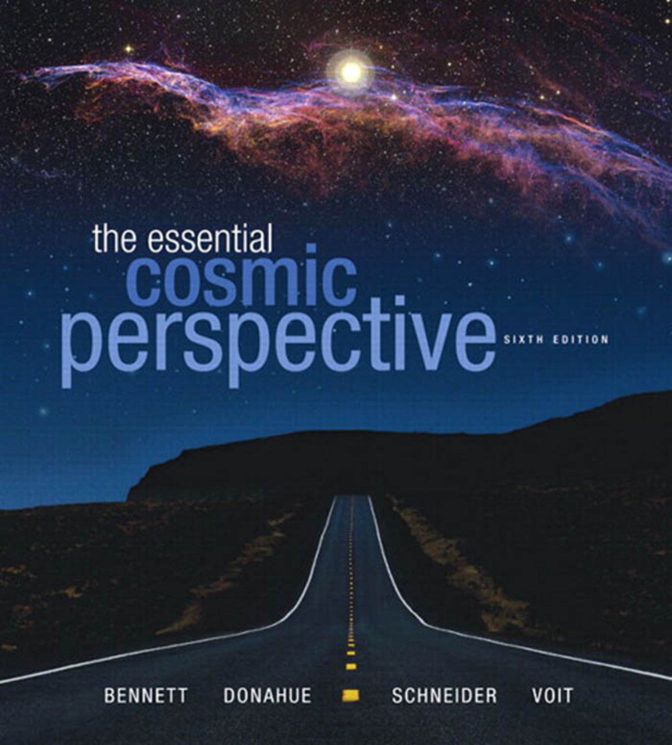

the essential cosmic perspective

SIXTH EDITION

BENNETT DONAHUE SCHNEIDER VOIT

the essential 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).

the essential cosmic perspective

SIXTH EDITION

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Addison-Wesley
Boston Columbus Indianapolis New York San Francisco Upper Saddle River
Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montréal Toronto
Delhi Mexico City São Paulo Sydney Hong Kong Seoul Singapore Taipei Tokyo

Publisher: James Smith
Executive Editor: Nancy Whilton
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Production Service: Lifland et al., Bookmakers
Composition: Progressive Information Technologies
Interior and Cover Design: Marilyn Perry
Photo Research: David Chavez
Illustrations: Dartmouth Publishing, Inc.
Manufacturing Buyer: Jeffrey Sargent
Manager, Rights and Permissions: Zina Arabia
Manager, Cover Visual Research & Permissions: Karen Sanatar
Image Permission Coordinator: Elaine Soares
Printer and Binder: Courier, Kendallville
Cover Printer: Lehigh-Phoenix Color
Cover Images: Deserted road with starry night sky, Credit: Steven Puetzer/Getty Images; NGC 6960: The Witch's Broom Nebula, T. A. Rector (U. Alaska), WIYN, NOAO, AURA, NSF

Library of Congress Cataloging-in-Publication Data

The essential cosmic perspective / Jeffrey Bennett ... [et al.]. -- 6th ed.
p. cm.
Includes index.
ISBN 978-0-321-71823-5
1. Astronomy--Textbook. I. Bennett, Jeffrey O.
QB43.3.E87 2012
520--dc22
2010037813

ISBN 10-digit 0-321-71823-2; 13-digit 978-0-321-71823-5 (Student edition)
ISBN 10-digit 0-321-73104-2; 13-digit 978-0-321-73104-3 (Exam copy)

Addison-Wesley
is an imprint of

PEARSON

www.pearsonhighered.com

1 2 3 4 5 6 7 8 9 10—CRK—16 15 14 13 12 11

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 III

Learning from Other Worlds

PART IV

Stars

Preface

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

This book grew out of our experience teaching astronomy to both college students and the general public over the past 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 Essential Cosmic Perspective is designed as a textbook for college courses in introductory astronomy, but is suitable for anyone who is curious about the universe. We assume no prior knowledge of astronomy or physics, and the book is especially written for students who do not intend to major in mathematics or science.

We have tailored *The Essential Cosmic Perspective* to one-semester survey courses in astronomy by carefully selecting the most important topics and presenting them with only as much depth as can be realistically learned in one semester. This book may also be used for two-semester astronomy sequences, though instructors of such courses may wish to consider our more comprehensive book, *The Cosmic Perspective.*

About the Sixth Edition

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

- **Fully Updated Science:** Astronomy is a fast-moving field, and numerous new developments have occurred since the prior edition was published. The topics updated in this edition include
  - New developments in the study of extrasolar planets and planetary systems, including early results from *Kepler*
  - New results and images from spacecraft exploring our solar system, including *Phoenix* and the *Mars Reconnaissance Orbiter* at Mars, *Venus Express* at Venus, *Cassini* at Saturn, *MESSENGER* at Mercury, *SOHO* and *TRACE* at the Sun, and more
  - The increasingly strong evidence for dark matter and dark energy
  - Recent results from major space observatories, including Hubble, Spitzer, Chandra, and Fermi
  - New research on the timing and possible origin of life on Earth
- **New Visual Overview of Scale:** These dynamic foldout diagrams, placed just inside the front cover, give students an at-a-glance reference to review the scale of space and time, addressing a key challenge students face in astronomy.
- **New Group Work Questions:** The end-of-chapter exercise sets now include a subsection of problems that can be easily done in class to foster peer learning and in-class participation.
- **New Content in MasteringAstronomy™ (www.masteringastronomy.com):** We have reached the point where *The Essential Cosmic Perspective* is no longer just a textbook; rather it is a "learning package" that combines a printed book with deeply integrated, interactive media that we have developed to support every chapter of our book. For students, MasteringAstronomy provides a wealth of tutorials and activities to build understanding, while quizzes and exercises allow them to test what they've learned. For instructors, MasteringAstronomy 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
  - A set of Math Skills tutorials, including Video Tutors to help students review the basic math concepts they'll

need to solve quantitative problems in introductory astronomy

- A set of interactive tours which explore celestial objects using Microsoft's WorldWide Telescope software
- A set of in-depth Group Work Activities for use in class or discussion section
- RSS feeds from a variety of notable astronomy publications
- A customizable Pearson eText with embedded links to multimedia and glossary terms

Themes of *The Essential Cosmic Perspective*

The Essential Cosmic Perspective offers a broad survey of our modern understanding of the cosmos and of how we have built that understanding. Such a survey can be presented in a number of different ways. We have chosen to interweave a few key themes throughout the book, each selected to help make the subject more appealing to students who may never have taken any formal science courses and who may begin the course with little understanding of how science works. Our book is built around the following five key themes:

- **Theme 1:** *We are a part of the universe and thus can learn about our origins by studying the universe.* This is the overarching theme of *The Essential Cosmic Perspective*, as we continually emphasize that learning about the universe helps us understand ourselves. Studying the intimate connections between human life and the cosmos gives students a reason to care about astronomy and also deepens their appreciation of the unique and fragile nature of our planet.
- **Theme 2:** *The universe is comprehensible through scientific principles that anyone can understand.* We can understand the universe because the same physical laws appear to be at work in every aspect, on every scale, and in every age of the universe. Moreover, while professional scientists generally have discovered the laws, anyone can understand their fundamental features. Students can learn enough in one or two terms of astronomy to comprehend the basic reasons for many phenomena that they see around them—ranging from seasonal changes and phases of the Moon to the most esoteric astronomical images that appear in the news.
- **Theme 3:** *Science is not a body of facts but rather a process through which we seek to understand the world around us.* Many students assume that science is just a laundry list of facts. The long history of astronomy shows that science is a process through which we learn about our universe—a process that is not always a straight line to the truth. That is why our ideas about the cosmos sometimes change as we learn more, as they did dramatically when we first recognized that Earth is a planet going around the Sun rather than the center of the universe. In this book, we continually emphasize the nature of science so that students can understand how and why modern theories have gained acceptance and why these theories may change in the future.
- **Theme 4:** *A course in astronomy is the beginning of a lifelong learning experience.* Building 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 to continue to participate in the ongoing human adventure of astronomical discovery.
- **Theme 5:** *Astronomy affects each of us personally with the new perspectives it offers.* We all conduct the daily business of our lives with reference to some "world view"—a set of personal beliefs about our place and purpose in the universe that we have developed through a combination of schooling, religious training, and personal thought. This world view shapes our beliefs and many of our actions. Although astronomy does not mandate a particular set of beliefs, it does provide perspectives on the architecture of the universe that can influence how we view ourselves and our world, which can potentially affect our behavior. In many respects, the role of astronomy in shaping world views may represent the deepest connection between the universe and the everyday lives of humans.

Pedagogical Principles of *The Essential Cosmic Perspective*

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

- **Stay focused on the big picture.** Astronomy is filled with interesting facts and details, but they are meaningless unless they fit into a big picture view of the universe. We therefore take care to stay focused on the big picture (essentially the themes discussed above) at all times. A major benefit of this approach is that although students may forget individual facts and details after the course is over, the big picture framework should stay with them for life.
- **Always provide context first.** We all learn new material more easily when we understand why we are learning it. We therefore begin the book (in Chapter 1) with a broad overview of modern understanding of the cosmos so that students know what they will be studying in the rest of the book. We maintain this "context first" approach throughout the book by always telling students what they will be learning, and why, before diving into the details.

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

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

The Essential Cosmic Perspective is organized into six broad topical areas (the six parts in the table of contents), each approached in a distinctive way designed to help maintain the focus on the themes discussed earlier. Here, we summarize the guiding philosophy through which we have approached each topic.

Every part concludes with a two-page Cosmic Context figure, which ties together into a coherent whole the diverse ideas covered in the individual chapters.

PART I: Developing Perspective (Chapters 1–3)

GUIDING PHILOSOPHY: *Introduce the big picture, the process of science, and the historical context of astronomy.*

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

The Cosmic Context for Part I appears on pp. 82–83.

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

GUIDING PHILOSOPHY: *Bridges to the familiar.*

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

The Cosmic Context for Part II appears on pp. 140–141.

PART III: Learning from Other Worlds (Chapters 6–9)

GUIDING PHILOSOPHY: *Learning about Earth by learning about other planets in our solar system and beyond.*

This set of chapters begins with a broad overview of the solar system and discussion of solar system formation in Chapter 6; this chapter also includes discussion of extrasolar planets. The next three chapters focus respectively on the terrestrial planets, the jovian planets, and the small bodies of the solar system. Note that Part III is essentially independent of Parts IV and V, and thus can be covered either before or after them.

The Cosmic Context for Part III appears on pp. 284–285.

PART IV: Stars (Chapters 10–13)

GUIDING PHILOSOPHY: *We are intimately connected to the stars.*

These are our chapters on stars and stellar life cycles. Chapter 10 covers the Sun in depth, so that it can serve as a concrete model for building an understanding of other stars. Chapter 11 describes the general properties of stars, how we measure these properties, and how we classify stars using the H-R diagram. Chapter 12 covers stellar evolution, tracing the birth-to-death lives of both low- and high-mass stars. Chapter 13 covers the end points of stellar evolution: white dwarfs, neutron stars, and black holes.

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

PART V: Galaxies and Beyond (Chapters 14–17)

GUIDING PHILOSOPHY: *Present galaxy evolution in a way that parallels the teaching of stellar evolution, integrating cosmological ideas in the places where they most naturally arise.*

These chapters cover galaxies and cosmology. Chapter 14 presents the Milky Way as a paradigm for galaxies in much the same way that Chapter 10 uses the Sun as a paradigm for stars. Chapter 15 presents the variety of galaxies, how we determine key parameters such as galactic distances and age, and current understanding of galaxy evolution. Chapter 16 focuses on dark matter and dark energy and their role in the fate of the universe. Chapter 17 covers the theory of the Big Bang. Throughout these chapters, we integrate cosmological ideas as they arise. For example, we cover Hubble's law in Chapter 15 because of its importance to the cosmic distance scale and to our understanding of what we see when we look at distant galaxies.

The Cosmic Context for Part V appears on pp. 498–499.

PART VI: Life on Earth and Beyond (Chapter 18)

GUIDING PHILOSOPHY: *The study of life on Earth helps us understand the search for life in the universe.*

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

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

Pedagogical Features of *The Essential Cosmic Perspective*

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

- **Learning Goals** Presented as key questions, motivational learning goals begin every chapter, and every section of every chapter is carefully written to address the specific learning goal in the title. This helps students stay focused on the big picture and stay motivated by the understanding they will gain.
- **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.
- **Highlighted "Essential Points"** These call attention to key points and help students find the relevant discussion in the text.
- **Annotated Figures** Key figures in each chapter now include the research-proven technique of "annotation"—carefully crafted text placed on the figure (in blue) to guide students through interpreting graphs, following process figures, and translating between different representations.
- **Cosmic Context Two-Page Visual Summaries** These two-page figures pull together related ideas in spectacular visual summaries.
- **Wavelength/Observatory Icons** For astronomical photographs (or astronomy art that may be confused with photographs), simple icons identify the wavelength band; whether the image is a photo, artist's impression, or computer simulation; and whether the image came from ground-based or space-based observations.
- **MasteringAstronomy Self-Guided Tutorials** Lessons from within the highly acclaimed self-guided tutorials on www.masteringastronomy.com are referenced above specific section titles to direct students to targeted, self-paced help.
- **Think About It** This feature, which appears throughout the book as short questions integrated into the narrative, gives students the opportunity to reflect on important new concepts. It also serves as an excellent starting point for classroom discussions.
- **See It for Yourself** This feature, which appears throughout the book as short questions integrated into the narrative, gives students the opportunity to conduct simple observations or experiments that will help them understand key concepts.
- **Common Misconceptions** These boxes address popularly held but incorrect ideas related to the chapter material.
- **Special Topic Boxes** These boxes contain supplementary discussion topics related to the chapter material but not prerequisite to the continuing discussion.
- **Cosmic Calculations Boxes** These boxes contain optional mathematics, set in the margin of the text.
- **The Big Picture** Every chapter narrative ends with this feature. It helps students put what they've learned in the chapter into the context of the overall goal of gaining a broader perspective on ourselves and our planet.
- **End-of-Chapter Questions** 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:

- 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 for each of which students are expected to determine whether the statement makes sense, and to explain 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 and discussion questions that ask students to reflect on how science is done and how astronomers have learned about the universe over time.
- NEW! Group Work Exercises: Questions designed for collaborative learning in class.
- Short-Answer/Essay Questions: Questions that go beyond the Review Questions in asking for conceptual interpretation.
- Quantitative Problems: Problems that require some mathematics, usually based on topics covered in the Cosmic Calculations boxes.
- Discussion Questions: Open-ended questions for class discussions.
- Web Projects: Online research projects designed for independent study.

Nearly all end-of-chapter questions are available at www.masteringastronomy.com for online homework assignment and automatic grading and diagnostics.

- **Visual Skills Check** Each chapter summary is followed by a set of questions designed to help students build their skills at interpreting the many types of visual information used in astronomy. Answers to these questions appear in Appendix J.
- **Glossary** A detailed glossary makes it easy for students to look up important terms.
- **Appendixes** The appendixes include a number of useful references and tables, including key constants (Appendix A), key formulas (Appendix B), key mathematical skills (Appendix C), and numerous data tables and star charts (Appendixes D–I), plus the answers to the Visual Skills Check questions (Appendix J).

MasteringAstronomy—A New Paradigm in Astronomy Teaching

What is the single most important factor in student success in astronomy? Both research and common sense reveal the same answer: *study time.* No matter how good the teacher, or how good the textbook, students learn only when they spend adequate time studying. Unfortunately, limitations on resources for grading have prevented most instructors from assigning much homework despite its obvious benefits to student learning. And limitations on help and office hours have made it difficult for students to make sure they use self-study time effectively. That, in a nutshell, is why we have created MasteringAstronomy. For students, it provides the first adaptive-learning, online system to coach them *individually*—responding to their errors with specific, targeted feedback, and providing hints for partial credit to help them when they get stuck. For professors, MasteringAstronomy provides the unprecedented ability to automatically monitor and record students' step-by-step work and evaluate the effectiveness of assignments and exams. As a result, we believe that MasteringAstronomy will create a paradigm shift in the way astronomy courses are taught: For the first time, it will be 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 versions of key figures and photos, and quizzes and other activities for self-assessment covering every chapter and every week. For professors, MasteringAstronomy provides the first library of tutoring activities and assessment problems pretested and informed by students nationally. You can choose from more than 4500 activities and problems to automatically assign, grade, and track: pre- and post-lecture diagnostic quizzes, tutoring activities, end-of-chapter problems, even test bank questions. You can find a walk-through of the major features of Mastering-Astronomy in the front of this book, though of course the best way to become familiar with it is to spend some time on the Web site. We invite you to visit www.masteringastronomy.com to see it for yourself.

Finally, in a world where every publisher walks into a professor's office and claims that their Web site is better than anyone else's, we'd like to point out four reasons why you'll discover that MasteringAstronomy really does stand out from the crowd:

- MasteringAstronomy has been built specifically to support the structure and pedagogy of *The Essential Cosmic Perspective*. You'll find the same concepts emphasized in the book and the Web site, using the same terminology and the same pedagogical approaches. This type of consistency ensures that students focus on the concepts, without the risk of becoming confused by different presentations.
- Nearly all MasteringAstronomy content has been developed either directly by *The Essential Cosmic Perspective* author team or in close collaboration with outstanding educators including Jim Dove, Ed Prather, Tim Slater, Daniel Lorenz, Jonathan Williams, Lauren Jones, and others. The direct involvement of book authors ensures that you can expect the same high level of quality in our Web site 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 tutorial and assessment system), developed by a group led by MIT physicist David Pritchard. This robust platform gives instructors unprecedented power not only to tailor content to their own courses, but also to evaluate the effectiveness of assignments and exams, thereby enabling instructors to adapt their lectures, assignments, and tests to the students' needs as the course progresses.

Additional Supplements for *The Essential Cosmic Perspective*

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

- **Voyager: SkyGazer v5.0 College Edition™** Based on *Voyager V*, one of the world's most popular planetarium programs, *SkyGazer* makes it easy for students to learn constellations and explore the wonders of the sky through interactive exercises. Accompanying activities are available in LoPresto's *Astronomy Media Workbook*, Seventh Edition.
- **Starry Night™ College Planetarium Software (ISBN 0-321-71295-1)** Now available as an additional option with *The Essential Cosmic Perspective*, *Starry Night* has been acclaimed as the world's most realistic desktop planetarium software, and is available as an additional bundle. Ask your Pearson sales representative for details.
- **Astronomy Media Workbook, Seventh Edition (ISBN 0-321-74124-2)** The *Astronomy Media Workbook* by Michael LoPresto includes a wide selection of in-depth activities based on the Interactive Figures™ and RSS Feeds on MasteringAstronomy, and *Voyager: SkyGazer v5.0* planetarium software. These thought-provoking projects are suitable for labs or homework assignments.

Instructor-Only Supplements

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

- **Instructor Resource DVD (ISBN 0-321-72433-X)** This DVD provides a wealth of lecture and teaching resources, including high-resolution JPEGs of all images from the book for in-class projection, Interactive Figures and Photos™ based on figures from the book, informative applets and animations, pre-built PowerPoint® Lecture Outlines, and PRS-enabled Clicker Quizzes based on the book and book-specific interactive media.
- **Clickers in the Astronomy Classroom (ISBN 0-8053-9616-0)** 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 0-321-72436-4)** This guide contains a detailed overview of the text, sample syllabi for courses of different emphasis and duration, suggestions for teaching strategies, answers or discussion points for all Think About It and See It for Yourself questions in the text, solutions to end-of-chapter problems, and a detailed reference guide summarizing media resources available for every chapter and section in the book. Word files can be downloaded from the Instructor Resource Center (www.pearsonhighered.com/irc).
- **Carl Sagan's Cosmos DVD Box Set (ISBN 0-8053-8572-X)** The complete, revised, enhanced, and updated *Cosmos* series is available free to qualified adopters of *The Essential Cosmic Perspective*. A week-by-week guide of segments to include in your course is provided in the *Instructor Guide*.
- **Test Bank (ISBN 0-321-72437-2)** The *Test Bank* includes hundreds of multiple-choice, true/false, and short answer questions, plus a new set of Process of Science questions for each chapter. TestGen® and Word files can be downloaded from the Instructor Resource Center and the instructor resource section of the study area in MasteringAstronomy.

Acknowledgments

A textbook may carry author names, but it is the result of hard work by a long list of committed individuals. We could not possibly list everyone who has helped, but we would like to call attention to a few people who have played particularly important roles. First, we thank our editors and friends at Addison-Wesley, who have stuck with us through thick and thin, including Nancy Whilton, Linda Davis, Adam Black, Michael Gillespie, Ashley Eklund, Katie Conley, Kerry Chapman, and Mary O'Connell. Special thanks to our past and present production teams, especially Joan Marsh, Mary Douglas, Brandi Nelson, and Sally Lifland; our art and design team, Mark Ong, Judy and John Waller, and Dartmouth Publishing; our interactive media team, Jim Dove, Lauren Jones, Kate Brayton, and Cadre Design; and our MasteringAstronomy™ team, Deb Greco, Wendy Romaniecki, and Caroline Power.

We've also been fortunate to have an outstanding group of reviewers, whose extensive comments and suggestions helped us shape the book. We thank all those who have reviewed the book in various stages, including

Marilyn Akins, *Broome Community College*
Christopher M. Anderson, *University of Wisconsin*
John Anderson, *University of North Florida*
Peter S. Anderson, *Oakland Community College*
Keith Ashman, *University of Missouri—Kansas City*

Simon P. Balm, *Santa Monica College*
Nadine Barlow, *Northern Arizona University*
John Beaver, *University of Wisconsin at Fox Valley*
Peter A. Becker, *George Mason University*
Timothy C. Beers, *Michigan State University*
Jim Bell, *Cornell University*
Priscilla J. Benson, *Wellesley College*
Bernard W. Bopp, *University of Toledo*
Sukanta Bose, *Washington State University*
David Brain, *University of California Berkeley Space Sciences Laboratory*
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Eric Carlson, *Wake Forest University*
David A. Cebula, *Pacific University*
Supriya Chakrabarti, *Boston University*
Kwang-Ping Cheng, *California State University Fullerton*
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Josh Colwell, *University of Colorado*
Anita B. Corn, *Colorado School of Mines*
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Kelli Corrado, *Montgomery County Community College*
John Cowan, *University of Oklahoma*
Kevin Crosby, *Carthage College*
Christopher Crow, *Indiana University—Purdue University Fort Wayne*
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Lawrence Pinsky, *University of Houston*
Stephanie Plante, *Grossmont College*
Jascha Polet, *California State Polytechnic University, Pomona*
Matthew Price, *Oregon State University*
Harrison B. Prosper, *Florida State University*
Monica Ramirez, *Aims College, Colorado*
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Todd M. Rigg, *City College of San Francisco*
Elizabeth Roettger, *DePaul University*
Roy Rubins, *University of Texas at Arlington*
Carl Rutledge, *East Central University*
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Rex Saffer, *Villanova University*
John Safko, *University of South Carolina*
James A. Scarborough, *Delta State University*
Britt Scharringhausen, *Ithaca College*
Ann Schmiedekamp, *Pennsylvania State University, Abington*
Joslyn Schoemer, *Denver Museum of Nature and Science*
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Larry Sessions, *Metropolitan State College of Denver*
Ralph Siegel, *Montgomery College, Germantown Campus*
Philip I. Siemens, *Oregon State University*
Caroline Simpson, *Florida International University*
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Michael Skrutskie, *University of Virginia*
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Fred Walter, *State University of New York, Stony Brook*
James Webb, *Florida International University*
Mark Whittle, *University of Virginia*
Paul J. Wiita, *Georgia State University*
Lisa M. Will, *Mesa Community College*
Jonathan Williams, *University of Florida*
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Min S. Yun, *University of Massachusetts, Amherst*
Dennis Zaritsky, *University of California, Santa Cruz*
Robert L. Zimmerman, *University of Oregon*

Historical Accuracy Reviewer—Owen Gingerich, *Harvard–Smithsonian*

In addition, we thank the following colleagues who helped us clarify technical points or checked the accuracy of technical discussions in the book:

Nahum Arav, *University of Colorado*
Phil Armitage, *University of Colorado*
Thomas Ayres, *University of Colorado*
Cecilia Barnbaum, *Valdosta State University*
Rick Binzel, *Massachusetts Institute of Technology*
Howard Bond, *Space Telescope Science Institute*
David Brain, *University of California Berkeley Space Sciences Laboratory*
Humberto Campins, *University of Florida*
Robin Canup, *Southwest Research Institute*
Clark Chapman, *Southwest Research Institute*
Kelly Cline, *Carroll College*
Josh Colwell, *University of Colorado*
Mark Dickinson, *National Optical Astronomy Observatory*
Jim Dove, *Metropolitan State College of Denver*
Harry Ferguson, *Space Telescope Science Institute*
Andrew Hamilton, *University of Colorado*
Todd Henry, *Georgia State University*
Dennis Hibbert, *Everett Community College*
Dave Jewitt, *University of Hawaii*
Emily Lakdawalla, *The Planetary Society*
Hal Levison, *Southwest Research Institute*
Mario Livio, *Space Telescope Science Institute*
J. McKim Malville, *University of Colorado*
Mark Marley, *New Mexico State University*
Linda Martel, *University of Hawaii*

Kevin McLin, *University of Colorado*
Michael Mendillo, *Boston University*
Rachel Osten, *National Radio Astronomy Observatory*
Bob Pappalardo, *University of Colorado*
Bennett Seidenstein, *Arundel High School*
Michael Shara, *American Museum of Natural History*
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, *MPI/Lindau (Germany)*
Dimitri Veras, *University of Colorado*
John Weiss, *University of Colorado*
Francis Wilkin, *Union College*
Don Yeomans, *Jet Propulsion Laboratory*

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

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JEFFREY BENNETT holds a B.A. in biophysics from the University of California, San Diego, and an M.S. and Ph.D. in astrophysics from the University of Colorado, Boulder. He has taught at every level from preschool through graduate school, including more than 50 college classes in astronomy, physics, mathematics, and education. He served 2 years as a visiting senior scientist at NASA headquarters, where he created NASA's "IDEAS" program, started a program to fly teachers aboard NASA's airborne observatories (including SOFIA), and worked on numerous educational programs for the Hubble Space Telescope and other space science missions. He also proposed the idea for and helped develop both the Colorado Scale Model Solar System on the CU-Boulder campus and the *Voyage* Scale Model Solar System on the National Mall in Washington, D.C. (He is pictured here with the model Sun.) In addition to this astronomy textbook, he has written college-level textbooks in astrobiology, mathematics, and statistics; two books for the general public, *On the Cosmic Horizon* (Pearson Addison-Wesley, 2001) and *Beyond UFOs* (Princeton University Press, 2008/2011); and an award-winning series of children's books that includes *Max Goes to the Moon, Max Goes to Mars, Max Goes to Jupiter,* and *Max's Ice Age Adventure.* When not working, he enjoys participating in masters swimming and in the daily adventures of life with his wife, Lisa; his children, Grant and Brooke; and his dog, Cosmo. His personal Web site is www.jeffreybennett.com.

