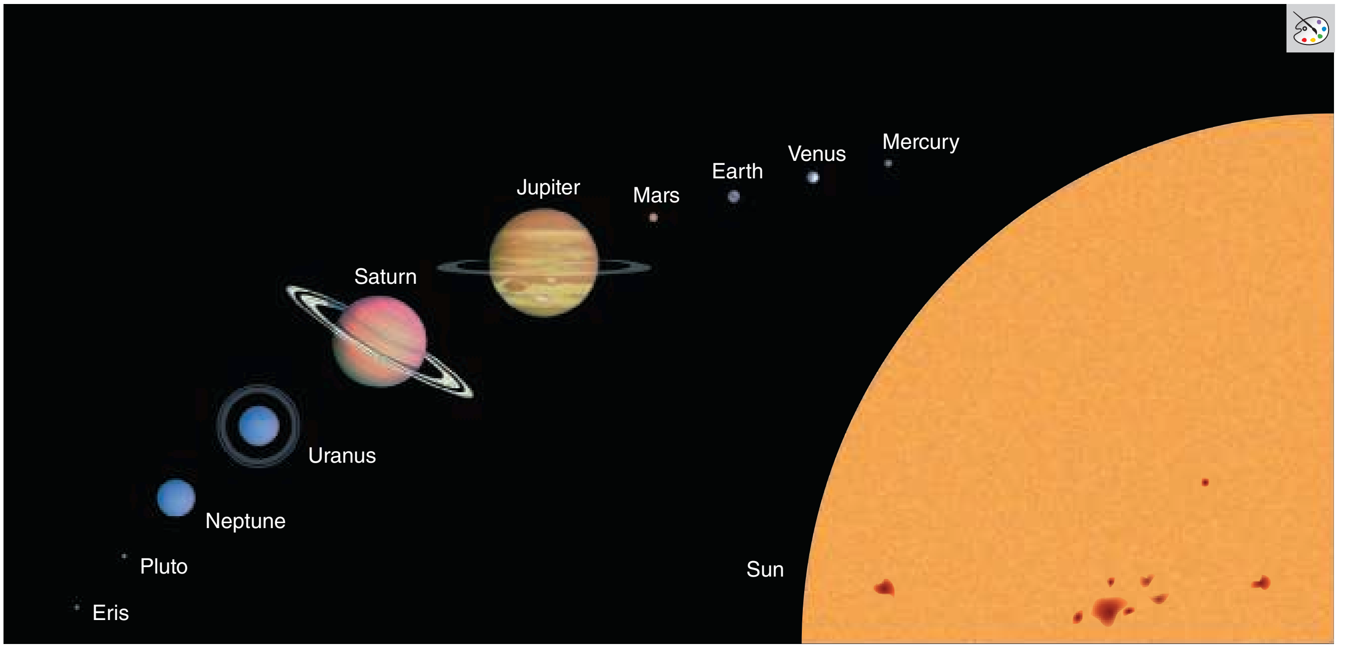
Step 3 Explain your result: In sentence form, our answer is "One light-year is about 9.46 trillion kilometers." This answer makes sense: It has the expected units of distance (kilometers) and it is a long way, which we expect for the distance that light can travel in a year. We say "about" in the answer 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. The building at the left is the National Air and Space Museum.

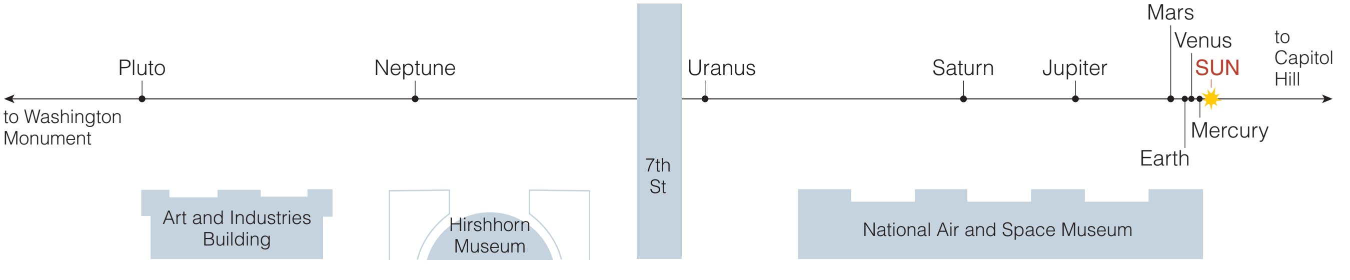
arranged in a grid. Spread over this large area, only the grapefruit-size Sun, the planets, and a few moons would be big enough to see. The rest of it would look virtually empty (that's why we call it *space!*).