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MEGAN DONAHUE is a professor in the Department of Physics and Astronomy at Michigan State University. Her current research is mainly on 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 a B.A. 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, for a thesis on theory and optical observations of intergalactic and intracluster gas. That thesis 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 in optical and X-ray observations 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 and the raising of their children, Michaela, Sebastian, and Angela. These days, Megan runs, orienteers, and plays piano and bass guitar whenever her children allow it.

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NICHOLAS SCHNEIDER is an associate professor in the Department of Astrophysical and Planetary Sciences at the University of Colorado and a researcher in the Laboratory for Atmospheric and Space Physics. He received his B.A. in physics and astronomy from Dartmouth College in 1979 and his Ph.D. in planetary science from the University of Arizona in 1988. In 1991, he received the National Science Foundation's Presidential Young Investigator Award. His research interests include planetary atmospheres and planetary astronomy, with a focus on the odd case of Jupiter's moon Io. He is also active in Mars research and leads the Imaging UltraViolet Spectrograph team for the *MAVEN* mission (Mars Atmosphere & Volatile Evolution). Scheduled to launch in 2013, *MAVEN* is a robotic orbiter that will measure how quickly Mars is losing its atmosphere today and whether Mars's atmosphere could have made the planet habitable in the past. He enjoys teaching at all levels and is active in efforts to improve undergraduate astronomy education. Off the job, he enjoys exploring the outdoors with his family and figuring out how things work.

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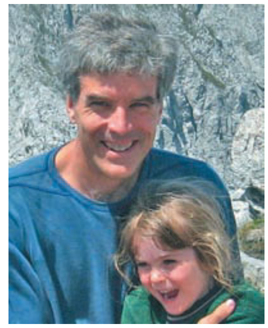


MARK VOIT is a professor in the Department of Physics and Astronomy at Michigan State University. He earned his B.A. in astrophysical sciences at Princeton University and his Ph.D. in astrophysics at the University of Colorado in 1990. He continued his studies at the California Institute of Technology, 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 was the scientist behind NASA's HubbleSite. His research interests range from interstellar processes in our own galaxy to the clustering of galaxies in the early universe. He is married to coauthor Megan Donahue, and they try to play outdoors with their three children whenever possible, enjoying hiking, camping, running, and orienteering. Mark is also author of the popular book *Hubble Space Telescope: New Views of the Universe.*

How to Succeed in Your Astronomy Course

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. Next, get an overview of the key concepts by studying the illustrations and reading their captions. The illustrations highlight almost all of the 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 *Cosmic Context* figures to be especially useful. Also look for the Interactive Figure icons—when you see one, go to the MasteringAstronomy™ Web site (www.masteringastronomy.com) to try the interactive version.
  3. Read the chapter narrative, but save the boxed features (Common Misconceptions, Special Topics, Cosmic Calculations) to read later. As you read, make notes on the pages to remind yourself of ideas you'll want to review later. Avoid using a highlight pen; <u>underlining</u> with pen or pencil is far more effective, because it forces you to take greater care and therefore helps keep you alert as you study. Be careful to underline selectively—it won't help you later if you've underlined everything.
  4. After reading the chapter once, go back through and read the boxed material. You should read all of the Common Misconceptions and Special Topics boxes; whether you choose to read the Cosmic Calculations is up to you and your instructor. Also watch for the MasteringAstronomy tutorial icons throughout the chapter; if a concept is giving you trouble, go to the MasteringAstronomy site to try the relevant tutorial.
  5. Then turn your attention to the chapter summary. The best way to use the summary is to try to answer the Learning Goal questions for yourself before reading the short answers given in the summary.
- After completing the reading as described above, start testing your understanding with the end-of-chapter exercises. A good way to begin is to make sure you can answer all of the Review Questions; if you don't know an answer, look back through the chapter until you figure it out. Then test your understanding a little more deeply by trying the "Does It Make Sense?", Quick Quiz, and Visual Skills Check questions.
- You can further check your understanding and get feedback on difficulties by trying the online quizzes at www.masteringastronomy.com. Each chapter has three quizzes: a Reading Quiz, a Concept Quiz, and a Visual Quiz. Try the Reading Quiz first. Once you clear up any difficulties you have with it, try the Concept and Visual quizzes.
- If your course has a quantitative emphasis, work through all of the examples in the Cosmic Calculations before trying the quantitative problems for yourself. Remember that you should always try to answer questions qualitatively before you begin plugging numbers into a calculator. For example, make an order-of-magnitude estimate of what your answer should be so that you'll know your calculation is on the right track, and be sure that your answer makes sense and has the appropriate units.
- If you have done all the above, you will have already made use of numerous resources on the MasteringAstronomy Web site (www.masteringastronomy.com). Don't stop there; visit the site again and make use of other 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 astronomy 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 on the Web site and using them.

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.

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

As a rough guideline, your studying time in astronomy might be divided as shown in the table at the top of this page. 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.

General Strategies for Studying

- 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.
- Take advantage of the resources offered by your professor, whether it be e-mail, office hours, review sessions, online chats, or simply finding 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.
- 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.
- If a concept gives you trouble, do additional reading or studying beyond what has been assigned. And if you still have trouble, ask for help: You surely can find friends, peers, or teachers who will be glad to help you learn.
- Working together with friends can be valuable in helping you understand difficult concepts. However, be sure that you learn *with* your friends and do not become dependent on them.
- Be sure that any work you turn in is of *collegiate quality:* neat and easy to read, well organized, and demonstrating mastery of the subject matter. Although it takes extra effort to make your work look this good, the effort will help you solidify your learning and is also good practice for the expectations that future professors and employers will have.

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.
- Study the relevant online tutorials and chapter quizzes available at www.masteringastronomy.com.
- 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.

Foreword

The Meaning of *The Cosmic Perspective*

© Neil deGrasse Tyson

by Neil deGrasse Tyson

Astrophysicist Neil deGrasse Tyson is the Frederick P. Rose Director of New York City's Hayden Planetarium at the American Museum of Natural History. He has written numerous books and articles, hosts the PBS series NOVA scienceNOW, *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.

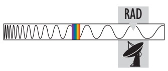
During our brief stay on planet Earth, we owe ourselves and our descendants the opportunity to explore—in part because it's fun to do. But there's a far nobler reason. The day our knowledge of the cosmos ceases to expand, we risk regressing to the childish view that the universe figuratively and literally 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.

Key to Wavelength Icons on Figures

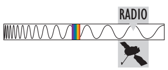
You'll see the following icons on figures throughout the book. They are used to indicate the wavelength of light shown in each image, and to identify photo-realistic artworks and images made by computer simulations.


Indicates an artist's representation

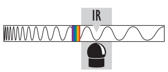

Indicates a graphic generated using computer simulations



Indicates an image based on data from an observatory on Earth observing radio waves



Indicates an image based on data from a spacecraft observing radio waves



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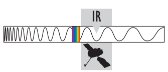

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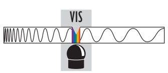

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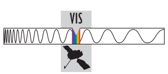

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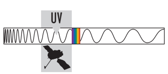

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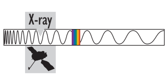
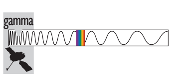


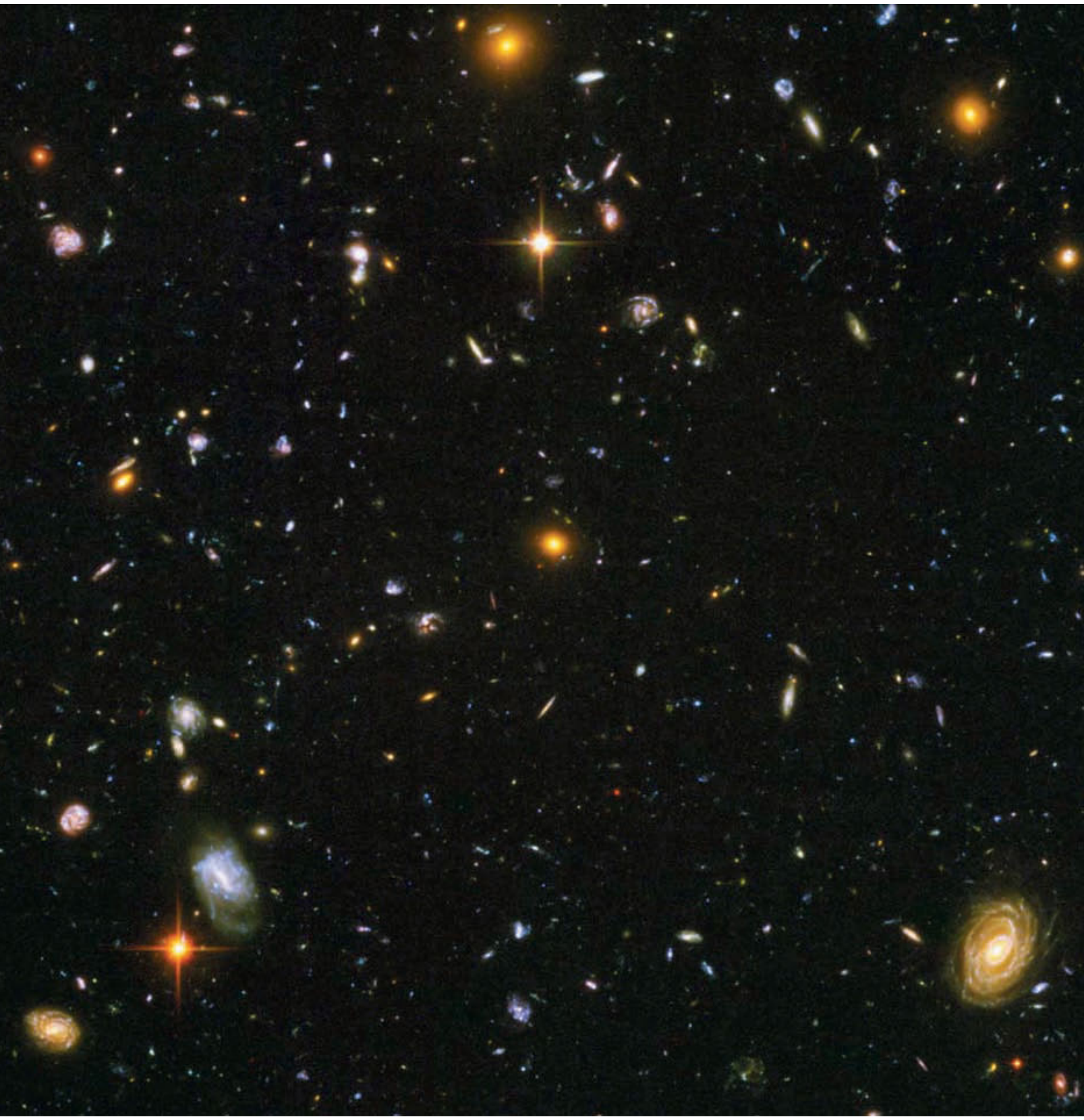
Indicates an image based on data from a spacecraft observing X rays



Indicates an image based on data from a spacecraft observing gamma rays

1

Our Place in the Universe



learning goals

1.1 Our Modern View of the Universe
- What is our place in the universe?
- How did we come to be?
- How can we know what the universe was like in the past?
- Can we see the entire universe?

1.2 The Scale of the Universe
- How big is Earth compared to our solar system?
- How far away are the stars?
- How big is the Milky Way Galaxy?
- How big is the universe?
- How do our lifetimes compare to the age of the universe?

1.3 Spaceship Earth
- How is Earth moving in our solar system?
- How is our solar system moving in the Milky Way Galaxy?
- How do galaxies move within the universe?
- Are we ever sitting still?

essential preparation

1. How to Succeed in Your Astronomy Course **[pp. xxii–xxiii]**
2. Powers of 10 **[Appendixes C.1, C.2]**
3. Working with Units **[Appendix C.3]**
4. The Metric System (SI) **[Appendix C.4]**

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

Modern science offers answers to many of our fundamental questions about the universe and our place within it. We now know the basic content and scale of the universe. We know the age of Earth and the approximate age of 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 content and history of the universe, the scale of the universe, and the motions of Earth. We'll develop a "big picture" perspective of our place in the universe that will provide a base to build upon in the rest of the book.

1.1 Our Modern View of the Universe

If you observe the sky carefully, you can see why most of our ancestors believed that the heavens revolved about a stationary Earth. The Sun, Moon, planets, and stars appear to circle around our sky each day, and we cannot feel the constant motion of Earth as it rotates on its axis and orbits the Sun. It therefore seems quite natural to assume that we live in an Earth-centered, or *geocentric*, universe.

Nevertheless, we now know that Earth is a planet orbiting a rather average star in a vast universe. The historical path to this knowledge was long and complex. In later chapters, we'll see that many ancient beliefs made sense in their day and changed only when people were confronted by strong evidence to the contrary. We'll also see how the process of science enabled us to acquire this evidence and to learn that we are connected to the stars in ways our ancestors never imagined. 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?

Figure 1.1 illustrates our place in the universe with what we might call our "cosmic address." Earth is a planet in our **solar system,** which consists of the Sun and all the objects that orbit it: the planets and their moons, and countless smaller objects including rocky *asteroids* and icy *comets*.

Our Sun is a star, just like the stars we see in our night sky. The Sun and all the stars we can see with the naked eye make up only a small part of a huge, disk-shaped collection of stars called the **Milky Way Galaxy**. A **galaxy** is a great island of stars in space, containing from a few hundred million to a trillion or more stars. The Milky Way Galaxy is relatively large, containing more than 100 billion stars. Our solar system is located a little over halfway from the galactic center to the edge of the galactic disk.

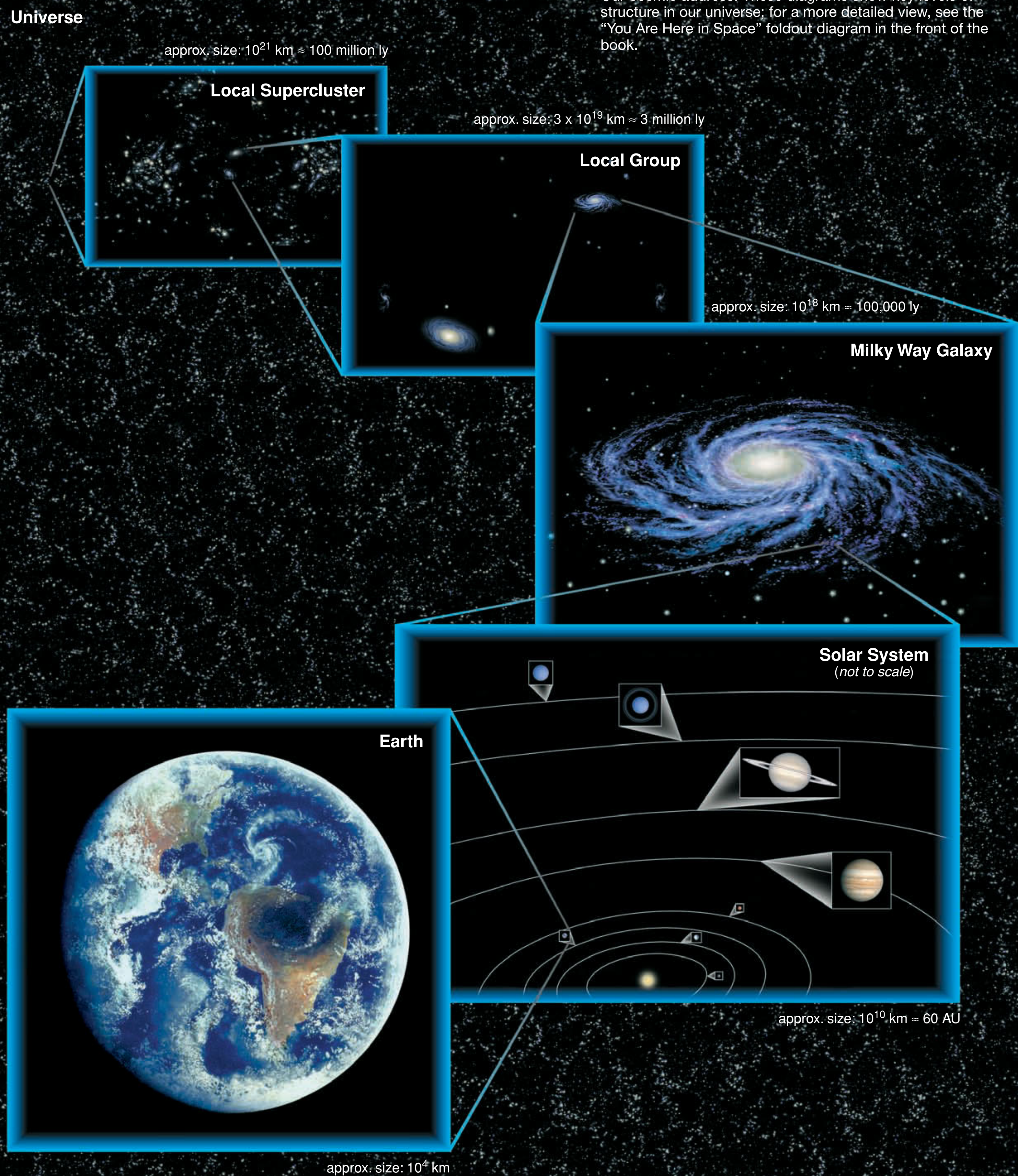


Figure 1.1

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.

Billions of other galaxies are scattered throughout space. Some galaxies are fairly isolated, but many others are found in groups. Our Milky Way, for example, is one of the two largest among about 40 galaxies in the **Local Group**. Groups of galaxies with more than a few dozen members are often called **galaxy clusters**.

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

On a very large scale, observations show that galaxies and galaxy clusters appear to be arranged in giant chains and sheets with huge voids between them. 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.

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. Study the more detailed view of our cosmic address in the "You Are Here in Space" foldout diagram in the front of the book. What do *you* think?

• How did we come to be?

According to modern science, we humans are newcomers in an old universe. We'll devote much of the rest of this textbook to studying the scientific evidence that backs up this idea. To help prepare you for this study, let's look at a quick overview of the scientific history of the universe, as summarized in Figure 1.2 (pages 6–7).

The Big Bang and the Expanding Universe Telescopic observations of distant galaxies show that the entire universe is *expanding,* meaning that the average distances between galaxies are increasing with time. This fact implies that galaxies must have been closer together in the past, and if we go back far enough, we must reach the point at which the expansion began. We call this beginning the **Big Bang**, and from the observed rate of expansion we estimate that it occurred about 14 billion years ago. The three cubes in the upper left corner of Figure 1.2 represent the expansion of a small piece of the universe over time.

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

The universe as a whole has continued to expand ever since the Big Bang, but on smaller scales the force of gravity has drawn matter together. Structures such as galaxies and galaxy clusters occupy regions where gravity has won out against the overall expansion. That is, while the universe as a whole continues to expand, individual galaxies and galaxy clusters do *not* expand. This idea is also illustrated by the three cubes in Figure 1.2. Notice that as the region as a whole grew larger, the matter within it clumped into galaxies and galaxy clusters. Most galaxies, including our own Milky Way, probably formed within a few billion years after the Big Bang.

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

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

In its final death throes, a star blows much of its content back out into space. In particular, massive stars die in titanic explosions called *supernovae*. The returned matter mixes with other matter floating between the stars in the galaxy, eventually becoming part of new clouds of gas and dust from which future generations of stars can be born. Galaxies therefore function as cosmic recycling plants, recycling material expelled from dying stars into new generations of stars and planets. This cycle is illustrated in the lower right of Figure 1.2. Our own solar system is a product of many generations of such recycling.

basic astronomical objects, units, and motions

This box summarizes a few key astronomical definitions introduced in this chapter and used throughout the book.

Basic Astronomical Objects

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

planet A moderately large object that orbits a star and shines primarily by reflecting light from its star. According to a definition approved in 2006, 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* can 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.

Collections of Astronomical Objects

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

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

galaxy A great island of stars in space, containing from a few hundred million to a trillion or more stars, all held together by gravity and orbiting a common center.

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

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

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

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

Astronomical Distance Units

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

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

Terms Relating to Motion

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

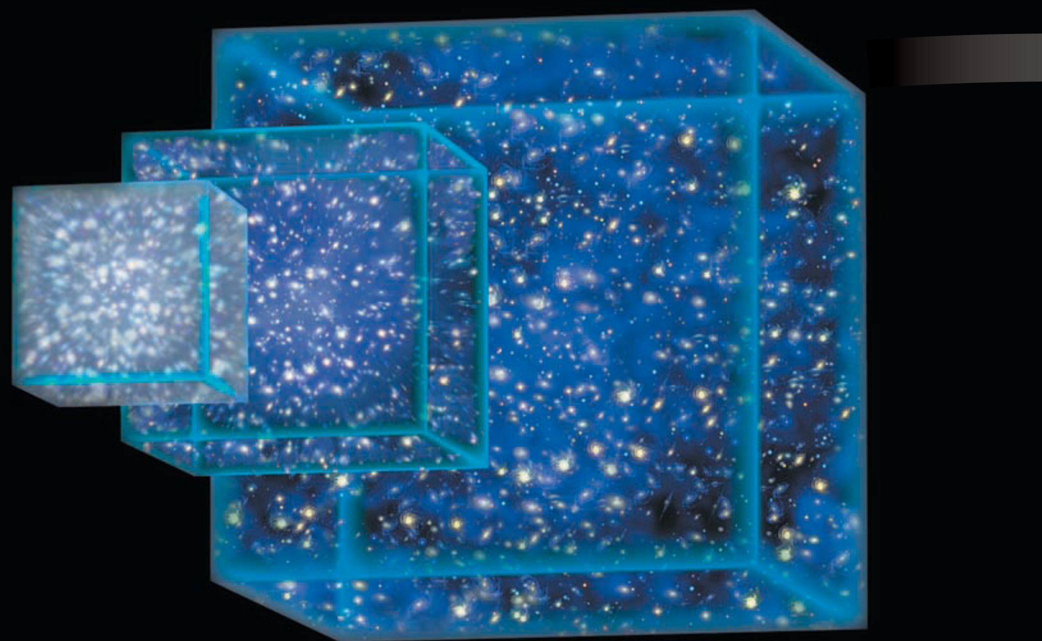
orbit (revolution) The orbital motion of one object around another. For example, Earth orbits around the Sun once each year.

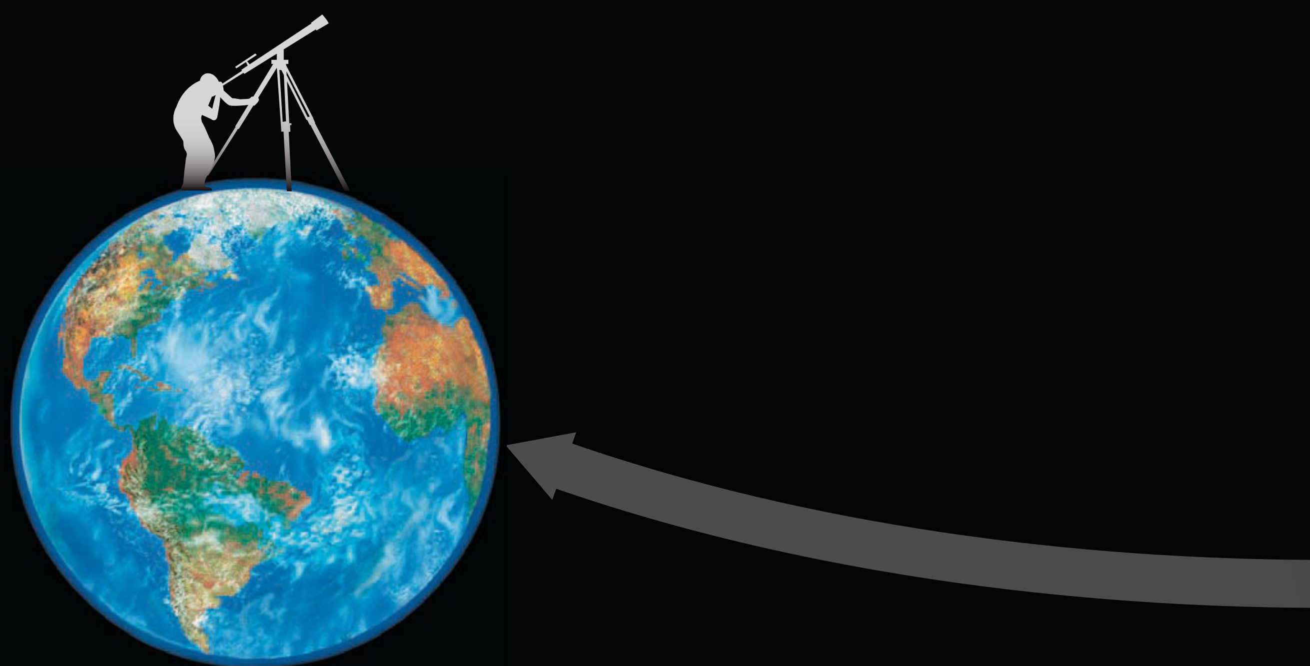
expansion (of the universe) The increase in the average distance between galaxies as time progresses. Note that while the universe as a whole is expanding, individual galaxies and galaxy clusters do *not* expand.

Figure 1.2. Our Cosmic Origins

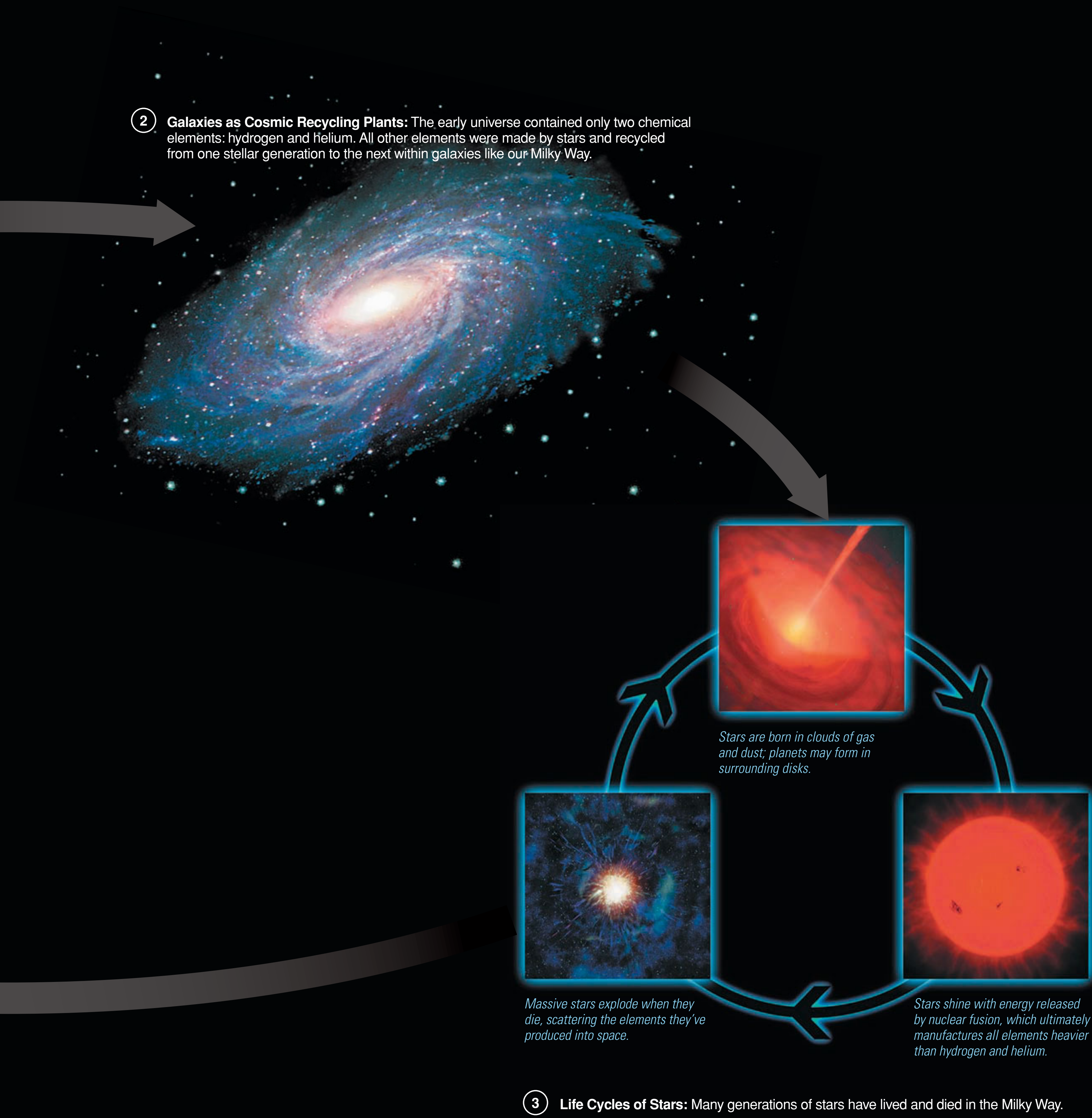
Throughout this book we will see that human life is intimately connected with the development of the universe as a whole. This illustration presents an overview of our cosmic origins, showing some of the crucial steps that made our existence possible.

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





4 **Earth and Life:** By the time our solar system was born, 4½ billion years ago, about 2% of the original hydrogen and helium had been converted into heavier elements. We are therefore “star stuff,” because we and our planet are made from elements manufactured in stars that lived and died long ago.



2 **Galaxies as Cosmic Recycling Plants:** The early universe contained only two chemical elements: hydrogen and helium. All other elements were made by stars and recycled from one stellar generation to the next within galaxies like our Milky Way.
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.
3 **Life Cycles of Stars:** Many generations of stars have lived and died in the Milky Way.

cosmic Calculations 1.1

How Far Is a Light-Year?

One light-year (ly) is defined as the distance that light can travel in 1 year. This distance is fixed because light always travels at the same speed—the *speed of light,* which is 300,000 km/s (186,000 mi/s).

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

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

For example, if you travel at a speed of 50 km/hr for 2 hours, you will travel 100 km. To find the distance represented by 1 light-year, we simply multiply the speed of light by 1 year:

$$1 \text{ light-year} = (\text{speed of light}) \times (1 \text{ yr})$$

Because we are given the speed of light in units of kilometers per second but the time as 1 year, we must carry out the multiplication while converting 1 year into seconds. You can find a review of unit conversions in Appendix C; here, we show the result for this particular case:

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

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

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 light-years are a unit of *distance*, not time. If you are unsure whether the term *light-year* is being used correctly, try testing the statement by replacing "1 light-year" with its equivalent distance of "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.

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

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

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

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

• How can we know what the universe was like in the past?

You may wonder how we can claim to know anything about what the universe was like in the distant past. It's possible because we can actually see into the past by studying light from distant stars and galaxies.

Light travels extremely fast by earthly standards. The speed of light is 300,000 kilometers per second, a speed at which it would be possible to circle Earth nearly eight times in just 1 second. Nevertheless, even light takes time to travel the vast distances in space. For example, light takes about 1 second to reach Earth from the Moon, and about 8 minutes to reach Earth from the Sun. Light from stars takes many years to reach us, so we measure distances to stars in units called **light-years**. One light-year is the distance that light can travel in 1 year—about 10 trillion kilometers, or 6 trillion miles (see Cosmic Calculations 1.1). Note that a light-year is a unit of *distance,* not time.

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

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

The effect is more dramatic at greater distances. The Andromeda Galaxy (also known as M31) lies about 2.5 million light-years from Earth. Figure 1.3 is therefore a picture of how this galaxy looked about 2.5 million years ago, when early humans were first walking on Earth. We see more distant galaxies as they were even further back into the past.

It's also amazing to realize that any "snapshot" of a distant galaxy is a picture of both space and time. For example, because the Andromeda Galaxy is about 100,000 light-years in diameter, the light we see from the far side of the galaxy must have left on its journey to us 100,000 years before the light 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.

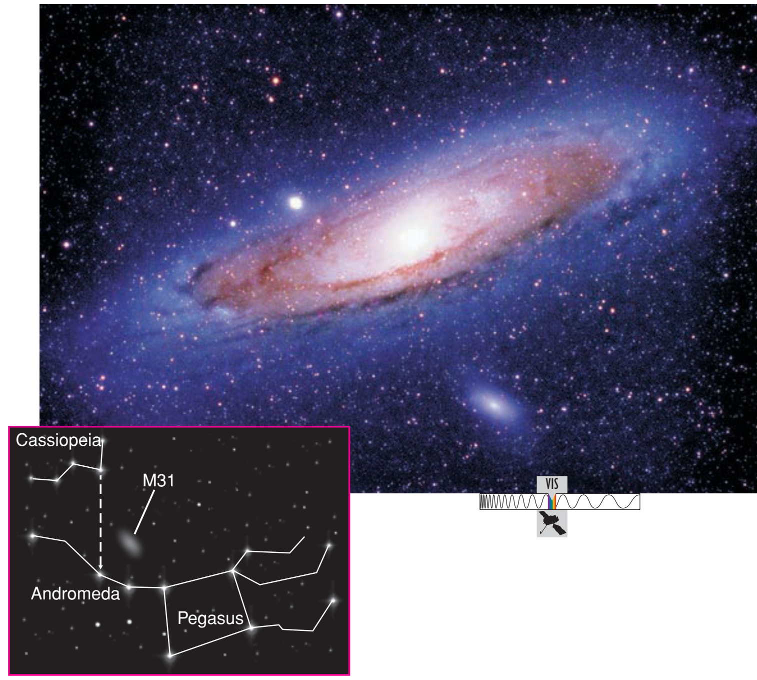


Figure 1.3

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

see it for yourself The glow from the central region of the Andromeda Galaxy is faintly visible to the naked eye and easy to see with binoculars. Use a star chart to find it in the night sky. Contemplate the fact 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?

• Can we see the entire universe?

Recall that the observed expansion of the universe implies that it is about 14 billion years old. This fact, combined with the fact that looking far 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 on page 1), we see it as it was 12 billion years ago, when the universe was only 2 billion years old. And if we tried to look beyond 14 billion light-years, we'd be looking back to a time more than 14 billion years ago—which is before the universe existed, so there is nothing to see. This distance of 14 billion light-years therefore marks the boundary of our **observable universe**—the portion of the entire universe that we can potentially observe. Note that this fact does not put any limit on the size of the *entire* universe, which may be far larger than our observable universe. We simply have no hope of seeing or studying anything beyond the bounds of our observable universe.

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

Figure 1.4

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

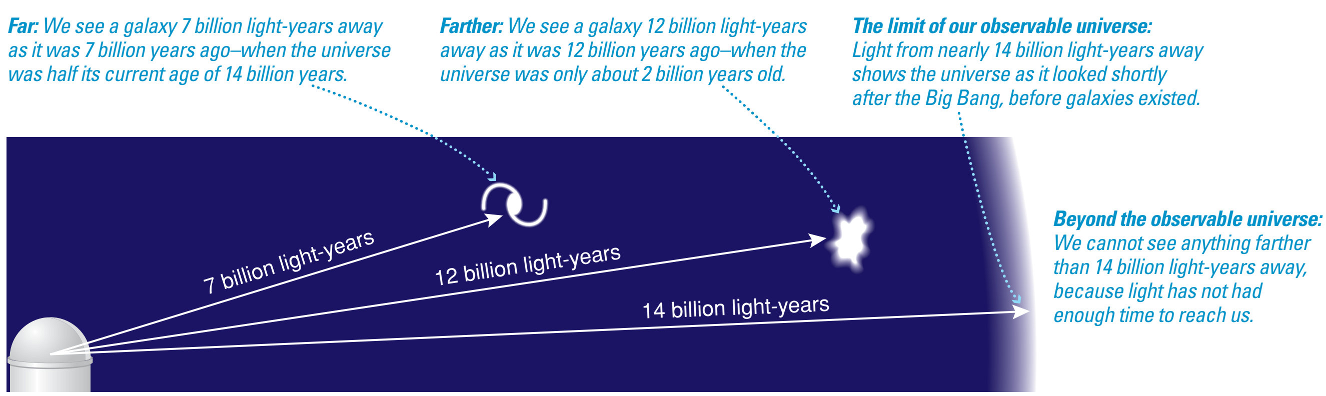


Figure 1.5

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.

MA Scale of the Universe Tutorial, Lessons 1–3

1.2 The Scale of the Universe

The numbers in our description of the size and age of the universe have little meaning for most people—after all, they are literally astronomical—but understanding them is crucial in astronomy. In this section, we will try to give meaning to astronomical distances and times.

• How big is Earth compared to our solar system?

Illustrations and photo montages often make our solar system look like it is crowded with planets and moons, but the reality is far different. 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 in Washington, D.C., makes such a walk possible (Figure 1.5). The Voyage model shows the Sun and the planets, and the distances between them, at *one ten-billionth* of their actual sizes and distances.

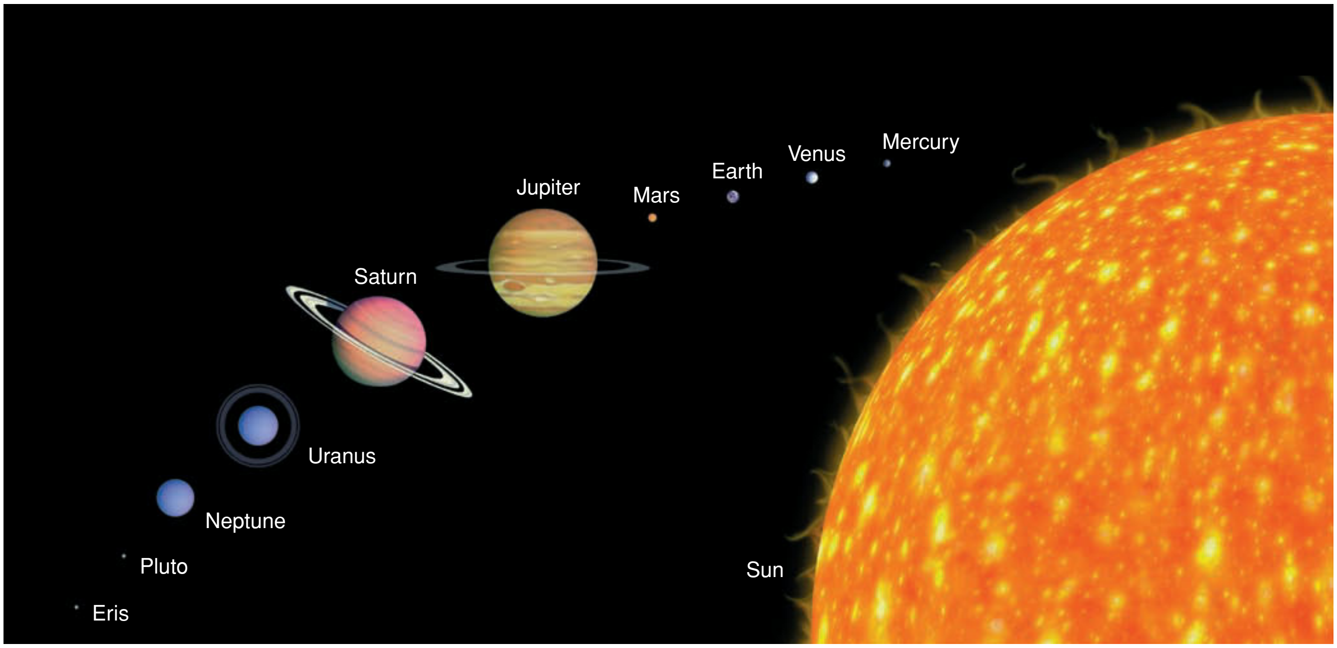
Figure 1.6a shows the Sun and planets at their correct sizes (but not distances) on the Voyage scale: The model Sun is about the size of a large grapefruit, Jupiter is about the size of a marble, and Earth is about the size of a pinhead or the ball point in a pen. You can immediately see some key facts 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 more than 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 Figure 1.6a) could swallow up the entire Earth.

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

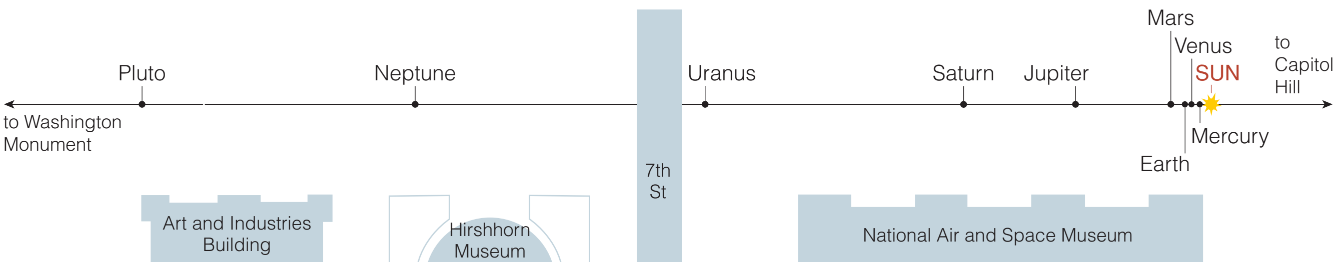
The scale of the solar system becomes even more remarkable when you combine the sizes shown in Figure 1.6a with the distances illustrated by the map of the Voyage model in Figure 1.6b. For example, the ball point–sized Earth is located about 15 meters (16.5 yards) from the grapefruit-sized Sun, which means you can picture Earth's orbit by imagining a ball point taking a year to make a circle of radius 15 meters around a grapefruit.

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

think about it Earth is the only place in our solar system—and the only place we yet know of in the universe—with conditions suitable for human life. How does visualizing Earth to scale affect your perspective on human existence? How does it affect your perspective on our planet? Explain.



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



b This map shows the locations of the Sun and planets in the Voyage model; 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 MA 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, which was built before the International Astronomical Union classified Pluto as a dwarf planet.

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 some 200 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 the Sun to Pluto in a few minutes on the Voyage scale, the *New Horizons* spacecraft that is currently making the real journey will have been in space nearly a decade by the time it flies past Pluto in 2015.

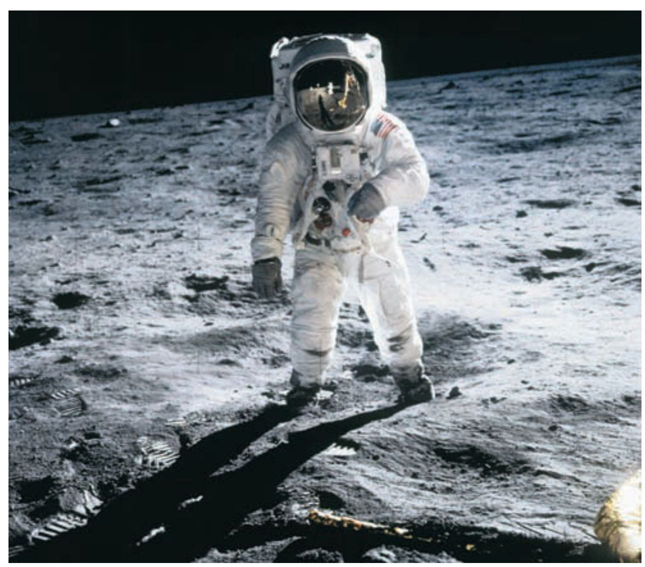


Figure 1.7

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."

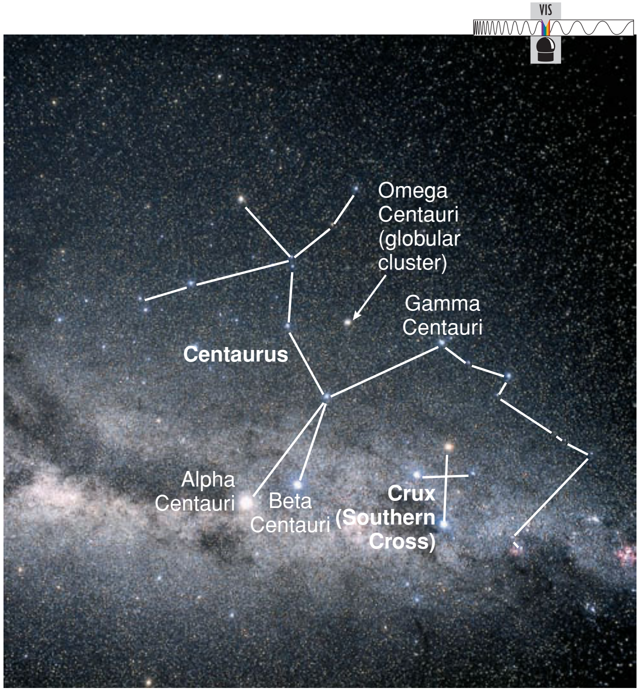


Figure 1.8

This photograph and diagram show the constellation Centaurus, visible from tropical and southern latitudes. Alpha Centauri's real distance of 4.4 light-years becomes 4400 kilometers (2700 miles) on the 1-to-10-billion Voyage scale.

• How far away are 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. But how far would you have to walk to reach the next star on this scale?

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

On the same scale on which Pluto is just a few minutes' walk from the Sun or Earth, the distance to the nearest stars is equivalent to the distance across the United States.

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

Now, consider the difficulty of detecting *planets* orbiting nearby stars. It 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 remarkable to realize that we have already detected hundreds of such planets **[Section 6.5]**.

The vast distances to the stars also offer a sobering lesson about interstellar travel. Although science fiction shows and movies 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

special**Topic:** | How Many Planets Are There in Our Solar System?

AS CHILDREN, WE were taught that there are nine planets in our solar system. However, in 2006 astronomers voted to demote Pluto to a dwarf *planet,* leaving our solar system with only eight official planets. Why the change, and is this really the end for Pluto as a planet?

When Pluto was discovered in 1930, it was assumed to be similar to other planets. But as we'll discuss in Chapter 9, we've since learned 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 than Pluto, astronomers could no longer avoid the question of what objects should count as planets.

At a contentious meeting in 2006, members of the International Astronomical Union (IAU) voted to define a *planet* as an object that (1) orbits a star (but is itself neither a star nor a moon); (2) is massive enough for its own gravity to give it a nearly round shape; and (3) has cleared the neighborhood around its orbit. Objects that meet the first two criteria but that have not cleared their orbital neighborhoods—including Pluto, Eris and the asteroid Ceres—are designated *dwarf planets*. The myriad objects that orbit the Sun but are too small to be round, including most asteroids and comets, make up a class called *small solar system bodies*.

Not all astronomers were happy with the new definitions, but for now they seem likely to hold. Of course, some people are likely to keep thinking of Pluto as a planet regardless of what professional astronomers say, much as many people still talk of Europe and Asia as separate continents even though both belong to the same land mass (Eurasia). So if you're a Pluto fan, don't despair: It's good to know the official definitions, but it's better to understand the science behind them.

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.

• How big is the Milky Way Galaxy?

The 1-to-10-billion scale is useless for thinking about distances beyond the nearest stars, because more distant stars would not fit on Earth on this scale. Visualizing the entire galaxy requires a new scale.

Let's reduce our solar system scale by another factor of 1 billion (making it a scale of 1 to 10^{19}). On this new scale, each light-year becomes 1 millimeter, and the 100,000-light-year diameter of the Milky Way Galaxy becomes 100 meters, or about the length of a football field. Visualize a football field with a scale model of our galaxy centered over midfield. Our entire solar system is a microscopic dot located around the 20-yard line. The 4.4-light-year separation between our solar system and Alpha Centauri becomes just 4.4 millimeters on this scale—smaller than the width of your little finger. If you stood at the position of our solar system in this model, millions of star systems would lie within reach of your arms.