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



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



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

FIGURE 1.6 interactive figure The Voyage scale model represents the solar system at *one ten-billionth* of its actual size. Pluto is included in the Voyage model for context.

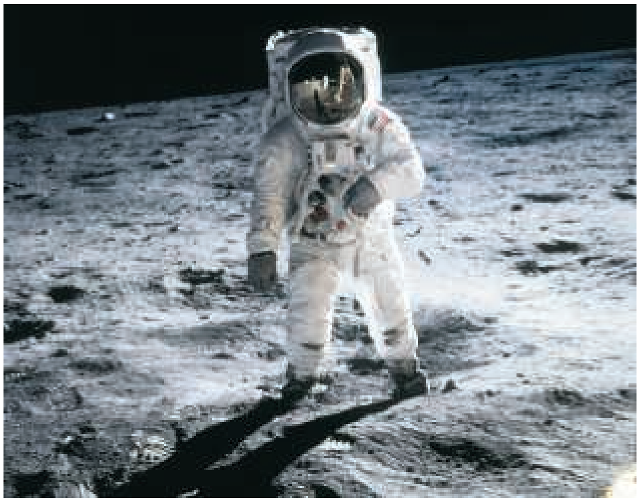


FIGURE 1.7 This famous photograph from the first Moon landing (*Apollo 11* in July 1969) shows astronaut Buzz Aldrin, with Neil Armstrong reflected in his visor. Armstrong was the first to step onto the Moon's surface, saying, "That's one small step for a man, one giant leap for mankind."

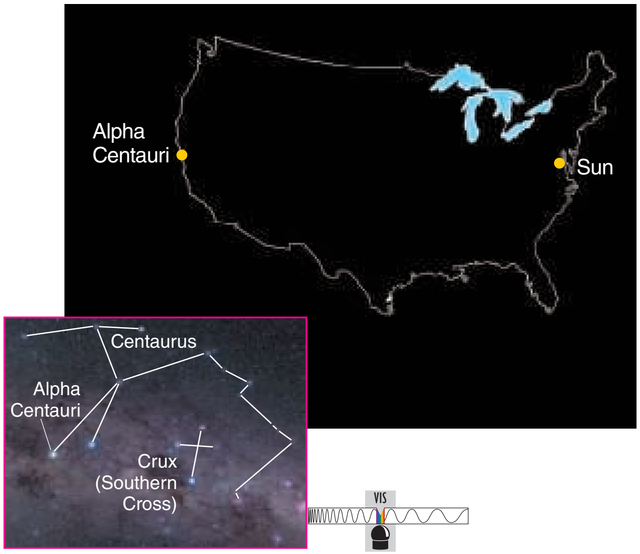


FIGURE 1.8 On the same 1-to-10 billion scale on which you can walk from the Sun to Pluto in just a few minutes, you'd need to cross the United States to reach Alpha Centauri, the nearest other star system. The inset shows the location and appearance of Alpha Centauri in the night sky.

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 $\div$ 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

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

Until recently, children were taught that our solar system had nine planets. However, in 2006 astronomers voted to demote Pluto to a *dwarf planet*, leaving our solar system with only eight official planets (**FIGURE 1**). Why the change?

When Pluto was discovered in 1930, it was assumed to be similar to other planets. But as we'll discuss in Chapter 12, we now know that Pluto is much smaller than any of the first eight planets and that it shares the outer solar system with thousands of other icy objects. Still, as long as Pluto was the largest known of these objects, most astronomers were content to leave the planetary status quo. Change was forced by the 2005 discovery of an object called Eris. Because Eris is slightly larger in mass than Pluto, astronomers could no longer avoid the question of what objects should count as planets.

Official decisions on astronomical names and definitions rest with the International Astronomical Union (IAU), an organization made up of professional astronomers from around the world. In 2006, an IAU vote defined "planet" in a way that left out Pluto and Eris (see Basic Astronomical Definitions on page 4), but added the "dwarf planet" category to accommodate them. Three smaller solar system objects are also now considered dwarf planets (the asteroid Ceres and the Kuiper belt objects Makemake and Haumea), and more than a half dozen other objects are still being studied to determine if they meet the dwarf planet definition.

Some astronomers still object to these definitions, which may yet be revisited. Pluto and other objects will remain the same either way. Indeed, in much the same way that we attempt to classify flowing waterways as creeks, streams, and rivers, this case offers a good example of the difference between the fuzzy boundaries of nature and the human preference for categories.

FIGURE 1 Notes left at the Voyage scale model solar system Pluto plaque upon Pluto's demotion to dwarf planet.

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**].

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

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

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

Another way to put the galaxy into perspective is to consider its number of stars—more than 100 billion.

MATHEMATICAL INSIGHT 1.2

MA Math Review Video: 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:

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

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 km $= 10^3$ m and 1 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:

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

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.