Another way to put the galaxy into perspective is to consider its number of stars—more than 100 billion. Imagine that tonight you are having difficulty falling asleep (perhaps because you are contemplating the scale of the universe). Instead of counting sheep, you decide to count stars. If you are able to count about one star each second, on average, how long would it take you to count 100 billion stars in the Milky Way? Clearly, the answer is 100 billion (10^{11}) seconds, but how long is that?

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

Amazingly, 100 billion seconds turns out to be more than 3000 years. (You can confirm this by dividing 100 billion by the number of seconds in 1 year.) You would need thousands of years just to *count* the stars in the Milky Way Galaxy, and this assumes you never take a break—no sleeping, no eating, and absolutely no dying!

• How big is the universe?

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

Think for a moment about the total number of stars in all these galaxies. If we assume 100 billion stars per galaxy, the total number of stars in the observable universe is roughly 100 billion × 100 billion, or 10,000,000,000,000,000,000,000 (10^{22}).

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

How big is this number? Visit a beach. Run your hands through the fine-grained sand. Imagine counting each tiny grain of sand as it slips through your fingers. Then imagine counting every grain of sand on the beach and continuing on to count every grain of dry sand on *every* beach on Earth. If you could actually complete this task, you would find that,

common Misconceptions

Confusing Very Different Things

Most people are familiar with the terms *solar system* and *galaxy*, but some people mix them up. Remember that our solar system is a single star system, while our galaxy is a collection of more than 100 billion star systems—so many that it would take thousands of years just to count them. Confusing the terms *solar system* and *galaxy* therefore means making a mistake by a factor of 100 billion—a fairly big mistake!

Figure 1.9

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

Figure 1.10

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

roughly speaking, the number of grains of sand is comparable to the number of stars in the observable universe (Figure 1.9).

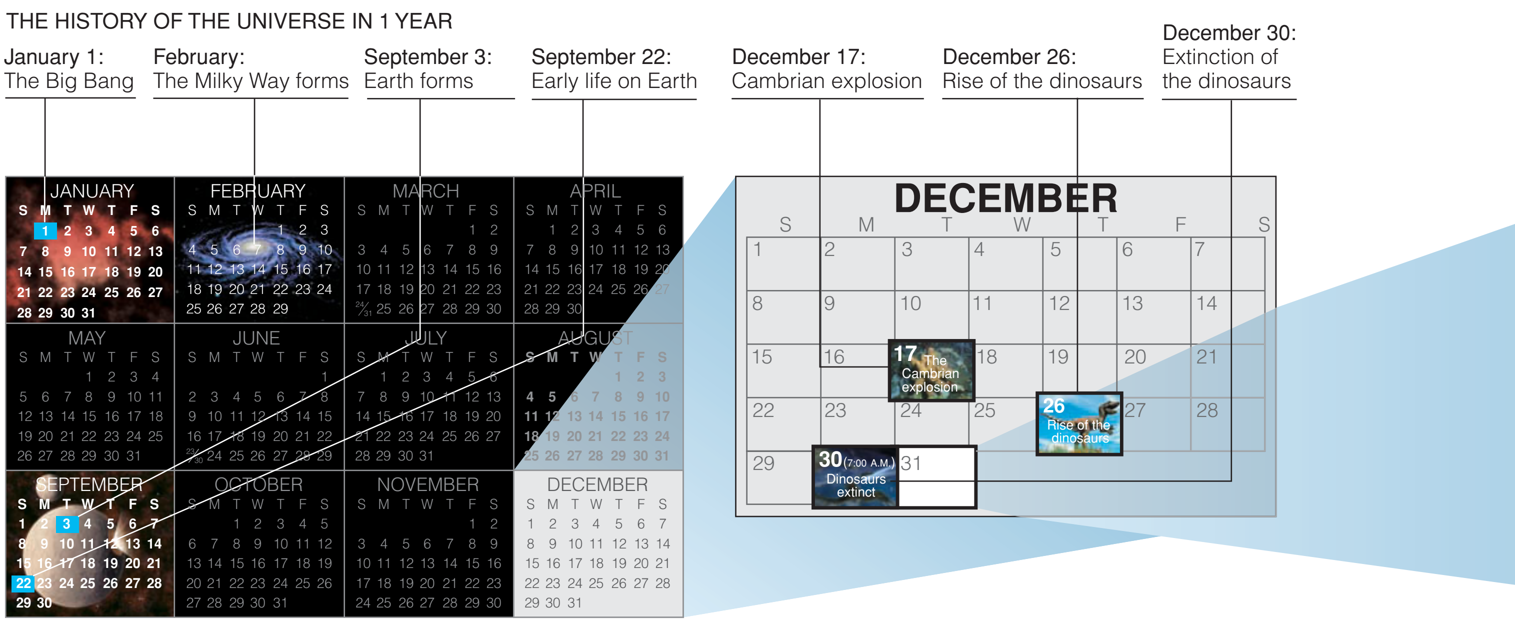
think about it Contemplate the fact that there are as many stars in the observable universe as grains of sand on all the beaches on Earth and that each star is a potential sun for a system of planets. With so many possible homes for life, do you think it is conceivable that life exists only on Earth? Why or why not?

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

Now that we have developed some perspective on the scale of space, we can do the same for the scale of time. Imagine the entire history of the universe, from the Big Bang to the present, compressed into a single year. We can represent this history with a *cosmic calendar*, on which the Big Bang takes place at the first instant of January 1 and the present day is the stroke of midnight on December 31 (Figure 1.10). For a universe that is about 14 billion years old, each month on the cosmic calendar represents a little more than 1 billion years.

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

Our solar system and our planet did not form until early September on this scale, or $4\frac{1}{2}$ billion years ago in real time. By late September, life on Earth was flourishing. However, for most of Earth's history, living organisms remained relatively primitive and microscopic. On the scale of the cosmic calendar, recognizable animals became prominent only in mid-December. Early dinosaurs appeared on the day after Christmas. Then, in a cosmic instant, the dinosaurs disappeared forever—probably due to the impact of an asteroid or a comet **[Section 9.4]**. In real time, the death of the dinosaurs occurred some 65 million years ago, but on the cosmic calendar it was only yesterday. With the dinosaurs gone, small



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

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

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

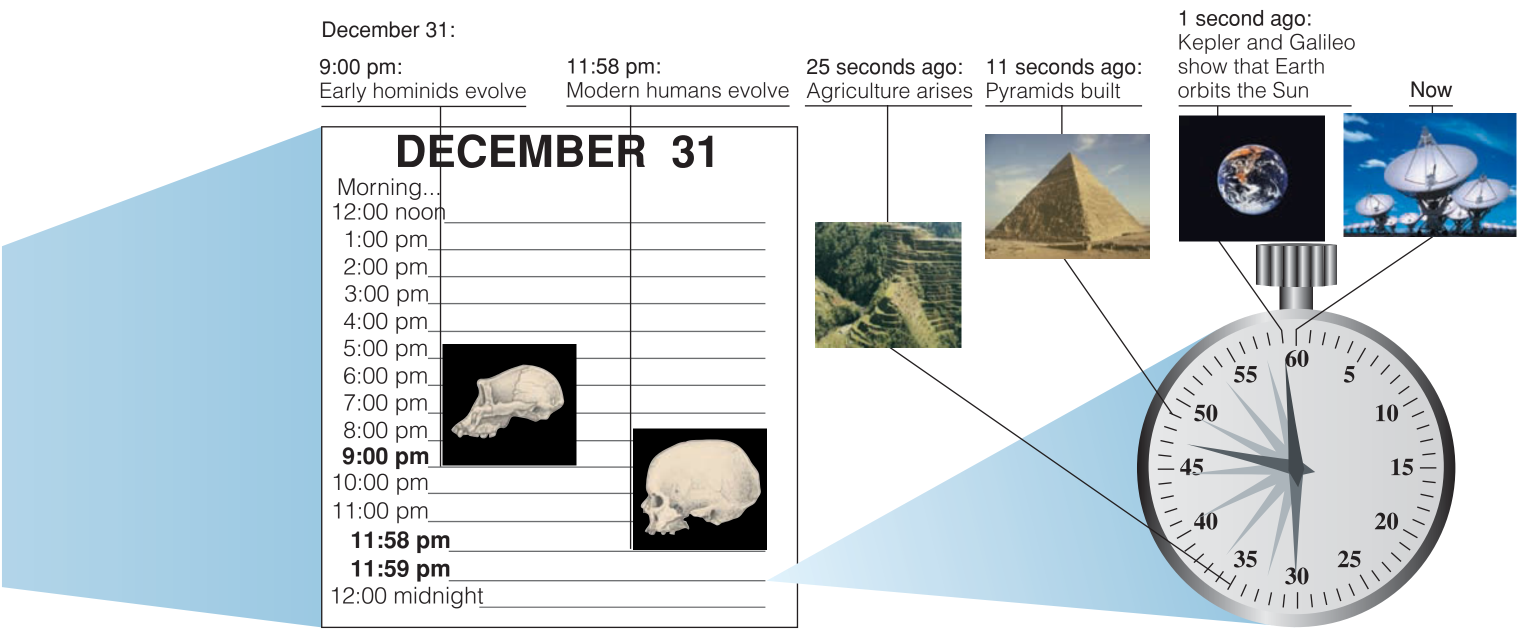
1.3 Spaceship Earth

Wherever you are as you read this book, you probably have the feeling that you're "just sitting here." Nothing could be further from the truth. In fact, you are being spun in circles as Earth rotates, you are racing around the Sun in Earth's orbit, and you are careening through the cosmos in the Milky Way Galaxy. In the words of noted inventor and philosopher R. Buckminster Fuller (1895–1983), you are a traveler on *spaceship Earth*. In this section, we'll take a brief look at the motion of spaceship Earth through the universe.

• How is Earth moving in our solar system?

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

Earth rotates once each day around its axis, which is the imaginary line connecting the North Pole to the South Pole. Earth rotates from west to east—counterclockwise as viewed from above the North Pole—which is why the Sun and stars appear to rise in the east and set in the west



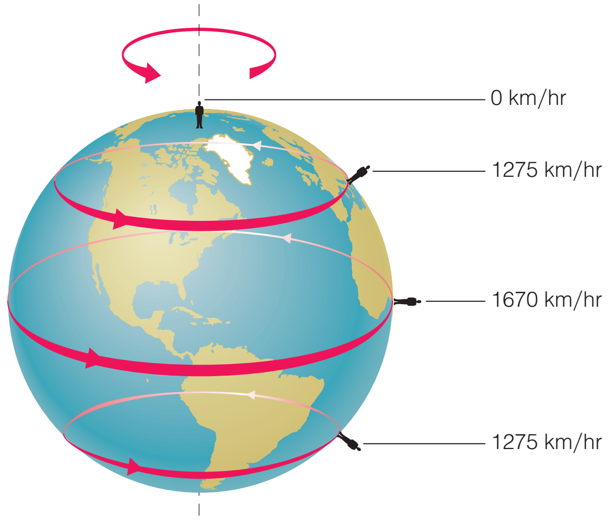


Figure 1.11

As Earth rotates, your speed around Earth's axis depends on your location: The closer you are to the equator, the faster you travel with rotation. Notice that Earth rotates from west to east, which is why the Sun appears to rise in the east and set in the west.

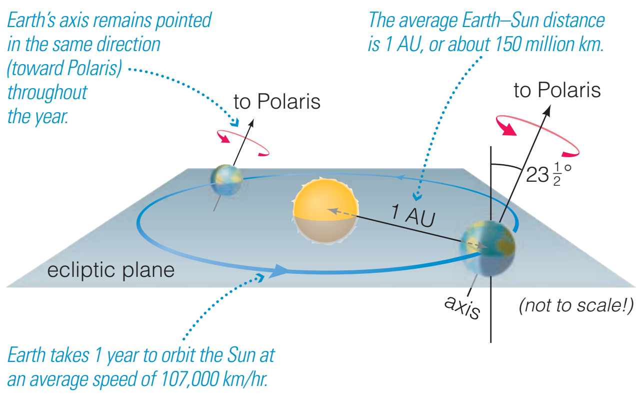


Figure 1.12

Earth takes a year to complete an orbit of the Sun, but its orbital speed is still surprisingly fast. Notice that Earth both rotates and orbits counterclockwise as viewed from above the North Pole.

each day. Although we do not feel any obvious effects from Earth's rotation, the speed of rotation is substantial (Figure 1.11). Unless you live very near the North or South Poles, you are whirling around Earth's axis at a speed of more than 1000 kilometers per hour (600 miles per hour)—faster than most airplanes travel.

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

At the same time Earth is rotating, it is also orbiting the Sun, completing one orbit each year (Figure 1.12). Earth's average orbital distance is called an **astronomical unit**, or **AU**, equivalent to about 150 million kilometers (93 million miles). Again, even though we don't feel the effects of this motion, the speed is impressive: At all times we are racing around the Sun at a speed in excess of 100,000 kilometers per hour (60,000 miles per hour), faster than any spacecraft yet launched.

As you study Figure 1.12, notice that Earth's orbital path defines a flat plane that we call the **ecliptic plane**. Earth's axis is tilted by $23\frac{1}{2}°$ from a line *perpendicular* to the ecliptic plane. This **axis tilt** happens to be oriented so that it points almost directly at a star called *Polaris,* or the *North Star*. Keep in mind that the idea of axis tilt makes sense only in relation to the ecliptic plane. That is, the idea of "tilt" by itself has no meaning in space, where there is no absolute up or down. In space, "up" and "down" mean only "away from the center of Earth (or another planet)" and "toward the center of Earth," respectively.

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

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

• How is our solar system moving in the Milky Way Galaxy?

Rotation and orbit are only part of the travels of spaceship Earth. Our entire solar system is on a great journey within the Milky Way Galaxy.

Our Local Solar Neighborhood Let's begin with the motion of our solar system relative to nearby stars in what we call our *local solar neighborhood,* the region of the Sun and nearby stars. The small box in Figure 1.13 shows that stars within the local solar neighborhood (like the stars of any other small region of the galaxy) move essentially at random relative to one another. They also generally move quite fast. For example, we are moving relative to nearby stars at an average speed of about 70,000 kilometers per hour (40,000 miles per hour), about three times as fast as the Space Station orbits Earth.

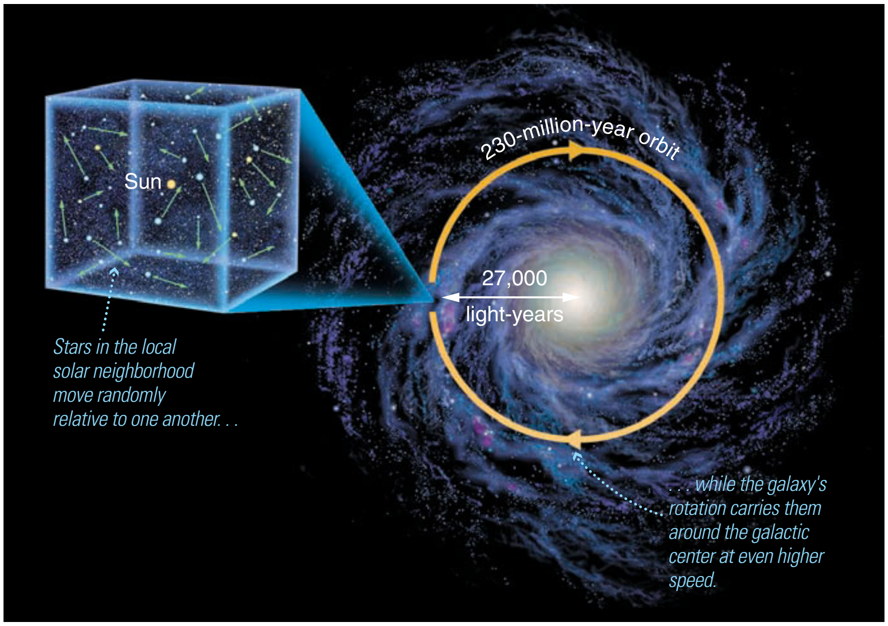


Figure 1.13

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

Given these high speeds, why don't we see nearby stars racing around the sky? The answer lies in their vast distances from us. You've probably noticed that a distant airplane appears to move through the sky more slowly than one flying close overhead. Stars are so far away that even at speeds of 70,000 kilometers per hour, their motions would be noticeable to the naked eye only if we watched them for thousands of years. That is why the patterns in the constellations seem to remain fixed. Nevertheless, in 10,000 years the constellations will be noticeably different from those we see today. In 500,000 years they will be unrecognizable. If you could watch a time-lapse movie made over millions of years, you *would* see stars racing across the sky.

Stars in our local solar neighborhood move in essentially random directions relative to each other.

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

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

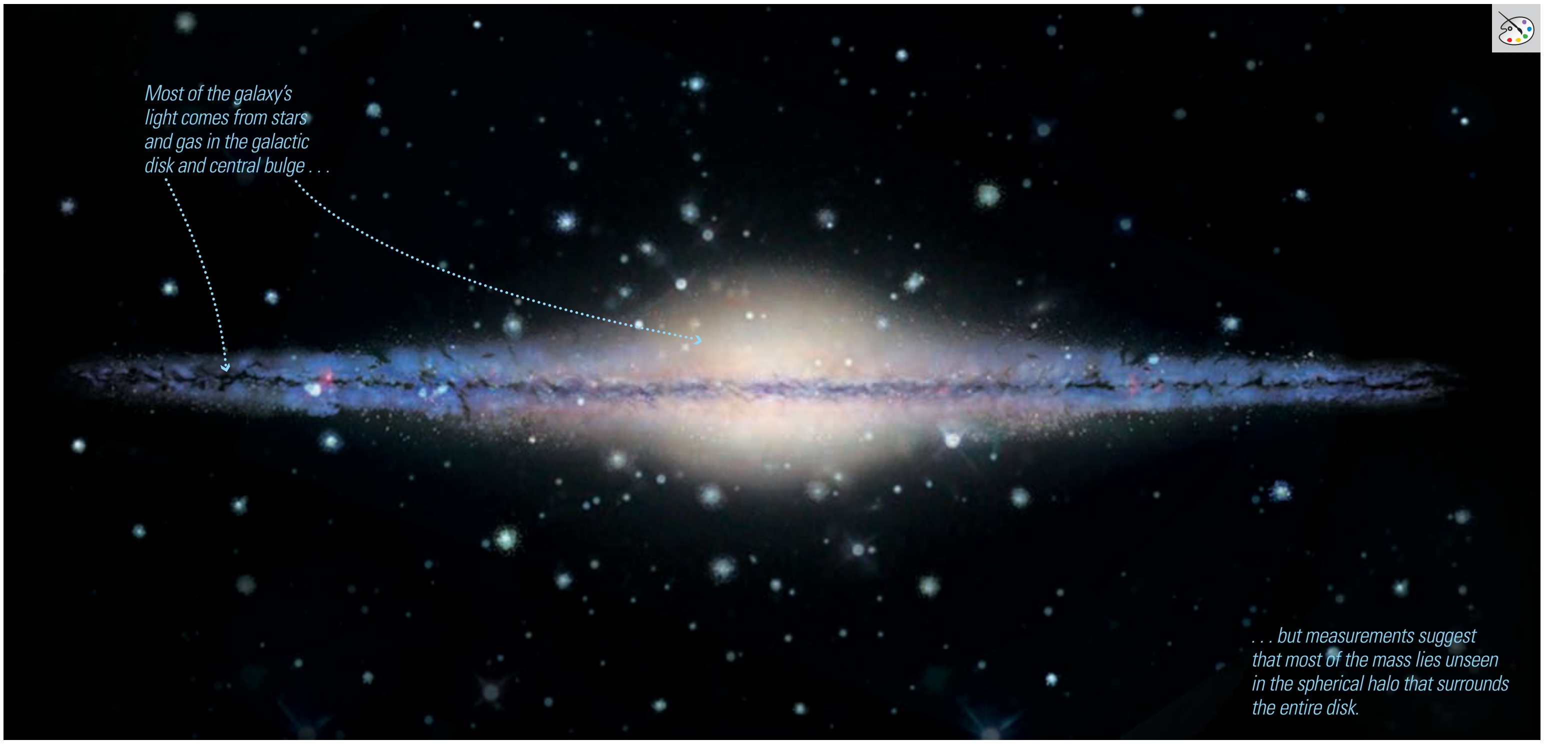


Figure 1.14

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

Careful study of the galaxy's rotation reveals one of the greatest mysteries in science. Stars at different distances from the galactic center orbit at different speeds, and we can learn how mass is distributed in the galaxy by measuring these speeds. Such studies indicate that the stars in the disk of the galaxy represent only the "tip of the iceberg" compared to the mass of the entire galaxy (Figure 1.14). Most of the mass of the galaxy seems to be located outside the visible disk, in what we call the *halo*. We don't know the nature of this mass, but we call it *dark matter* because we have not detected any light coming from it. Studies of other galaxies suggest that they also are made mostly of dark matter, which means this mysterious matter must significantly outweigh the ordinary matter that makes up planets and stars. An even more mysterious *dark energy* seems to make up much of the total energy content of the universe. We'll discuss the mysteries of dark matter and dark energy in Chapter 16.

The Sun and other stars in our neighborhood orbit the center of the galaxy every 230 million years, because the entire galaxy is rotating.

• How do galaxies move within the universe?

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

When we look outside the Local Group, however, we find two astonishing facts recognized in the 1920s by Edwin Hubble, for whom the Hubble Space Telescope was named:

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

These facts might make it sound like we suffer from a cosmic case of chicken pox, but there is a much more natural explanation: *The entire universe is expanding.* We'll save the details for later in the book (Chapter 15), but you can understand the basic idea by thinking about a raisin cake baking in an oven.

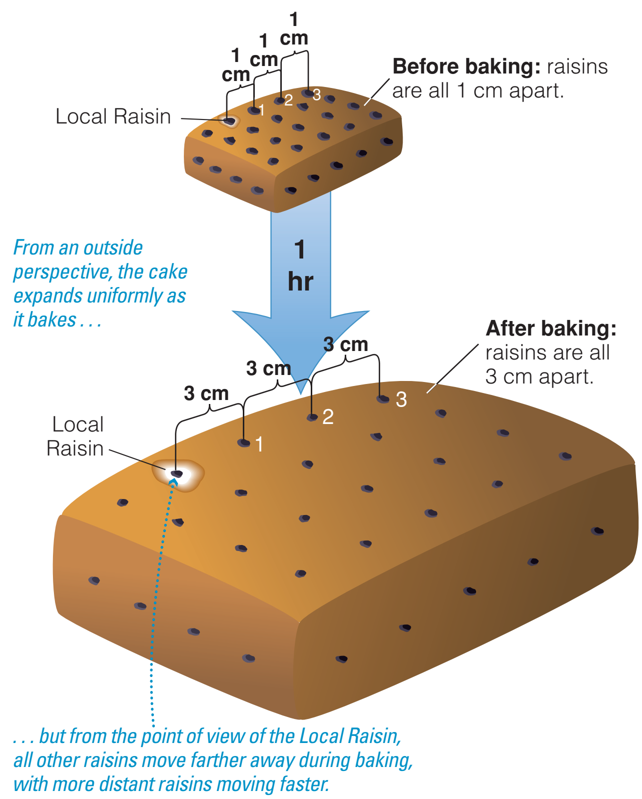
Imagine that you make a raisin cake in which the distance between adjacent raisins is 1 centimeter. You place the cake into the oven, where it expands as it bakes. After 1 hour, you remove the cake, which has expanded so that the distance between adjacent raisins has increased to 3 centimeters (Figure 1.15). The expansion of the cake seems fairly obvious. But what would you see if you lived *in* the cake, as we live in the universe?

Pick any raisin (it doesn't matter which one) and call it the Local Raisin. Figure 1.15 shows one possible choice, with three nearby raisins also labeled. The accompanying table summarizes what you would see if you lived within the Local Raisin. Notice, for example, that Raisin 1 starts out at a distance of 1 centimeter before baking and ends up at a distance of 3 centimeters after baking, which means it moves a distance of 2 centimeters away from the Local Raisin during the hour of baking. Hence, its speed as seen from the Local Raisin is 2 centimeters per hour. Raisin 2 moves from a distance of 2 centimeters before baking to a distance of 6 centimeters after baking, which means it moves a distance of 4 centimeters away from the Local Raisin during the hour. Hence, its speed is 4 centimeters per hour, or twice as fast as the speed of Raisin 1. Generalizing, the fact that the cake is expanding means that all the raisins are moving away from the Local Raisin, with more distant raisins moving away faster.

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

Hubble's discovery that galaxies are moving in much the same way as the raisins in the cake, with most moving away from us and more distant ones moving away faster, implies that our universe is expanding much like the raisin cake. If you now imagine the Local Raisin as representing our Local Group of galaxies and the other raisins as representing more distant galaxies or clusters of galaxies, you have a basic picture of the expansion of the universe. Like the expanding batter between the raisins in the cake, *space* itself is growing between galaxies. More distant galaxies move away from us faster because they are carried along with this expansion like the raisins in the expanding cake. Many billions of light-years away, we see galaxies moving away from us at speeds approaching the speed of light.

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



Distances and Speeds as Seen from the Local Raisin

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

Figure 1.15 MA interactive figure

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

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

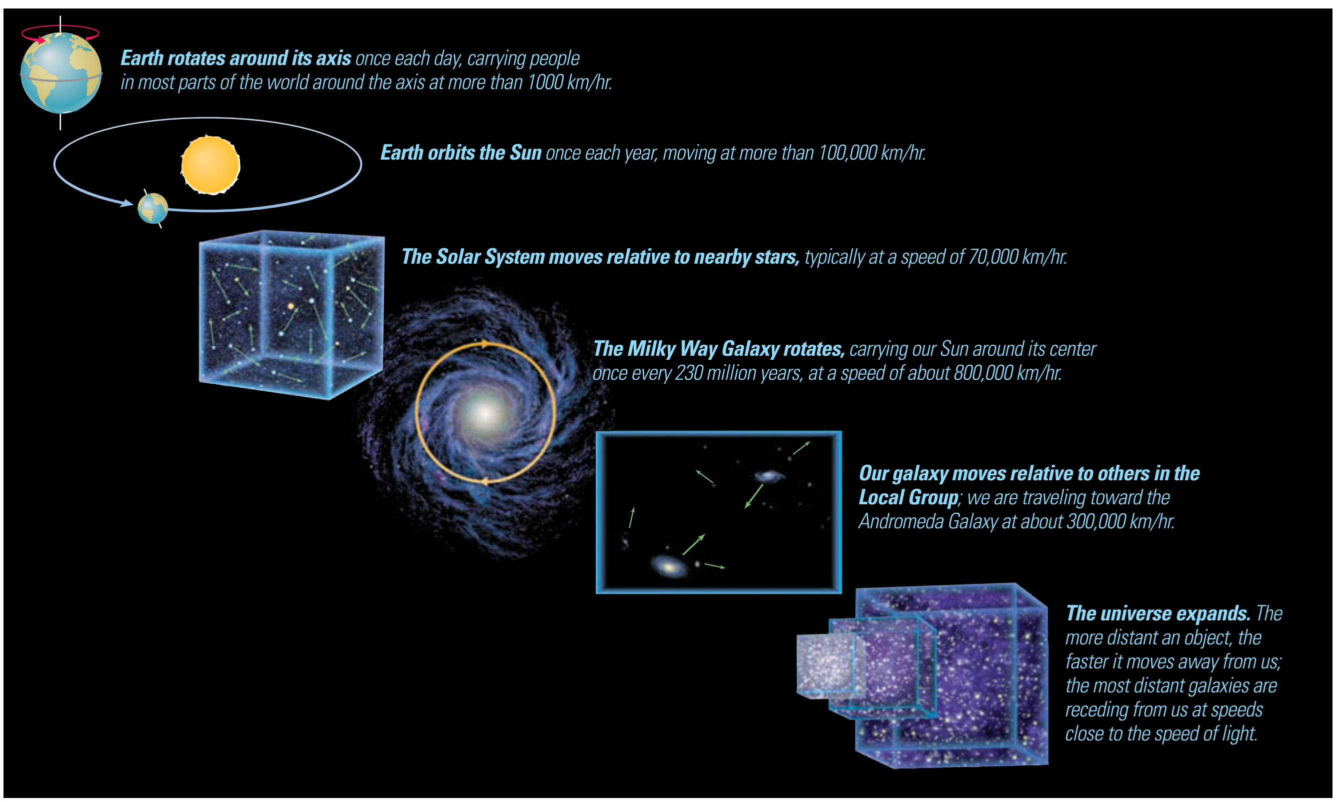
• Are we ever sitting still?

As we have seen, we are never truly sitting still. Figure 1.16 summarizes the motions we have covered. We spin around Earth's axis at more than 1000 km/hr, while our planet orbits the Sun at more than 100,000 km/hr. Our solar system moves among the stars of the local solar neighborhood at typical speeds of 70,000 km/hr, while also orbiting the center of the Milky Way Galaxy at a speed of about 800,000 km/hr. Our galaxy moves among the other galaxies of the Local Group, while all other galaxies move away from us at speeds that increase with distance in our expanding universe. Spaceship Earth is carrying us on a remarkable journey.

We and our planet are constantly on the move through the universe, and at surprisingly high speeds.

Figure 1.16

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



the big picture

Putting Chapter 1 into Perspective

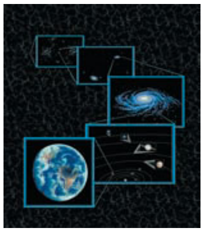
In this first chapter, we developed a broad overview of our place in the universe. As we consider the universe in more depth in the rest of the book, remember the following "big picture" ideas:

- Earth is not the center of the universe but instead is a planet orbiting a rather ordinary star in the Milky Way Galaxy. The Milky Way Galaxy, in turn, is one of billions of galaxies in our observable universe.
- We are "star stuff." The atoms from which we are made began as hydrogen and helium in the Big Bang and were later fused into heavier elements by massive stars. Stellar deaths released these atoms into space, where our galaxy recycled them into new stars and planets. Our solar system formed from such recycled matter some $4\frac{1}{2}$ billion years ago.
- Cosmic distances are literally astronomical, but we can put them in perspective with the aid of scale models and other scaling techniques. When you think about these enormous scales, don't forget that every star is a sun and every planet is a unique world.
- We are latecomers on the scale of cosmic time. The universe was already more than half its current age when our solar system formed, and it took billions of years more before humans arrived on the scene.
- All of us are being carried through the cosmos on spaceship Earth. Although we cannot feel this motion, the associated speeds are surprisingly high. Learning about the motions of spaceship Earth gives us a new perspective on the cosmos and helps us understand its nature and history.

summary of key concepts

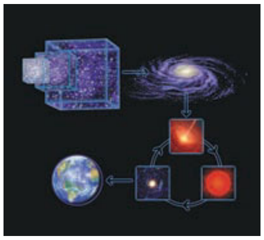
1.1 Our Modern View of the Universe

- **What is our place in the universe?**



Earth is a planet orbiting the Sun. Our Sun is one of more than 100 billion stars in the **Milky Way Galaxy**. Our galaxy is one of about 40 galaxies in the **Local Group**. The Local Group is one small part of the **Local Supercluster**, which is one small part of the **universe**.

- **How did we come to be?**

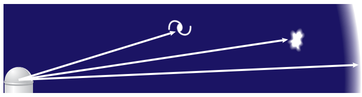


The universe began in the **Big Bang** and has been expanding ever since, except in localized regions where gravity has caused matter to collapse into galaxies and stars. The Big Bang essentially produced only two chemical elements: hydrogen and helium. The rest have been produced by stars, which is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

- **How can we know what the universe was like in the past?**

Light takes time to travel through space, so the farther away we look in distance, the further back we look in time. When we look billions of **light-years** away, we see pieces of the universe as they were billions of years ago.

- **Can we see the entire universe?**



No. The age of the universe limits the extent of our **observable universe**. Because the universe is about 14 billion years old, our observable universe extends to a distance of about 14 billion light-years. If we tried to look beyond that distance, we'd be trying to look to a time before the universe existed.

1.2 The Scale of the Universe

- **How big is Earth compared to our solar system?**

On a scale of 1 to 10 billion, the Sun is about the size of a grapefruit. Planets are much smaller, with Earth the size of a ball point and Jupiter the size of a marble on this scale. The distances between planets are huge compared to their sizes, with Earth orbiting 15 meters from the Sun on this scale.

- **How far away are the stars?**

On the 1-to-10-billion scale, it is possible to walk from the Sun to Pluto in just a few minutes. On the same scale, the nearest stars besides the Sun are thousands of kilometers away.

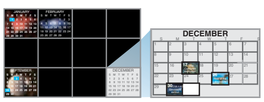
- **How big is the Milky Way Galaxy?**

Using a scale on which the Milky Way galaxy is the size of a football field, the distance to the nearest star would be only about 4 millimeters. There are so many stars in our galaxy that it would take thousands of years just to count them.

- **How big is the universe?**

The observable universe contains roughly 100 billion galaxies, and the total number of stars is comparable to the number of grains of dry sand on all the beaches on Earth.

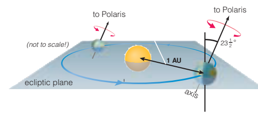
- **How do our lifetimes compare to the age of the universe?**



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

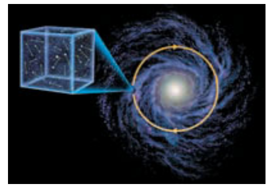
1.3 Spaceship Earth

- **How is Earth moving in our solar system?**



Earth **rotates** on its axis once each day and **orbits** the Sun once each year. Earth orbits at an average distance from the Sun of 1 **AU** and with an **axis tilt** of $23\frac{1}{2}°$ to a line perpendicular to the **ecliptic plane**.

- **How is our solar system moving in the Milky Way Galaxy?**

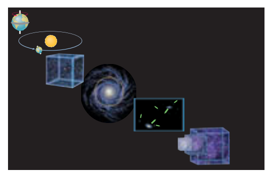


We move randomly relative to other stars in our local solar neighborhood. The speeds are substantial by earthly standards, but stars are so far away that their motion is undetectable to the naked eye. Our Sun and other stars in our neighborhood orbit the center of the galaxy every 230 million years, because the entire galaxy is rotating.

- **How do galaxies move within the universe?**

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

- **Are we ever sitting still?**



We are never truly sitting still. We spin around Earth's axis and orbit the Sun. Our solar system moves among the stars of the local solar neighborhood while orbiting the center of the Milky Way Galaxy. Our galaxy moves among the other galaxies of the Local Group, while all other galaxies move away from us in our expanding universe.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 1 Visual Quiz at www.masteringastronomy.com.

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

Diameter of Earth = 12,800 km
Earth–Moon distance = 384,000 km
Diameter of Sun = 1,400,000 km
Earth–Sun distance = 150,000,000 km

1. If you wanted to show the distance between Earth and the Moon on the same scale, about how far apart would you need to place the two photos on page 22?
   a. 10 centimeters (about the width of your hand)
   b. 1 meter (about the length of your arm)
   c. 100 meters (about the length of a football field)
   d. 1 kilometer (a little more than a half mile)
2. Suppose you wanted to show the Sun on the same scale. About how big would it need to be?
   a. 2.5 centimeters in diameter (the size of a golf ball)
   b. 25 centimeters in diameter (the size of a basketball)
   c. 2.5 meters in diameter (about 8 feet across)
   d. 2.5 kilometers in diameter (the size of a small town)
3. About how far away from Earth would the Sun be located on this scale?
   a. 3.75 meters (about 12 feet)
   b. 37.5 meters (about the height of a 12-story building)
   c. 375 meters (about the length of four football fields)
   d. 37.5 kilometers (the size of a large city)
4. Could you use the same scale to represent the distances to nearby stars? Why or why not?

exercises and problems

Mastering ASTRONOMY®

For instructor-assigned homework go to www.masteringastronomy.com.

Review Questions

1. What do we mean by a *geocentric* universe? Contrast a geocentric view with our modern view of the universe.
2. Briefly describe the major levels of structure (such as planet, star, galaxy) in the universe.
3. What do we mean when we say that the universe is *expanding*? How does expansion lead to the idea of the *Big Bang*?
4. What did Carl Sagan mean when he said that we are "star stuff"?
5. How fast does light travel? What is a *light-year*?
6. Explain the statement *The farther away we look in distance, the further back we look in time*.
7. What do we mean by the *observable universe?* Is it the same thing as the entire universe?
8. Describe the solar system as it looks on the 1-to-10-billion scale used in the text. How far away are other stars on this same scale?
9. Describe at least one way to put the scale of the Milky Way Galaxy into perspective and at least one way to put the size of the observable universe into perspective.
10. Use the cosmic calendar to describe how the human race fits into the scale of time.
11. Define *astronomical unit, ecliptic plane,* and *axis tilt*. Explain how each is related to Earth's rotation and/or orbit.
12. What is the shape of the Milky Way Galaxy? Describe our solar system's location and motion.
13. Distinguish between our galaxy's *disk* and *halo*. Where does the mysterious *dark matter* seem to reside?
14. What key observations lead us to conclude that the universe is expanding? Use the raisin cake model to explain how these observations imply expansion.

Test Your Understanding

Does It Make Sense?

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

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

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

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

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

25. Which of the following correctly lists our "cosmic address" from small to large? (a) Earth, solar system, Milky Way Galaxy, Local Group, Local Supercluster, universe (b) Earth, solar system, Local Group, Local Supercluster, Milky Way Galaxy, universe (c) Earth, Milky Way Galaxy, solar system, Local Group, Local Supercluster, universe
26. When we say the universe is *expanding,* we mean that (a) everything in the universe is growing in size. (b) the average distance between galaxies is growing with time. (c) the universe is getting older.

27. If stars existed but galaxies did not, (a) we would probably exist anyway. (b) we would not exist because life on Earth depends on the light of galaxies. (c) we would not exist because we are made of material that was recycled in galaxies.
28. Could we see a galaxy that is 20 billion light-years away? (a) Yes, if we had a big enough telescope. (b) No, because it would be beyond the bounds of our observable universe. (c) No, because a galaxy could not possibly be that far away.
29. The star Betelgeuse is about 425 light-years away. If it explodes tonight, (a) we'll know because it will be brighter than the full Moon in the sky. (b) we'll know because debris from the explosion will rain down on us from space. (c) we won't know about it until 425 years from now.
30. If we represented the solar system on a scale that allowed us to walk from the Sun to Pluto in a few minutes, then (a) the planets would be the size of basketballs and the nearest stars would be a few miles away. (b) the planets would all be marble-size or smaller and the nearest stars would be thousands of miles away. (c) the planets would be microscopic and the stars would be light-years away.
31. The total number of stars in the observable universe is roughly equivalent to (a) the number of grains of sand on all the beaches on Earth. (b) the number of grains of sand on Miami Beach. (c) infinity.
32. The age of our solar system is about (a) one-third of the age of the universe. (b) three-fourths of the age of the universe. (c) two billion years less than the age of the universe.
33. As astronomical unit is (a) any planet's average distance from the Sun. (b) Earth's average distance from the Sun. (c) any large astronomical distance.
34. The fact that nearly all galaxies are moving away from us, with more distant ones moving faster, tells us that (a) the universe is expanding. (b) galaxies repel each other like magnets. (c) our galaxy lies near the center of the universe.

Process of Science

35. *Earth as a Planet.* For most of human history, scholars assumed Earth was the center of the universe. Today, we know that Earth is just one planet orbiting the Sun, and the Sun is just one star in a vast universe. How did science make it possible for us to learn these facts about Earth?
36. *Thinking About Scale.* One key to success in science is finding a simple way to evaluate new ideas, and making a simple scale model is often helpful. Suppose someone tells you that the reason it is warmer during the day than at night is that the day side of Earth is closer to the Sun than the night side. Evaluate this idea by thinking about the size of Earth and its distance from the Sun in a scale model of the solar system.
37. *Looking for Evidence.* In this first chapter, we have discussed the scientific story of the universe but have not yet discussed most of the evidence that backs it up. Choose one idea presented in this chapter—such as the idea that there are billions of galaxies in the universe, or that the universe was born in the Big Bang, or that the galaxy contains more dark matter than ordinary matter—and briefly discuss the type of evidence you would want to see before accepting the idea. (*Hint*: It's okay to look ahead in the book to see the evidence presented in later chapters.)

Group Work Exercise

38. *Counting the Milky Way's Stars.* In this exercise, you will first make an estimate of the number of stars in the Milky Way, and then apply some scientific thinking to your estimation method. Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Proposer* (proposes explanations to the group), *Skeptic* (points out weaknesses in proposed explanations), and *Moderator* (leads group discussion and makes sure everyone contributes).
    a. Estimate the number of stars in the Milky Way as follows. First, count the number of stars within 12 light-years of the Sun, which are listed in Appendix F. Assuming that the Milky Way's disk is 100,000 light-years across and 1000 light-years thick, its volume is about 1 billion times the volume of the region of your star count. You should therefore multiply your count by 1 billion to get an estimate of the total number of stars in the Milky Way.
    b. Your estimate from part (a) is based on the number of stars near the Sun. Compare it to the value given in this chapter and determine whether your estimate is an underestimate or an overestimate of the total number of stars in the Milky Way. Write down a list of possible reasons why your technique gave you an under/overestimate.

Investigate Further

Short-Answer/Essay Questions

39. *Our Cosmic Origins.* Write one to three paragraphs summarizing why we could not be here if the universe did not contain both stars and galaxies.
40. *Alien Technology.* Some people believe that Earth is regularly visited by aliens who travel here from other star systems. For this to be true, how much more advanced than our own technology would the aliens' technology have to be? Write one to two paragraphs to give a sense of the technological difference. (*Hint:* The ideas of scale in this chapter can help you contrast the distance the aliens would have to travel with the distances we are now capable of traveling.)
41. *Stellar Collisions.* Is there any danger that another star will come crashing through our solar system in the near future? Explain.
42. *Raisin Cake Universe.* Suppose that all the raisins in a cake are 1 centimeter apart before baking and 4 centimeters apart after baking.
    a. Draw diagrams to represent the cake before and after baking.
    b. Identify one raisin as the Local Raisin on your diagrams. Construct a table showing the distances and speeds of other raisins as seen from the Local Raisin.
    c. Briefly explain how your expanding cake is similar to the expansion of the universe.
43. *The Cosmic Perspective.* Write a short essay describing how the ideas presented in this chapter affect your perspectives on your own life and on human civilization.

Quantitative Problems

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

44. *Distances by Light.* Just as a light-year is the distance that light can travel in 1 year, we define a light-second as the distance that light can travel in 1 second, a light-minute as the distance that

light can travel in 1 minute, and so on. Calculate the distance in both kilometers and miles represented by each of the following:

a. 1 light-second
b. 1 light-minute
c. 1 light-hour
d. 1 light-day

45. *Moonlight and Sunlight.* How long does it take light to travel from
    a. the Moon to Earth?
    b. the Sun to Earth?
46. *Saturn vs. the Milky Way.* Photos of Saturn and photos of galaxies can look so similar that children often think the photos show similar objects. In reality, a galaxy is far larger than any planet. About how many times larger is the diameter of the Milky Way Galaxy than the diameter of Saturn's rings? (*Data:* Saturn's rings are about 270,000 km in diameter; the Milky Way is 100,000 light-years in diameter.)
47. *Driving Trips.* Imagine that you could drive your car at a constant speed of 100 km/hr (62 mi/hr), even across oceans and in space. How long would it take to drive
    a. around Earth's equator? (*Hint:* Use Earth's circumference of about 40,000 km.)
    b. from the Sun to Earth?
    c. from the Sun to Pluto? (Hint: You can find Pluto's distance in Appendix E.)
    d. to Alpha Centauri (4.4 light-years away)?
48. *Faster Trip.* Suppose you wanted to reach Alpha Centauri in 100 years.
    a. How fast would you have to go, in km/hr?
    b. How many times faster is the speed you found in (a) than the speeds of our fastest current spacecraft (around 50,000 km/hr)?

Discussion Questions

49. *Vast Orbs.* Dutch astronomer Christiaan Huygens may have been the first person to truly understand both the large sizes of other planets and the great distances to other stars. In 1690, he wrote: "How vast those Orbs must be, and how inconsiderable this Earth, the Theatre upon which all our mighty Designs, all our Navigations, and all our Wars are transacted, is when compared to them. A very fit consideration, and matter of Reflection, for those Kings and Princes who sacrifice the Lives of so many People, only to flatter their Ambition in being Masters of some pitiful corner of this small Spot." What do you think he meant? Explain.
50. *Infant Species.* In the last few tenths of a second before midnight on December 31 of the cosmic calendar, we have developed an incredible civilization and learned a great deal about the universe, but we also have developed technology through which we could destroy ourselves. The midnight bell is striking, and the choice for the future is ours. How far into the next cosmic year do you think our civilization will survive? Defend your opinion.
51. *A Human Adventure.* Astronomical discoveries clearly are important to science, but are they also important to our personal lives? Defend your opinion.

Web Projects

52. *Astronomy on the Web.* The Web contains a vast amount of astronomical information. Spend at least an hour exploring astronomy on the Web. Write two or three paragraphs summarizing what you learned from your search. What was your favorite astronomical Web site, and why?
53. *NASA Missions.* Visit the NASA Web site to learn about upcoming astronomy missions. Write a one-page summary of the mission you feel is most likely to provide new astronomical information during the time you are enrolled in this astronomy course.
54. *The Hubble Ultra Deep Field.* The photo that opens this chapter is called the Hubble Ultra Deep Field. Find the photo on the Hubble Space Telescope Web site. Learn how it was taken, what it shows, and what we've learned from it. Write a short summary of your findings.

2

Discovering the Universe for Yourself

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

learning goals

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

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

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

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

This is an exciting time in the history of astronomy. A new generation of telescopes is scanning the depths of the universe. Increasingly sophisticated space probes are collecting new data about the planets and other objects in our solar system. Rapid advances in computing technology are allowing scientists to analyze the vast amount of new data and to model the processes that occur in planets, stars, galaxies, and the universe.

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

essential preparation

1. What is our place in the universe? [Section 1.1]
2. How far away are the stars? [Section 1.2]
3. Are we ever sitting still? [Section 1.3]

2.1 Patterns in the Night Sky

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

• What does the universe look like from Earth?

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

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

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

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

Recognizing the patterns of just 20 to 40 constellations is enough to make the sky seem as familiar as your own neighborhood. The best way to learn the constellations is to go out and view them, guided by a few visits to a planetarium and star charts like the ones in the back of this book [Appendix I].

Figure 2.1

This photo shows the Milky Way over Haleakala crater on the island of Maui, Hawaii. The bright spot just below and slightly left of the center of the band is the planet Jupiter.

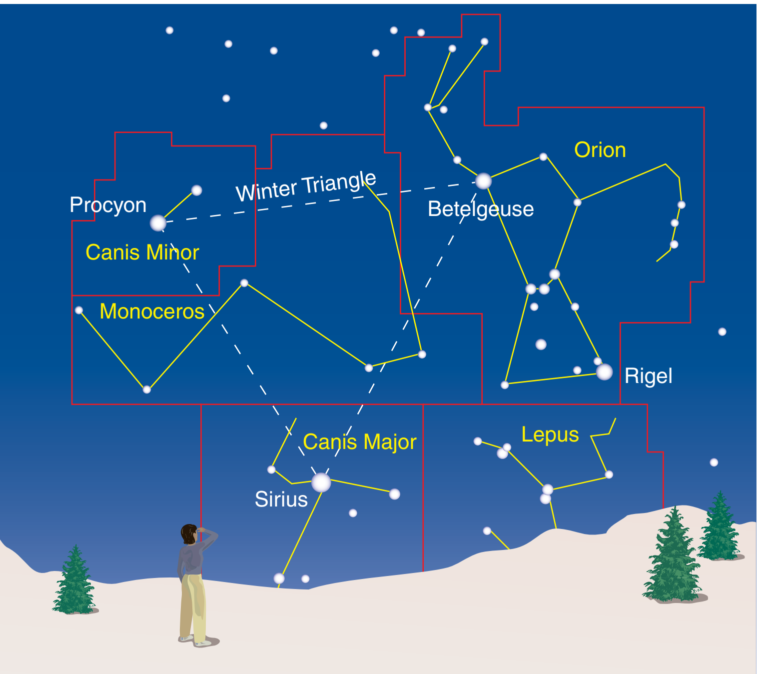


Figure 2.2

Red lines mark official borders of several constellations near Orion. Yellow lines connect recognizable patterns of stars within constellations. Sirius, Procyon, and Betelgeuse form a pattern that spans several constellations and is called the *Winter Triangle*. It is easy to see on clear winter evenings.

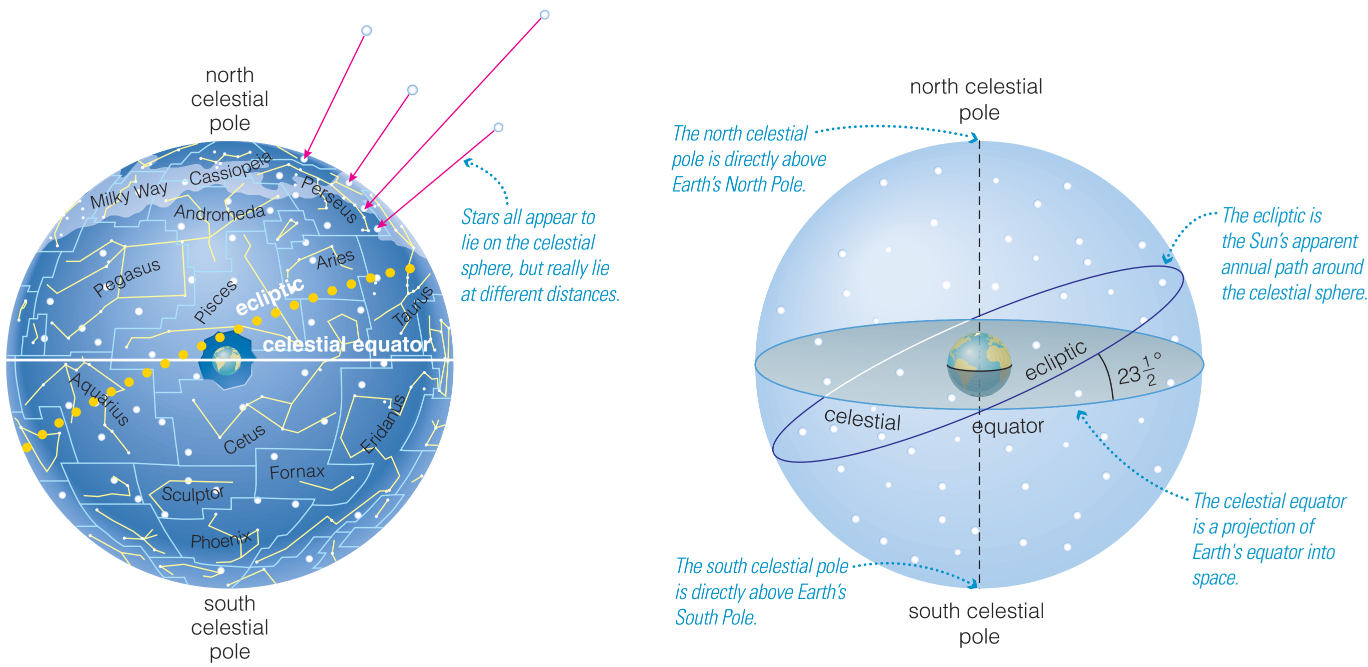
The Celestial Sphere The stars in a particular constellation appear to lie close to one another but may actually be at very different distances from Earth. This illusion occurs because we lack depth perception when we look into space, a consequence of the fact that the stars are so far away **[Section 1.2]**. The ancient Greeks mistook this illusion for reality, imagining the stars and constellations to lie on a great **celestial sphere** that surrounds Earth (Figure 2.3a).

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

We now know that Earth seems to be in the center of the celestial sphere only because it is where we are located as we look out into space. Nevertheless, the celestial sphere is a useful illusion, because it allows us to map the sky as seen from Earth. For reference, we identify the following special features on the celestial sphere (Figure 2.3b).

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

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



a A model of the celestial sphere shows stars and constellations much like the way a globe of Earth shows cities and national borders.

b This schematic diagram shows key features of the celestial sphere.

Figure 2.3

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

Figure 2.4 shows the idea. The Milky Way Galaxy is shaped like a thin pancake with a bulge in the middle. We view the universe from our location a little more than halfway out from the center of this "pancake." In all directions that we look within the pancake, we see the countless stars and vast interstellar clouds that make up the Milky Way in the night sky; that is why the band of light makes a full circle around our sky. The Milky Way appears somewhat wider in the direction of the constellation Sagittarius, because when we look in that direction, we are looking toward the galaxy's central bulge. We have a clear view to the distant universe only when we look *away* from the galactic plane, along directions that have relatively few stars and clouds to block our view.

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

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

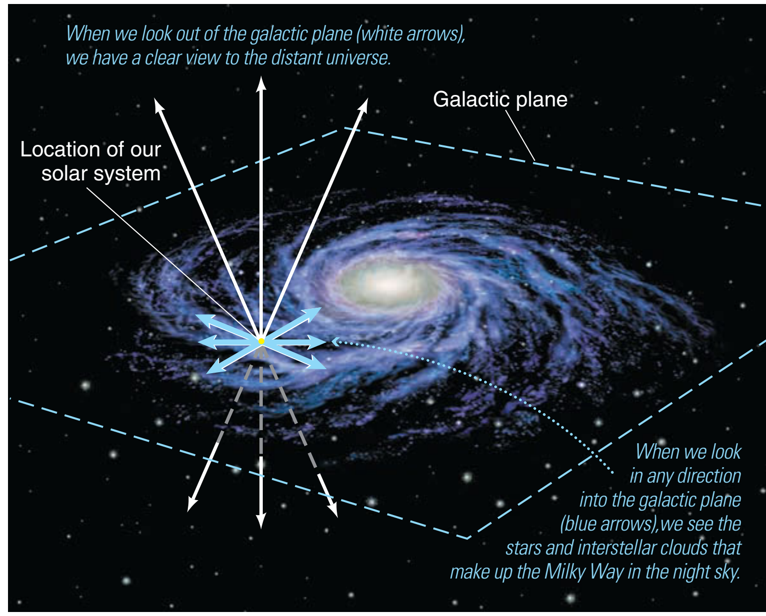


Figure 2.4

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

The Local Sky

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

Figure 2.5 shows key reference features of the local sky. The boundary between Earth and sky defines the **horizon**. The point directly overhead is the **zenith**. The **meridian** is an imaginary half-circle stretching from the horizon due south, through the zenith, to the horizon due north.

We pinpoint an object in the local sky by stating its altitude above the horizon and direction along the horizon.

We can pinpoint the position of any object in the local sky by stating its **direction** along the horizon (sometimes stated as *azimuth*, which is degrees clockwise from due north) and its **altitude** above the horizon. For example, Figure 2.5 shows a person pointing to a star located in the southeast direction at an altitude of 60°. Note that the zenith has altitude 90° but no direction, because it is straight overhead.

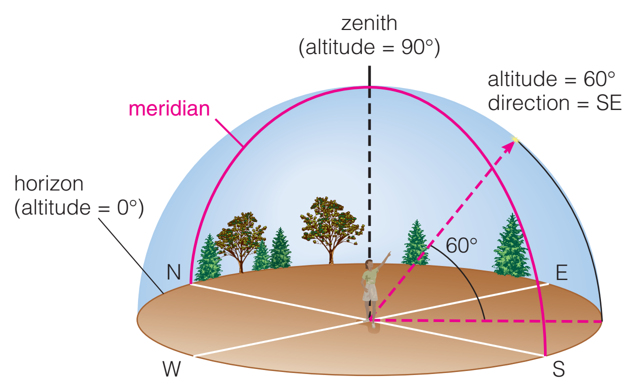


Figure 2.5

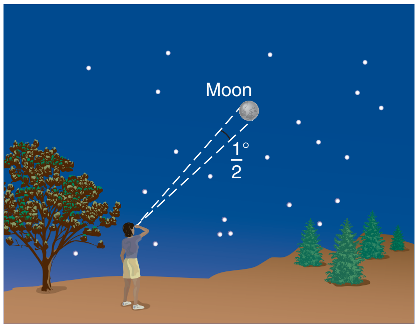
From any place on Earth, the local sky looks like a dome (hemisphere). This diagram shows key reference points in the local sky. It also shows how we can describe any position in the local sky by its altitude and direction.

Angular Sizes and Distances

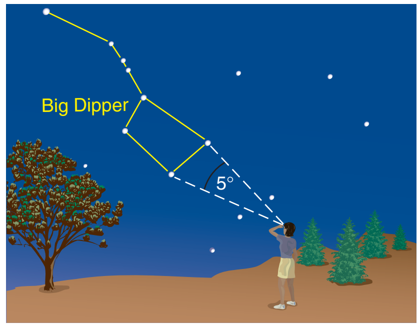
Our lack of depth perception on the celestial sphere makes it difficult to judge the true sizes or separations of the objects we see in the sky. However, we can describe the *angular* sizes or separations of objects even without knowing how far away they are.

The **angular size** of an object is the angle it appears to span in your field of view. For example, the angular sizes of the Sun and the Moon are each about $\frac{1}{2}°$ (Figure 2.6a). Note that angular size does not by itself tell us an object's true size, because angular size also depends on distance: The farther away an object is, the smaller its angular size. For example, the Sun is about 400 times larger in diameter than the Moon, but it has the same angular size in our sky because it is also about 400 times farther away.

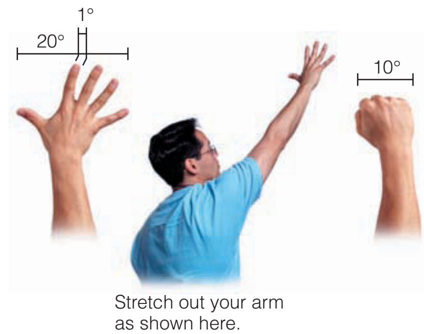
The farther away an object is, the smaller its angular size.



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



b The angular distance between the two "pointer stars" of the Big Dipper is about 5°.



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

Figure 2.6

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

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

The **angular distance** between a pair of objects in the sky is the angle that appears to separate them. For example, the angular distance between the "pointer stars" at the end of the Big Dipper's bowl is about 5° (Figure 2.6b). You can use your outstretched hand to make rough estimates of angles in the sky (Figure 2.6c).

For more precise astronomical measurements, we subdivide each degree into 60 **arcminutes** (abbreviated ′) and subdivide each arcminute into 60 arcseconds (abbreviated ″) (Figure 2.7). For example, we read 35°27′15″ as "35 degrees, 27 arcminutes, 15 arcseconds."

• Why do stars rise and set?

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

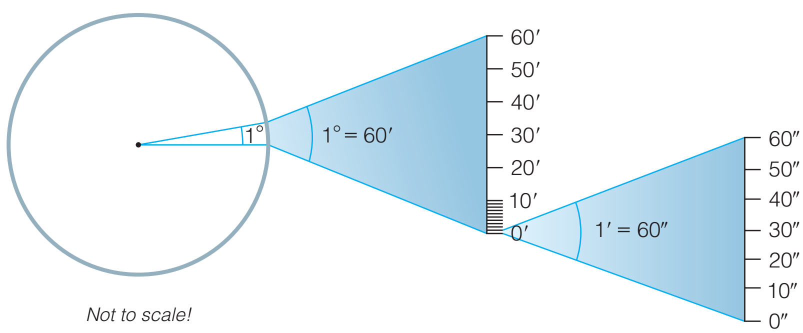


Figure 2.7

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

common Misconceptions

The Moon Illusion

You've probably noticed that the full moon appears to be larger when it is near the horizon than when it is high in your sky. However, this apparent size change is an illusion. If you measure the angular size of the full moon on a particular night, you'll find that it is about the same whether the Moon is near the horizon or high in the sky. The Moon's angular size in the sky depends only on its true size and its distance from Earth. Although this distance varies over the course of the Moon's monthly orbit, it does not change enough to cause a noticeable effect on a single night. You can confirm that the Moon's angular size remains the same by measuring it. You may also be able to make the illusion go away by viewing the Moon upside down between your legs when it is on the horizon.

universe, and that is why the Sun, Moon, planets, and stars all move across our sky each day.

We can picture the movement of the sky by imagining the celestial sphere rotating around Earth (Figure 2.8a). From this perspective you can see how the universe seems to turn around us: Every object on the celestial sphere appears to make a simple daily circle around Earth. However, the motion can look a little more complex in the local sky, because the horizon cuts the celestial sphere in half. Figure 2.8b shows the idea for a location in the United States. If you study the figure carefully, you'll notice the following key facts about the paths of various stars through the local sky:

- Stars near the north celestial pole do not rise or set; rather, they remain above the horizon and make daily counterclockwise circles around the north celestial pole. We say that such stars are **circumpolar**.
- Stars near the south celestial pole never rise above the horizon at all.
- All other stars have daily circles that are partly above the horizon and partly below it. Because Earth rotates from west to east (counterclockwise as viewed from above the North Pole), these stars appear to rise in the east and set in the west.

The time-exposure photograph that opens this chapter (p. 26) shows a part of the daily paths of stars. Paths of circumpolar stars are visible within the arch; notice that the complete daily circles for these stars are above the horizon, although the photo shows only a portion of each circle. The north celestial pole lies at the center of these circles. The circles grow larger for stars farther from the north celestial pole. If they are large enough, the circles cross the horizon, so that the stars rise in the east and set in the west. The same ideas apply in the Southern Hemisphere, except that circumpolar stars are those near the south celestial pole.

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

cosmic Calculations 2.1

Angular Size, Physical Size, and Distance

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

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

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

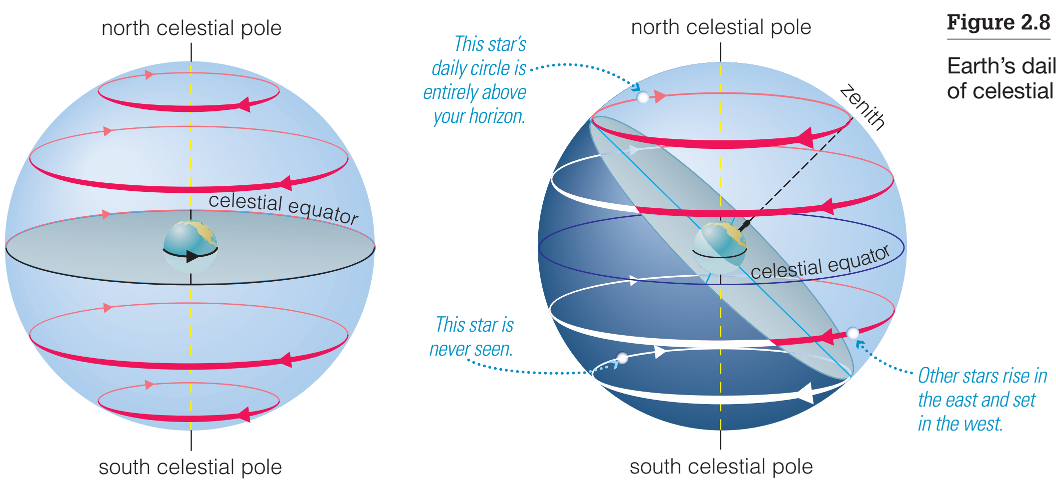
Solution: To solve the formula for physical size, we multiply both sides by $2\pi \times$ distance and rearrange:

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

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

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

The Moon's diameter is about 3300 km. (This differs from the precise value of 3476 km because we used inexact values for the angular size and distance.)



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

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

Figure 2.8

Earth's daily rotation explains the apparent daily motions of celestial objects in our sky.

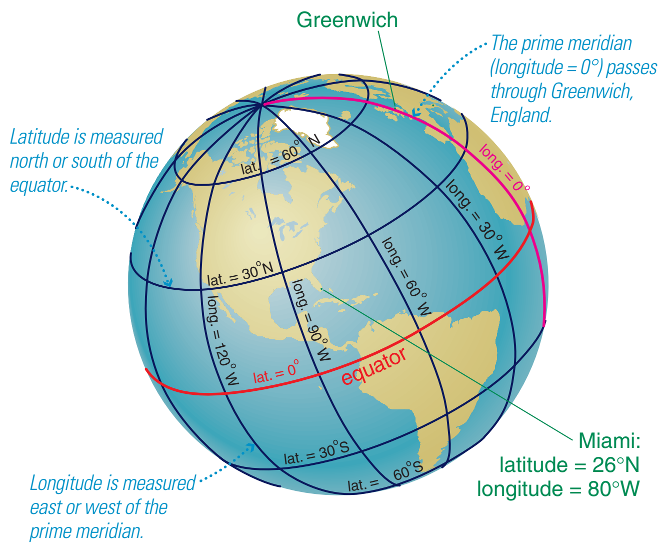


Figure 2.9

We can locate any place on Earth's surface by its latitude and longitude.

common Misconceptions

Stars in the Daytime

Stars may appear to vanish in the daytime and "come out" at night, but in reality the stars are always present. The reason you don't see stars in the daytime is that their dim light is overwhelmed by the bright daytime sky. You *can* see bright stars in the daytime with the aid of a telescope, or if you are fortunate enough to observe a total eclipse of the Sun. Astronauts can also see stars in the daytime. Above Earth's atmosphere, where there is no air to scatter sunlight, the Sun is a bright disk against a dark sky filled with stars. (However, the Sun is so bright that astronauts must block its light if they wish to see the stars.)

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

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

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

Variation with Latitude **Latitude** measures north-south position on Earth, and **longitude** measures east-west position (Figure 2.9). Latitude is defined to be 0° at the equator, increasing to 90°N at the North Pole and 90°S at the South Pole. By international treaty, longitude is defined to be 0° along a line passing through Greenwich, England. Stating a latitude and a longitude pinpoints a location on Earth. For example, Miami lies at about 26°N latitude and 80°W longitude.

The constellations you see depend on your latitude, but not on your longitude.

Latitude affects the constellations we see because it affects the locations of the horizon and zenith relative to the celestial sphere. Figure 2.10 shows how this works for the latitudes of the North Pole (90°N) and Sydney, Australia (34°S). Note that although the local sky varies with latitude, it does *not* vary with longitude. For example, Charleston (South Carolina) and San Diego (California) are at about the same latitude, so people in both cities see the same set of constellations at night.

You can learn much more about how the sky varies with latitude by studying diagrams like those in Figures 2.8 and 2.10. For example, at the North Pole, you can only see objects that lie on the northern half of the celestial sphere, and they are all circumpolar. That is why the Sun remains above the horizon for 6 months at the North Pole: The Sun lies north of the celestial equator for half of each year (see the yellow dots in Figure 2.3a), so during these 6 months, it circles the sky at the North Pole just like a circumpolar star.

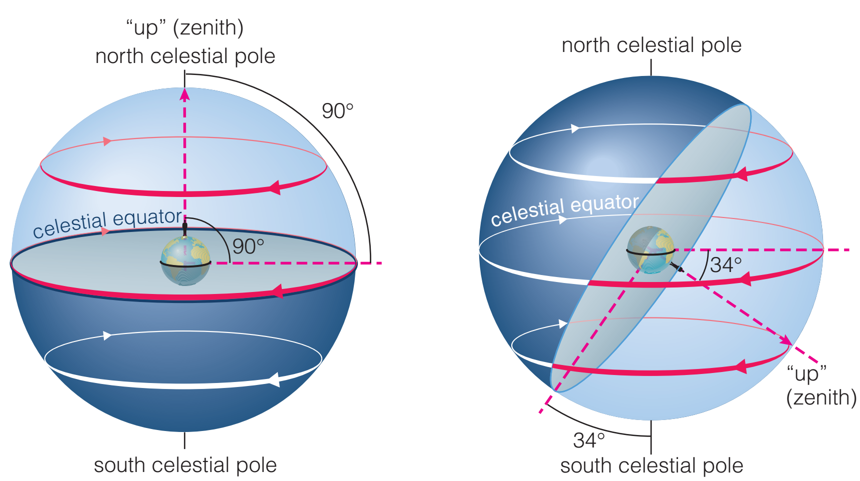
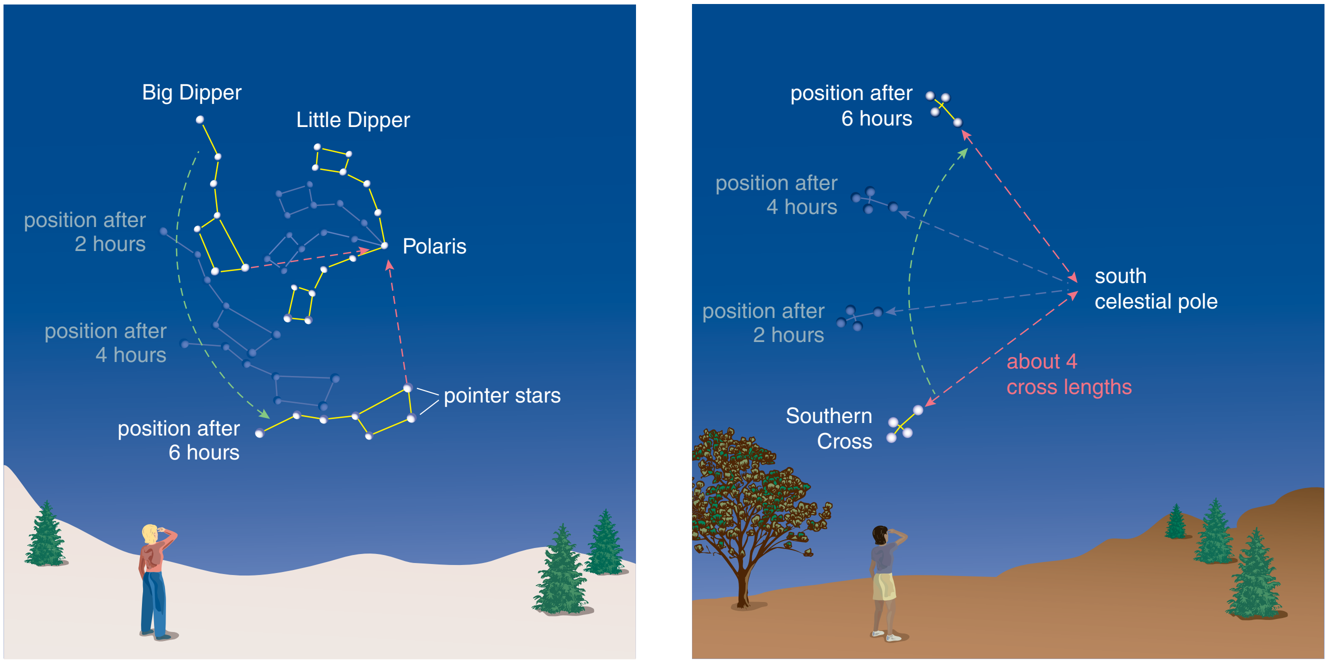


Figure 2.10

The sky varies with latitude. Notice that the altitude of the celestial pole that is visible in your sky is always equal to your latitude.

a The local sky at the North Pole (latitude 90°N).

b The local sky at Sydney, Australia (latitude 34°S).



looking northward in the Northern Hemisphere

a The pointer stars of the Big Dipper point to the North Star, Polaris, which lies within 1° of the north celestial pole. The sky appears to turn *counterclockwise* around the north celestial pole.

looking southward in the Southern Hemisphere

b The Southern Cross points to the south celestial pole, which is not marked by any bright star. The sky appears to turn *clockwise* around the south celestial pole.

Figure 2.11 MA **interactive figure**

You can determine your latitude by measuring the altitude of the celestial pole in your sky.

If you study the geometry of Figures 2.8 and 2.10 you'll also notice a fact that is very important to navigation: *The altitude of the celestial pole in your sky is equal to your latitude.* For example, if you see the north celestial pole at an altitude of 40° above your north horizon, your latitude is 40°N. Similarly, if you see the south celestial pole at an altitude of 34° above your south horizon, your latitude is 34°S. Finding the north celestial pole is fairly easy, because it lies very close to the star Polaris, also known as the North Star (Figure 2.11a). In the Southern Hemisphere, you can find the south celestial pole with the aid of the Southern Cross (Figure 2.11b).

The altitude of the celestial pole in your sky is equal to your latitude.

see it for yourself What is *your* latitude? Use Figure 2.11 to find the celestial pole in your sky, and estimate its altitude with your hand as shown in Figure 2.6c. Is its altitude what you expect?

Variation with Time of Year The night sky changes throughout the year because of Earth's changing position in its orbit around the Sun. Figure 2.12 shows the idea. As Earth orbits, the Sun *appears* to move steadily eastward along the ecliptic, with the stars of different constellations in the background at different times of year. The constellations along the ecliptic make up what we call the **zodiac**; tradition places 12 constellations along the zodiac, but the official borders include a thirteenth constellation, Ophiuchus.

common Misconceptions

What Makes the North Star Special?

Most people are aware that the North Star, Polaris, is a special star. Contrary to a relatively common belief, however, it is *not* the brightest star in the sky. More than 50 other stars are just as bright or brighter. Polaris is special not because of its brightness, but because it is so close to the north celestial pole and therefore very useful in navigation.

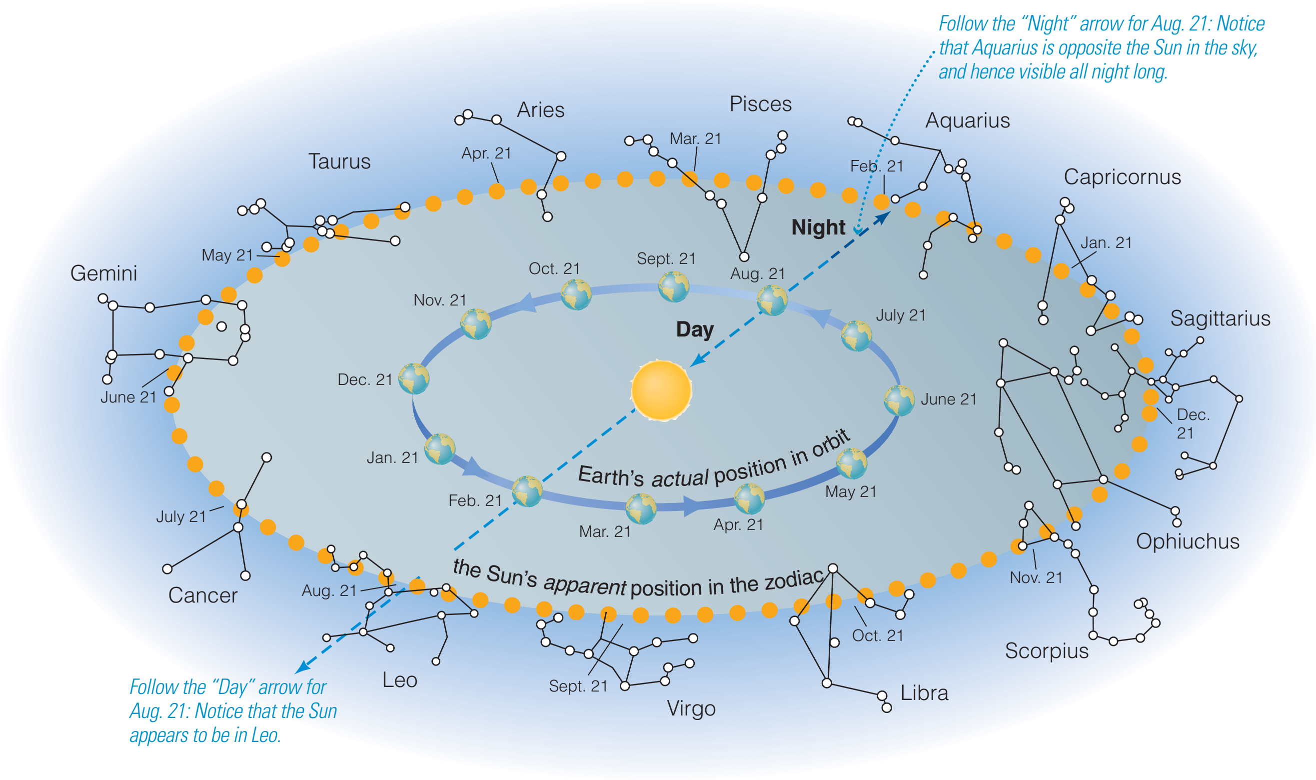


Figure 2.12 MA interactive figure

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

The Sun's apparent location along the ecliptic determines which constellations we see at night. For example, Figure 2.12 shows that the Sun appears to be in Leo in late August. We therefore cannot see Leo at this time (because it is in our daytime sky), but we can see Aquarius all night long because of its location opposite Leo on the celestial sphere. Six months later, in February, we see Leo at night while Aquarius is above the horizon only in the daytime.

The constellations visible at a particular time of night change as we orbit the Sun.

see it for yourself Based on Figure 2.12 and today's date, in what constellation does the Sun currently appear? What constellation of the zodiac will be on your meridian at midnight? What constellation of the zodiac will you see in the west shortly after sunset? Go outside at night to confirm your answers.

MA Seasons Tutorial, Lessons 1–3

2.2 The Reason for Seasons

We have seen how Earth's rotation makes the sky appear to circle us daily and how the night sky changes as Earth orbits the Sun each year. The combination of Earth's rotation and orbit also leads to the progression of the seasons. In this section, we'll explore the reason for seasons.

• What causes the seasons?

You know that we have seasonal changes, such as longer and warmer days in summer and shorter and cooler days in winter. But why do the seasons occur? The answer is that the tilt of Earth's axis causes sunlight to fall differently on Earth at different times of year.

Figure 2.13 (pp. 36–37) illustrates the key ideas. Step 1 shows that Earth's axis remains pointed in the same direction in space (toward Polaris) throughout the year. As a result, the orientation of the axis *relative to the Sun* changes over the course of each orbit: The Northern Hemisphere is tipped toward the Sun in June and away from the Sun in December, while the reverse is true for the Southern Hemisphere. That is why the two hemispheres experience opposite seasons. The rest of the figure shows how the changing angle of sunlight on the two hemispheres leads directly to seasons.

Earth's axis points in the same direction all year round, which means its orientation *relative to the Sun* changes as Earth orbits the Sun.

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

The sunlight angle gradually changes as Earth orbits the Sun. At the opposite side of Earth's orbit, Step 4 shows that it has become winter for the Northern Hemisphere and summer for the Southern Hemisphere. In between these two extremes, Step 3 shows that both hemispheres are

common **Misconceptions**

The Cause of Seasons

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

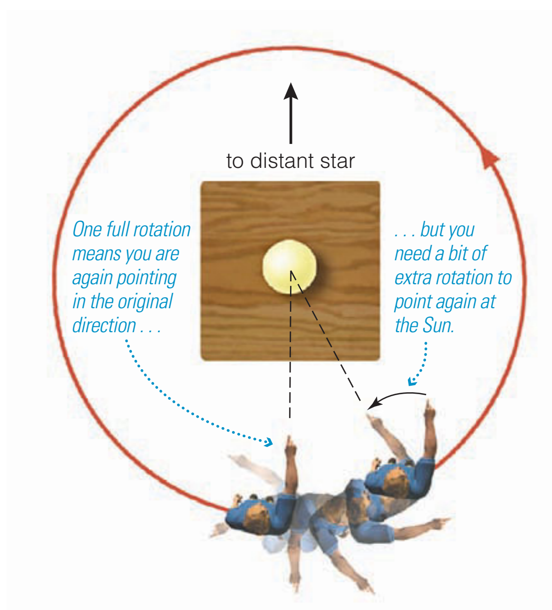
special**Topic** | How Long Is a Day?

We usually associate our 24-hour day with Earth's rotation, but if you measure the rotation period, you'll find that it is about 23 hours and 56 minutes (more precisely $23^h56^m4.09^s$)—or about 4 minutes short of 24 hours. What's going on?

Astronomically, we define two different types of day. Earth's 23 hour and 56 minute rotation period, which we measure by timing how long it takes any star to make one full circuit through our sky, is called a **sidereal day**; *sidereal* (pronounced *sy-dear-ee-al*) means "related to the stars." Our 24-hour day, which we call a **solar day**, is the average time it takes *the Sun* to make one circuit through the sky.

A simple demonstration shows why the solar day is about 4 minutes longer than the sidereal day. Set an object representing the Sun on a table, and stand a few steps away to represent Earth. Point at the Sun and imagine that you also happen to be pointing toward a distant star that lies in the same direction. If you rotate (counterclockwise) while standing in place, you'll again be pointing at both the Sun and the star after one full rotation. However, to show that Earth also orbits the Sun, you should take a couple of steps around the Sun (counterclockwise) as you rotate (see figure). After one full rotation, you will again be pointing in the direction of the distant star, so this rotation represents a sidereal day. But it does not represent a solar day, because you will not yet be pointing back at the Sun; you need to rotate a bit more. This "extra" bit of rotation makes a solar day longer than a sidereal day.

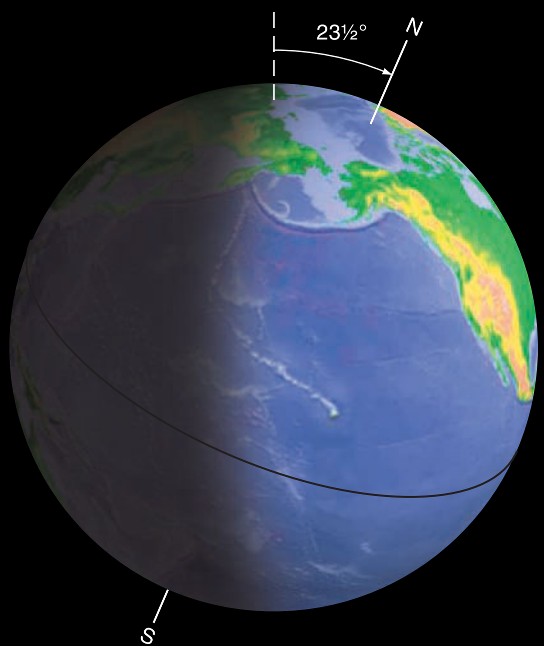
The only problem with this demonstration is that it exaggerates Earth's daily orbital motion. Earth takes about 365 days (1 year) to make a full 360° orbit around the Sun, which means about 1° per day. A solar day therefore represents about 361° of rotation, rather than the 360° for a sidereal day. The extra 1° rotation takes about $\frac{1}{360}$ of Earth's rotation period, which is about 4 minutes.



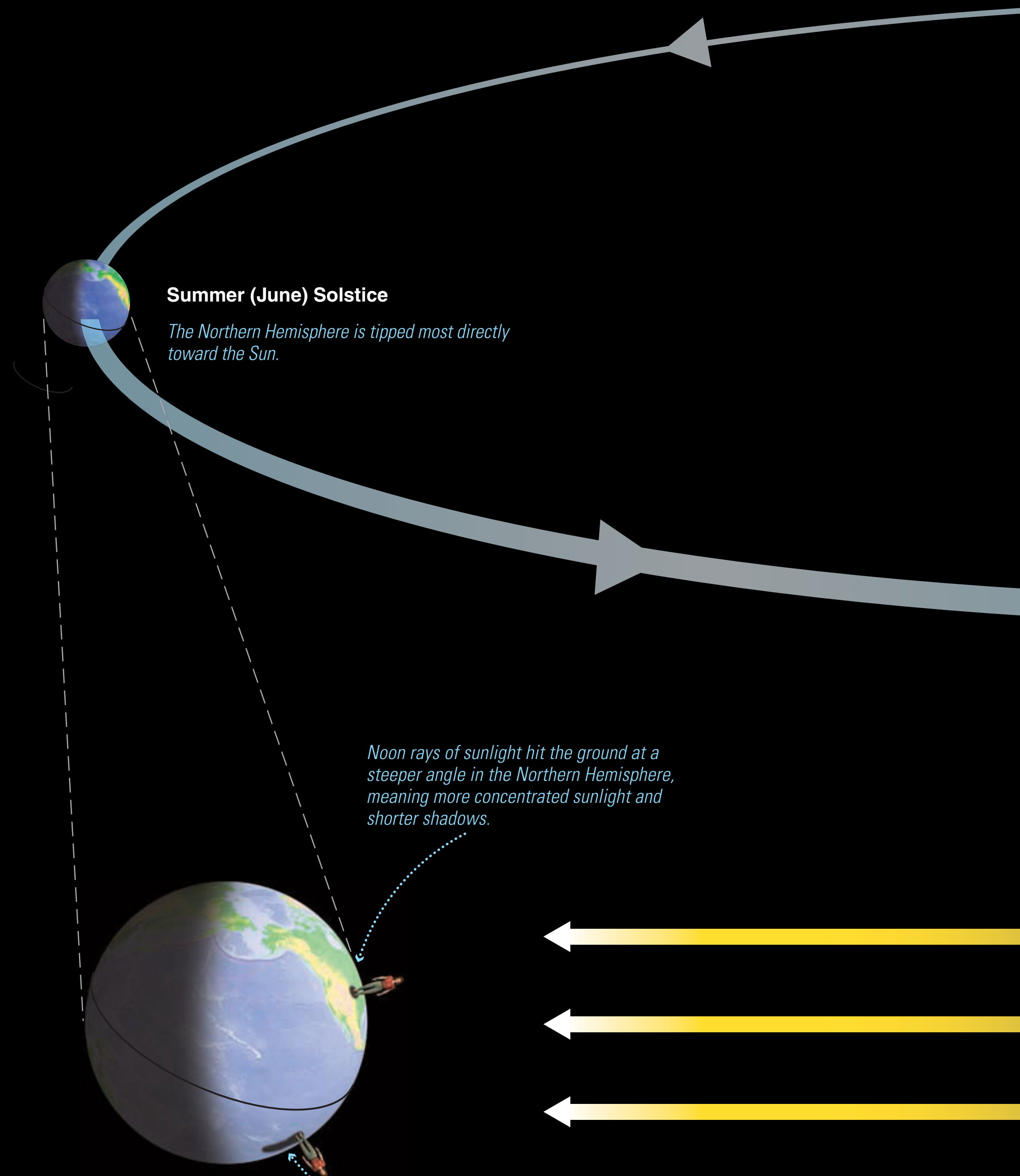
cosmic**Context** • **Figure 2.13. The Seasons**

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

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



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

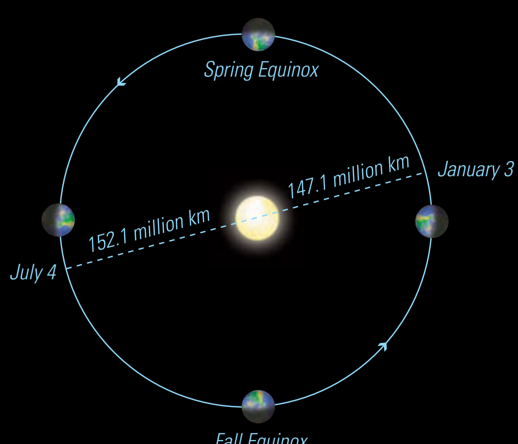


Interpreting the Diagram

To interpret the seasons diagram properly, keep in mind:

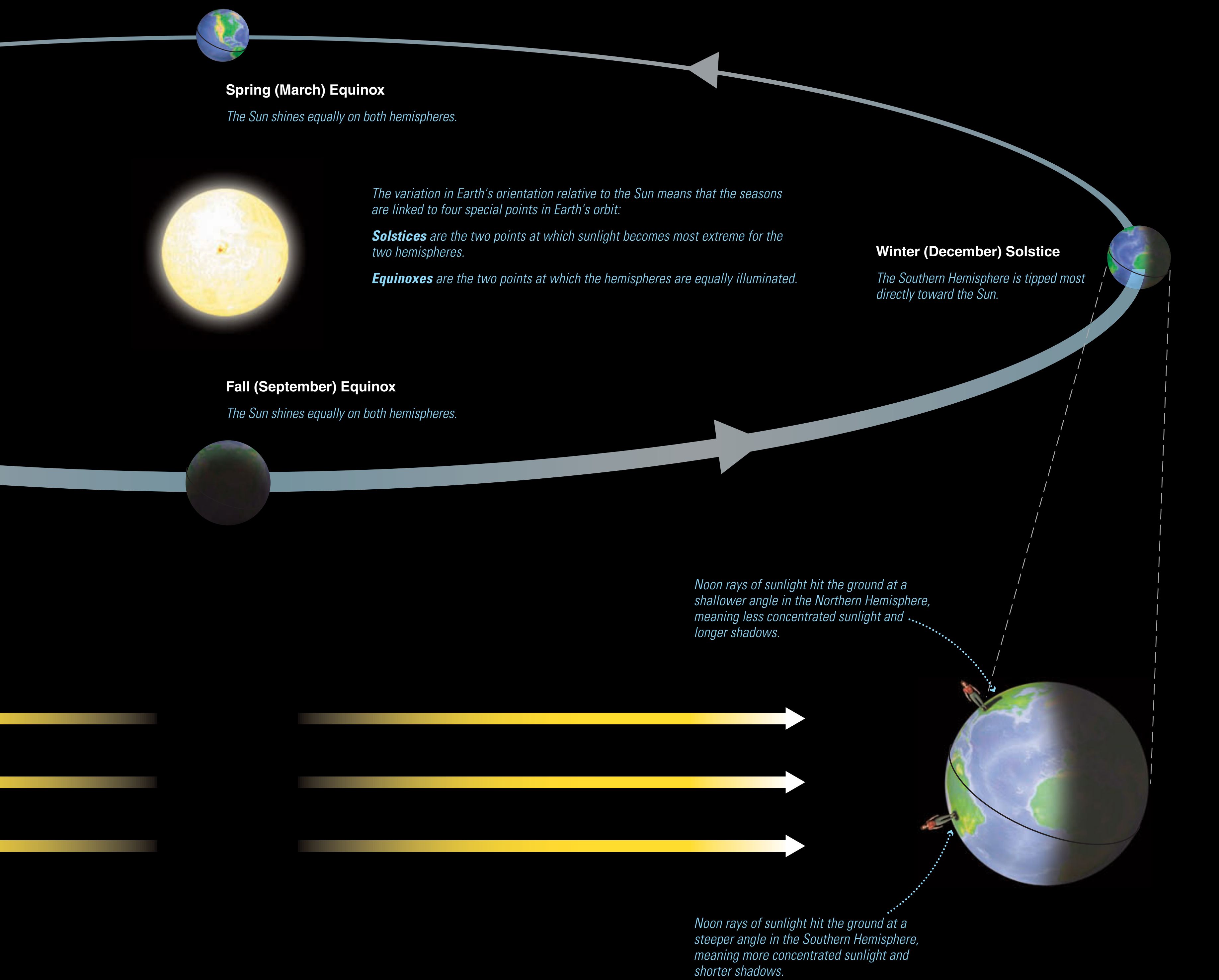
1. Earth's size relative to its orbit would be microscopic on this scale, meaning that both hemispheres are at essentially the same distance from the Sun.

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



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

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



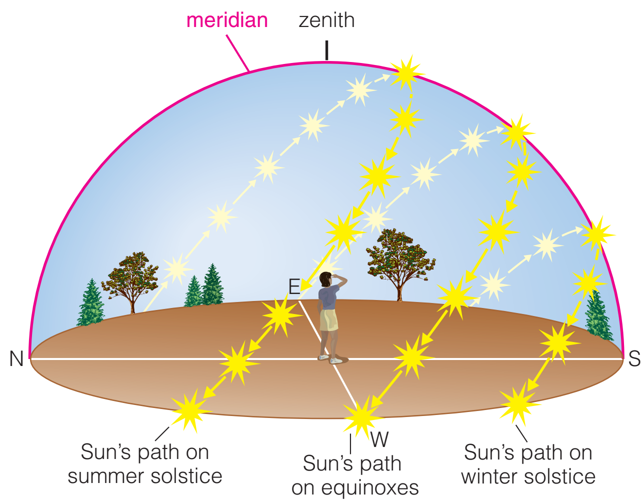


Figure 2.14

This diagram shows the Sun's path on the solstices and equinoxes for a Northern Hemisphere sky (latitude 40°N). The precise paths are different for other latitudes. Notice that the Sun rises exactly due east and sets exactly due west only on the equinoxes.

common Misconceptions

High Noon

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

illuminated equally in March and September. It is therefore spring for the hemisphere that is on the way from winter to summer, and fall for the hemisphere on the way from summer to winter.

Notice that the seasons on Earth are caused only by the axis tilt and *not* by any change in Earth's distance from the Sun. Although Earth's orbital distance varies over the course of each year, the variation is fairly small: Earth is only about 3% farther from the Sun at its farthest point than at its nearest. The difference in the strength of sunlight due to this small change in distance is tiny compared to the effects caused by the axis tilt. If Earth did not have an axis tilt, we would not have seasons.

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

Solstices and Equinoxes To help us mark the changing of the seasons, we define four special moments in the year, each of which corresponds to one of the four special positions in Earth's orbit shown in Figure 2.13.

- The **summer (June) solstice**, which occurs around June 21, is the moment when the Northern Hemisphere is tipped most directly toward the Sun (and the Southern Hemisphere is tipped most directly away from it).
- The **winter (December) solstice**, which occurs around December 21, is the moment when the Northern Hemisphere is tipped most directly away from the Sun (and the Southern Hemisphere is tipped most directly toward it).
- The **spring (March) equinox**, which occurs around March 21, is the moment when the Northern Hemisphere goes from being tipped slightly away from the Sun to being tipped slightly toward the Sun.
- The **fall (September) equinox**, which occurs around September 22, is the moment when the Northern Hemisphere first starts to be tipped away from the Sun.

We use the equinoxes and solstices to mark the progression of the seasons.

The exact dates and times of the solstices and equinoxes vary from year to year, but stay within a couple of days of the dates given above. In fact, our modern calendar includes leap years in a pattern specifically designed to keep the solstices and equinoxes around the same dates: We generally add a day (February 29) for leap year every fourth year, but skip leap year when a century changes (for example, in the years 1700, 1800, 1900) *unless* the century year is divisible by 400 (for example, 2000). This pattern makes the average length of the calendar year match the true length of the year,* which is about 11 minutes short of $365\frac{1}{4}$ days.

Ancient people recognized the days on which the solstices and equinoxes occur by observing the Sun in the sky. Many ancient structures were used for this purpose, including Stonehenge in England and the Sun Dagger in New Mexico [Section 3.1].

*Technically, we are referring here to the *tropical year*—the time from one spring equinox to the next. Axis precession (discussed later in this section) causes the tropical year to be slightly shorter (by about 20 minutes) than Earth's orbital period, called the *sidereal year*.

The equinoxes occur on the only two days of the year on which the Sun rises precisely due east and sets precisely due west (Figure 2.14). These are also the only two days when sunlight falls equally on both hemispheres. The summer solstice occurs on the day that the Sun follows its longest and highest path through the Northern Hemisphere sky (and its shortest and lowest path through the Southern Hemisphere sky). It is therefore the day that the Sun rises and sets farther to the north than on any other day of the year, and on which the noon Sun reaches its highest point in the Northern Hemisphere sky. The opposite is true on the day of the winter solstice, when the Sun rises and sets farthest to the south and the noon Sun is lower in the Northern Hemisphere sky than on any other day of the year. Figure 2.15 shows how the Sun's midday altitude varies over the course of the year.

The Sun rises precisely due east and sets precisely due west *only* on the days of the spring and fall equinoxes.

First Days of Seasons We usually say that each equinox and solstice marks the first day of a season. For example, the day of the summer solstice is usually called the "first day of summer." Notice, however, that the summer solstice occurs when the Northern Hemisphere has its *maximum* tilt toward the Sun. You might then wonder why we consider the summer solstice to be the beginning rather than the midpoint of summer.

Although the choice of the summer solstice as the "first" day of summer is somewhat arbitrary, it makes sense in at least two ways. First, it was much easier for ancient people to identify the days on which the Sun reached extreme positions in the sky—such as when it reached its highest point on the summer solstice—than other days in between. Second, we usually think of the seasons in terms of weather, and the solstices and equinoxes correspond well with the beginnings of seasonal weather patterns. For example, although the Sun's path through the Northern Hemisphere sky is longest and highest around the time of the summer solstice, the warmest days tend to come 1 to 2 months later. To understand why, think about what happens when you heat a pot of cold soup. Even though you may have the stove turned on high from the start, it takes a while for the soup to warm up. In the same way, it takes some time for sunlight to heat the ground and oceans from the cold of winter to the warmth of summer. "Midsummer" in terms of weather therefore comes in late July or early August, which makes the summer solstice a pretty good choice for the "first day of summer." For similar reasons, the winter solstice is a good choice for the first day of winter, and the spring and fall equinoxes are good choices for the first days of those seasons.

Seasons Around the World Notice that the names of the solstices and equinoxes generally reflect the northern seasons, and therefore sound backward to people who live in the Southern Hemisphere. For example, Southern Hemisphere winter begins when Earth is at the orbital point usually called the *summer* solstice. This apparent injustice to people in the Southern Hemisphere arose because the solstices and equinoxes were named by people living in the Northern Hemisphere. A similar injustice affects people living in equatorial regions. If you study Figure 2.13, you'll see that Earth's equator gets its most direct sunlight on the two equinoxes and its least direct sunlight on the solstices. People living near the equator therefore don't experience four seasons in the same way as people living at mid-latitudes. Instead, equatorial regions have rainy and dry seasons, with the rainy seasons coming when the Sun is higher in the sky.

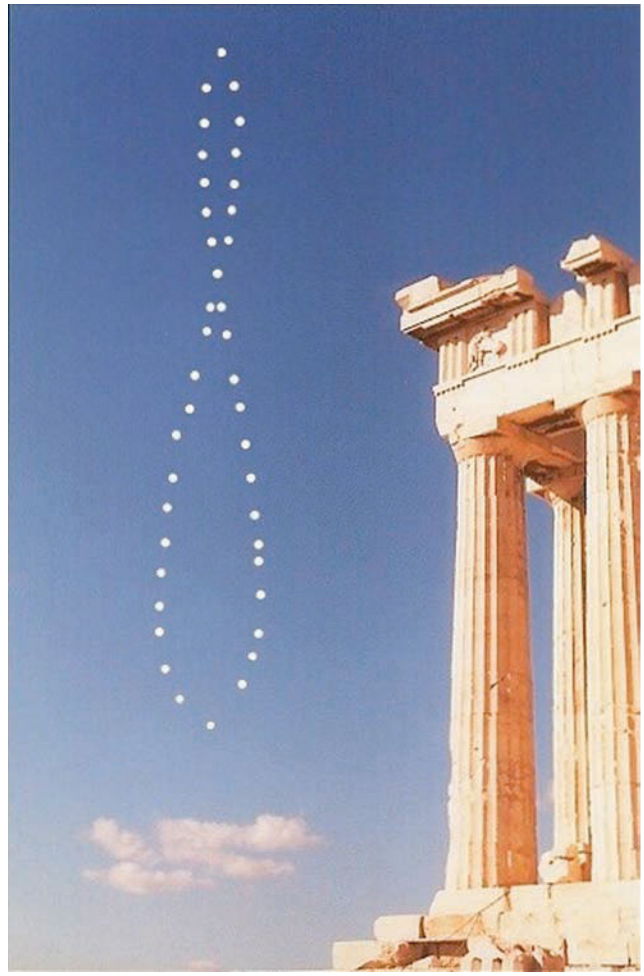


Figure 2.15

This composite photograph shows midday images of the Sun at 7- to 11-day intervals over the course of a year, always from the same spot (the Parthenon in Athens, Greece) and at the same time of day (technically, at the same "mean solar time"). Notice the dramatic change in the Sun's midday altitude over the course of the year. The "figure 8" shape (called an *analemma*) is due to the combination of Earth's axis tilt and Earth's varying speed as it orbits the Sun.

Figure 2.16

This sequence of photos shows the progression of the Sun all the way around the horizon on the summer solstice at the Arctic Circle. Notice that the Sun does not set but instead skims the northern horizon at midnight. It then gradually rises higher, reaching its highest point at noon, when it appears due south.

In addition, seasonal variations around the times of the solstices are more extreme at high latitudes. For example, Vermont has much longer summer days and much longer winter nights than Florida. At the Arctic Circle (latitude $66\frac{1}{2}°$), the Sun remains above the horizon all day long on the summer solstice (Figure 2.16), and below the horizon on the winter solstice (although bending of light by the atmosphere makes the Sun *appear* to be about a half-degree higher than it really is). The most extreme cases occur at the North and South Poles, where the Sun remains above the horizon for 6 months in summer and below the horizon for 6 months in winter.

At very high latitudes, the summer Sun remains above the horizon all day long.

• How does the orientation of Earth's axis change with time?

We have now discussed both daily and seasonal changes in the sky, but there are other changes that occur over longer periods of time. One of the most important of these slow changes is called **precession**, a gradual wobble that changes the orientation of Earth's axis in space.

Precession occurs with many rotating objects. You can see it easily by spinning a top (Figure 2.17a). As the top spins rapidly, you'll notice that its axis also sweeps out a circle at a slower rate. We say that the top's axis precesses. Earth's axis precesses in much the same way, but far more slowly (Figure 2.17b). Each cycle of Earth's precession takes about 26,000 years, gradually changing where the axis points in space. Today, the axis points toward Polaris, making it our North Star. Some 13,000 years from now, Vega will be the bright star closest to true north. At most times, the axis does not point near any bright star.

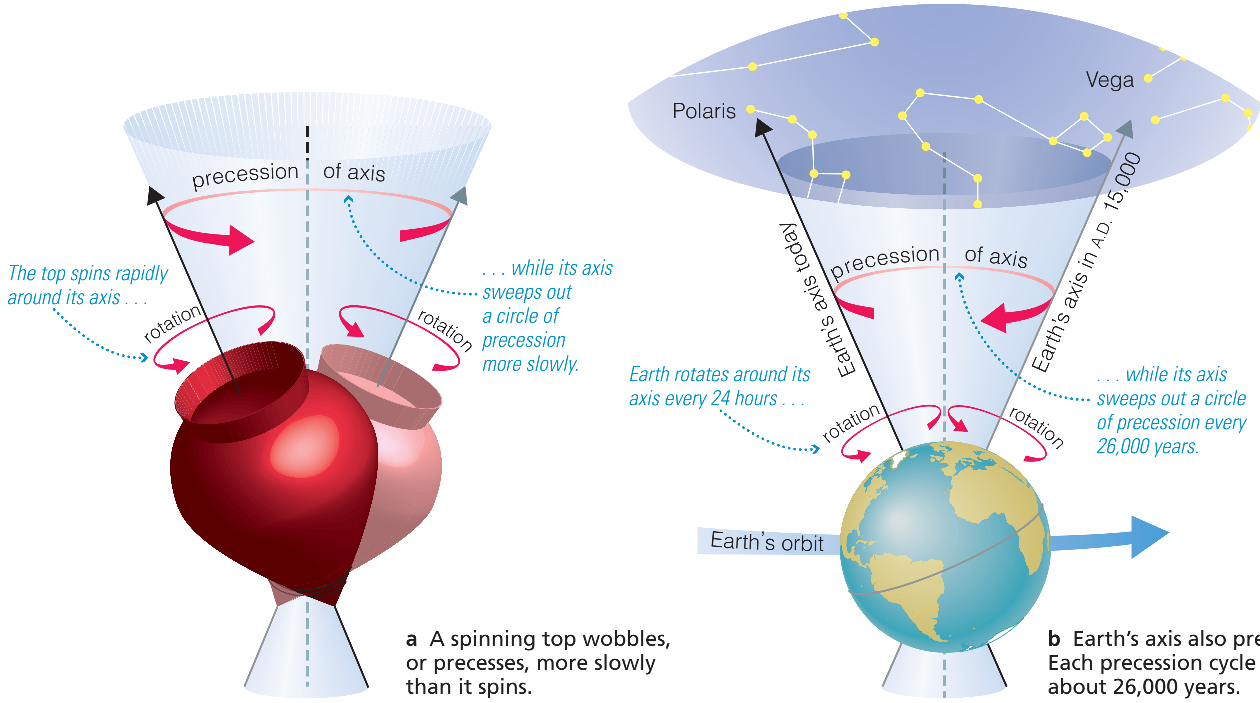
Notice that precession does not change the *amount* of the axis tilt (which stays close to $23\frac{1}{2}°$) and therefore does not affect the pattern of the seasons. However, because

The tilt of Earth's axis remains close to $23\frac{1}{2}°$, but the direction the axis points in space changes slowly with the 26,000-year cycle of precession.

common Misconceptions

Sun Signs

You probably know your astrological "Sun sign." When astrology began a few thousand years ago, your Sun sign was supposed to represent the constellation in which the Sun appeared on your birth date. However, because of precession, this is no longer the case for most people. For example, if your birthday is March 21, your Sun sign is Aries even though the Sun now appears in Pisces on that date. The astrological Sun signs are based on the positions of the Sun among the stars as they were almost 2000 years ago. Because Earth's axis has moved about $\frac{1}{13}$ of the way through its 26,000-year precession cycle since that time, astrological Sun signs are off by nearly a month from the actual positions of the Sun among the constellations today.



a A spinning top wobbles, or precesses, more slowly than it spins.

b Earth's axis also precesses. Each precession cycle takes about 26,000 years.

Figure 2.17 MA **interactive figure**

Precession affects the orientation of a spinning object's axis, but not the amount of its tilt.

the solstices and equinoxes correspond to points in Earth's orbit that depend on the direction the axis points in space, their positions in the orbit gradually shift with the cycle of precession. As a result, the constellations associated with the solstices and equinoxes change over time. For example, a couple thousand years ago the Sun appeared in the constellation Cancer on the day of the summer solstice, but it now appears in Gemini. This explains something you can see on any world map: The latitude at which the Sun is directly overhead on the summer solstice ($23\frac{1}{2}°$) is called the *Tropic of Cancer*, telling us that it was named back when the Sun appeared in Cancer on the summer solstice.

Why does precession occur? It is caused by gravity's effect on a tilted, rotating object that is *not* a perfect sphere. A spinning top precesses because Earth's gravity tries to pull over its lopsided, tilted spin axis. Gravity does not succeed in pulling it over—at least until friction slows the rate of spin—but instead causes the axis to precess. The spinning Earth precesses because gravitational tugs from the Sun and Moon try to "straighten out" our planet's bulging equator, which has the same tilt as the axis. Again, gravity does not succeed in straightening out the tilt but only causes the axis to precess.

MA **Phases of the Moon Tutorial, Lessons 1–3**

2.3 The Moon, Our Constant Companion

Aside from the Sun, the Moon is the brightest and most noticeable object in our sky. The Moon is our constant companion in space, orbiting Earth about once every $27\frac{1}{3}$ days.

Figure 2.18 shows the Moon's orbit on the same scale we used for the model solar system in Section 1.2. Remember that on this scale, the

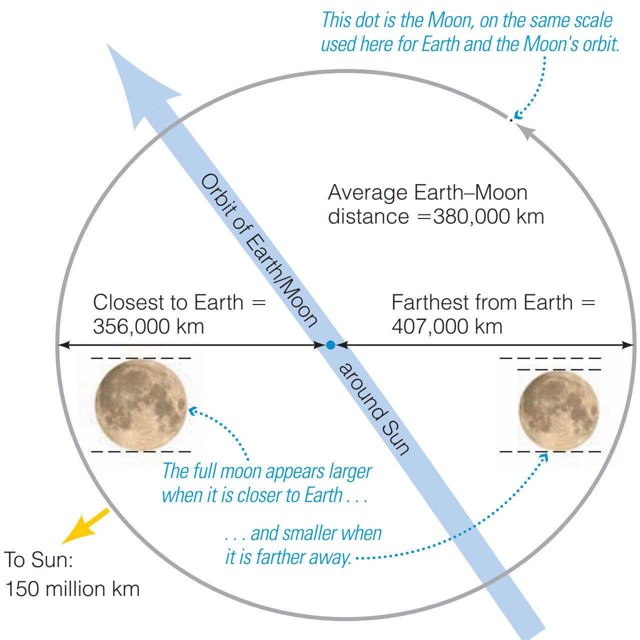


Figure 2.18

The Moon's orbit around Earth, shown on the 1-to-10-billion scale used in Section 1.2 (see Figure 1.6). The segment shown of our orbit around the Sun looks nearly straight because the distance to the Sun is so great in comparison to the size of the Moon's orbit. The inset photos contrast the relative angular size of the full moon in our sky when the Moon is at the near and far points of its orbit; of course, full moon occurs only when the Moon is opposite the Sun as seen from Earth.

Sun is about the size of a large grapefruit and is located about 15 meters from Earth. The entire orbit of the Moon would fit easily inside the Sun, and for practical purposes we can consider Earth and the Moon to share the same orbit around the Sun.

Like all objects in space, the Moon appears to reside on the celestial sphere. Earth's daily rotation makes the Moon appear to rise in the east and set in the west each day. In addition, because it orbits Earth, the Moon appears to move eastward from night to night through the constellations of the zodiac. Each circuit through the constellations takes the same $27\frac{1}{3}$ days that the Moon takes to orbit Earth. If you do the math, you'll see that this means the Moon moves relative to the stars by about $\frac{1}{2}°$—its own angular size—each hour. You can notice this gradual motion in just a few hours by checking the Moon's position compared to bright stars near it in the sky.

• Why do we see phases of the Moon?

As the Moon moves through the sky, both its appearance and the time at which it rises and sets change with the cycle of **lunar phases**. The phase of the Moon on any given day depends on its position relative to the Sun as it orbits Earth.

The phase of the Moon depends on its position relative to the Sun as it orbits Earth.

The easiest way to understand the lunar phases is with the simple demonstration illustrated in Figure 2.19. Take a ball outside on a sunny day. (If it's dark or cloudy, you can use a flashlight instead of the Sun; put the flashlight on a table a few meters away and shine it toward you.) Hold the ball at arm's length to represent the Moon while your head represents Earth. Slowly spin around (counterclockwise), so that the ball goes around you just like the Moon orbits Earth. As you turn, you'll see the ball go through phases just like the Moon. If you think about what's happening, you'll realize that the phases of the ball result from just two basic facts:

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

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

We see lunar phases for the same reason. Half the Moon is always illuminated by the Sun, but the amount of this illuminated half that we see from Earth depends on the Moon's position in its orbit. The photographs in Figure 2.19 show how the phases look. Each complete cycle of phases, from one new moon to the next, takes about $29\frac{1}{2}$ days—hence the origin of the word *month* (think "moonth"). This is about 2 days longer than the Moon's actual orbital period because of Earth's motion around the Sun during the time the Moon is orbiting around Earth.

The Moon's phase is directly related to when it rises, reaches its highest point in the sky, and sets. For example, the full moon must rise around sunset, because it occurs when the Moon is opposite the Sun in the sky. It

common Misconceptions

Moon in the Daytime

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

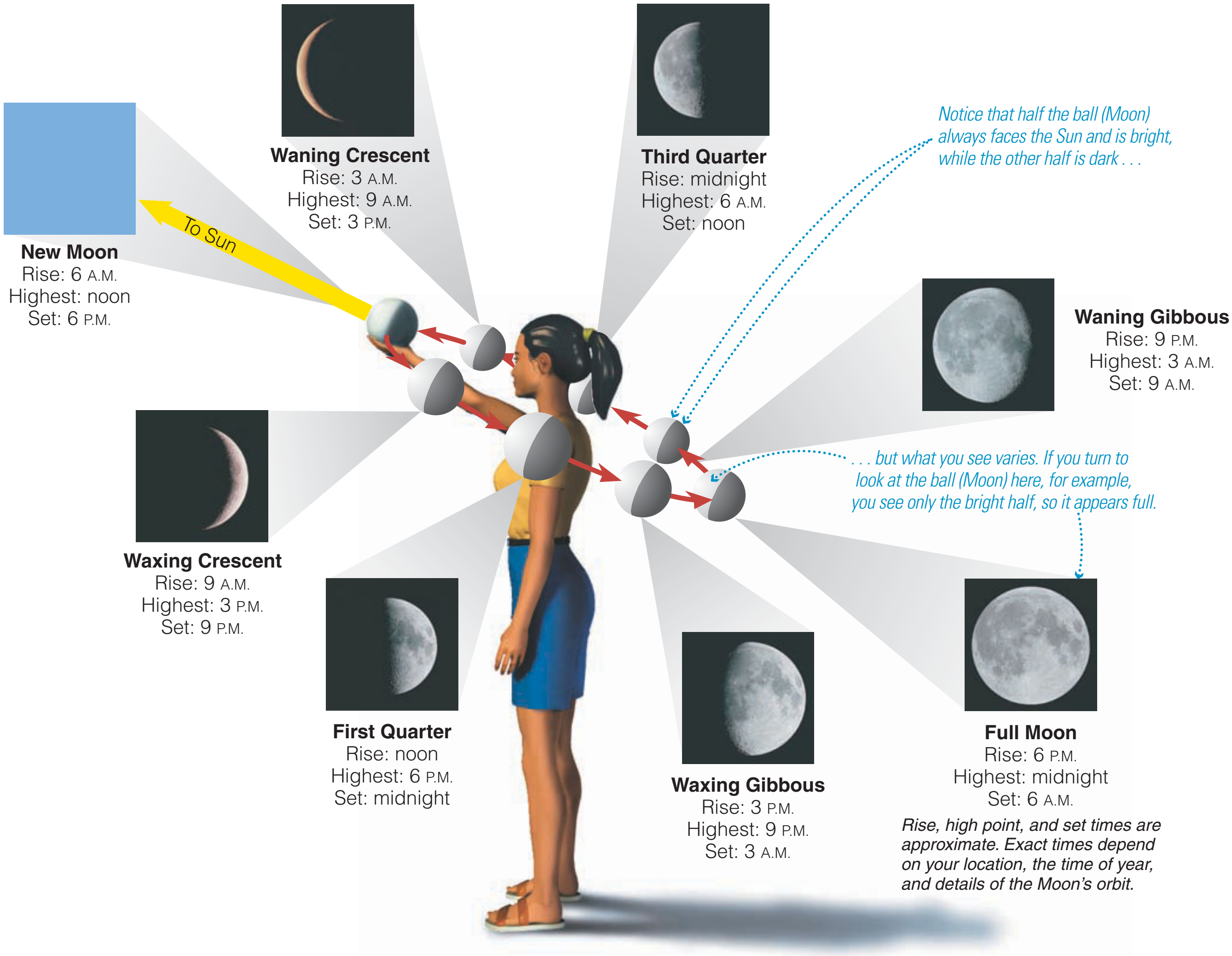


Figure 2.19 MA **interactive figure**

A simple demonstration illustrates the phases of the Moon. Hold a ball at arm's length; your head represents Earth and the ball represents the Moon. As you turn, you'll see the ball go through phases just like those of the Moon. The photos show what the Moon looks like at each orbital position. (The new moon photo shows blue sky, because a new moon is always close to the Sun in the sky and hence hidden from view by the bright light of the Sun.)

therefore reaches its highest point in the sky at midnight and sets around sunrise. Similarly, a first-quarter moon must rise around noon, reach its highest point around 6 p.m., and set around midnight, because it occurs when the Moon is about 90° east of the Sun in our sky. Figure 2.19 lists the approximate times for the rising, highest point, and setting of each phase.

The Moon's phase affects not only its appearance, but also its rise and set times.

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

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

common Misconceptions

The "Dark Side" of the Moon

From Earth, we always see (nearly) the same face of the Moon, a consequence of the fact that the Moon rotates in the same amount of time that it takes to orbit Earth (see Special Topic, p. 103). Perhaps as a result, some people mistakenly refer to the far side of the Moon—meaning the side that we never see from Earth—as the *dark side*. But the far side is not always dark. For example, during new moon the far side faces the Sun and hence is completely sunlit. In fact, because the Moon rotates with a period of approximately one month (the same time that it orbits Earth), points on both the near and far sides have two weeks of daylight alternating with two weeks of darkness.

MA Eclipses Tutorial, Lessons 1–3

• What causes eclipses?

Occasionally, the Moon's orbit around Earth causes events much more dramatic than lunar phases. The Moon and Earth cast shadows in sunlight, and these shadows can create **eclipses** when the Sun, Earth, and Moon fall into a straight line. Eclipses come in two basic types:

- A **lunar eclipse** occurs when Earth lies directly between the Sun and the Moon, so that Earth's shadow falls on the Moon.
- A **solar eclipse** occurs when the Moon lies directly between the Sun and Earth, so that the Moon's shadow falls on Earth. People living within the area covered by the Moon's shadow will see the Sun blocked or partially blocked from view.

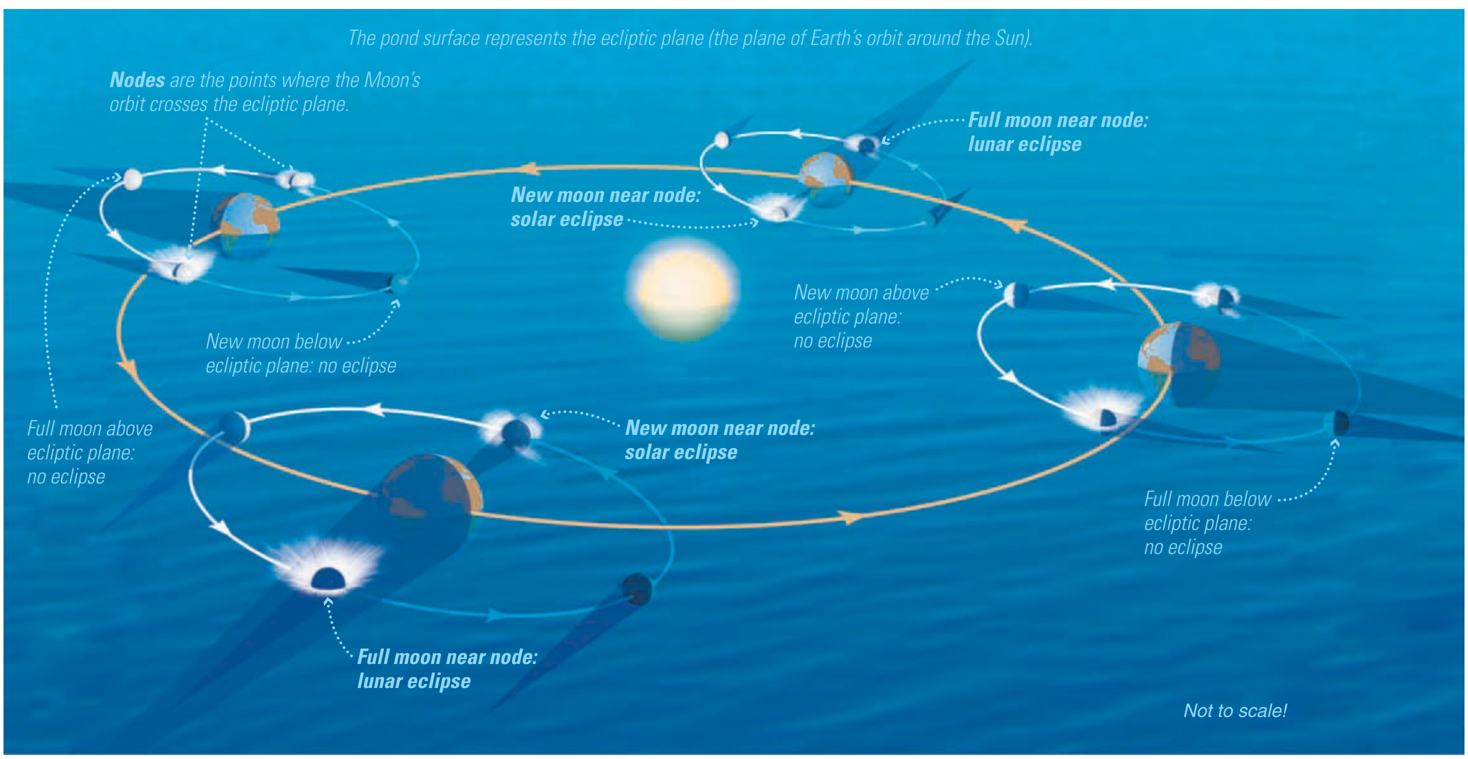
Conditions for Eclipses Look again at Figure 2.19. The figure makes it look like the Sun, Earth, and Moon line up with every new and full moon. If this figure told the whole story of the Moon's orbit, we would have both a lunar and a solar eclipse every month—but we don't.

We see a lunar eclipse when Earth's shadow falls on the Moon, and a solar eclipse when the Moon blocks our view of the Sun.

The missing piece of the story in Figure 2.19 is that the Moon's orbit is slightly inclined (by about 5°) to the ecliptic plane (the plane of Earth's orbit around the Sun). To visualize this inclination, imagine the ecliptic plane as the surface of a pond, as shown in Figure 2.20. Because of the inclination of its orbit, the Moon spends most of its time either above or below this surface. It crosses *through* this surface only twice during each orbit: once coming out

Figure 2.20

This illustration represents the ecliptic plane as the surface of a pond. The Moon's orbit is tilted by about 5° to the ecliptic plane, so the Moon spends half of each orbit above the plane (the pond surface) and half below it. Eclipses occur only when the Moon is at both a node (passing through the pond surface) and a phase of either new moon (for a solar eclipse) or full moon (for a lunar eclipse)—as is the case with the lower left and top right orbits shown.



and once going back in. The two points in each orbit at which the Moon crosses the surface are called the **nodes** of the Moon's orbit.

Notice that the nodes are aligned approximately the same way throughout the year (diagonally in Figure 2.20), which means they lie along a nearly straight line with the Sun and Earth about twice each year. Eclipses can occur only during these periods (called *eclipse seasons*) when the nodes line up with the Sun and Earth:

- A lunar eclipse occurs when a *full* moon occurs at or very near one of the nodes.
- A solar eclipse occurs when a *new* moon occurs at or very near one of the nodes.

We see an eclipse only when a full or new moon occurs at one of the points where the Moon's orbit crosses the ecliptic plane.

Although there are two basic types of eclipse—lunar and solar—each of these types can look different depending on precisely how the shadows fall. The shadow of the Moon or Earth consists of two distinct regions: a central **umbra**, where sunlight is completely blocked, and a surrounding **penumbra**, where sunlight is only partially blocked (Figure 2.21). Let's see how this affects eclipses.

Lunar Eclipses A lunar eclipse begins at the moment when the Moon's orbit first carries it into Earth's penumbra. After that, we will see one of three types of lunar eclipse (Figure 2.22). If the Sun, Earth, and Moon are nearly perfectly aligned, the Moon will pass through Earth's umbra and we will see a **total lunar eclipse**. If the alignment is somewhat less perfect, only part of the full moon will pass through the umbra (with the rest in the penumbra) and we will see a **partial lunar eclipse**. If the Moon passes *only* through Earth's penumbra, we will see a **penumbral lunar eclipse**.

Penumbral eclipses are slightly more common that total lunar eclipses and partial lunar eclipses, but they are the least visually impressive because the full moon darkens only slightly. Earth's umbral shadow clearly darkens part of the Moon's face during a partial lunar eclipse, and the curvature of this shadow demonstrates that Earth is round. A total lunar eclipse is particularly spectacular because the Moon becomes dark and eerily red during **totality**, the time during which the Moon is entirely engulfed in the umbra. Totality typically lasts about an hour. The Moon becomes dark because it is in shadow, and red because Earth's atmosphere bends some of the red light from the Sun toward the Moon.

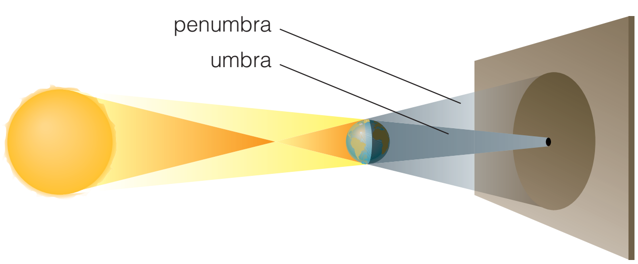


Figure 2.21

The shadow cast by an object in sunlight. Sunlight is fully blocked in the umbra and partially blocked in the penumbra.

common Misconceptions

Shadows and the Moon

Many people guess that the Moon's phases are caused by shadows falling on its surface, but this is not the case. As we've seen, the Moon's phases are caused by the fact that we see different portions of its day and night sides at different times as it orbits around Earth. The only time that Earth's shadow falls on the Moon is during lunar eclipses, which are relatively rare (occurring about twice each year) and which last just a few hours.

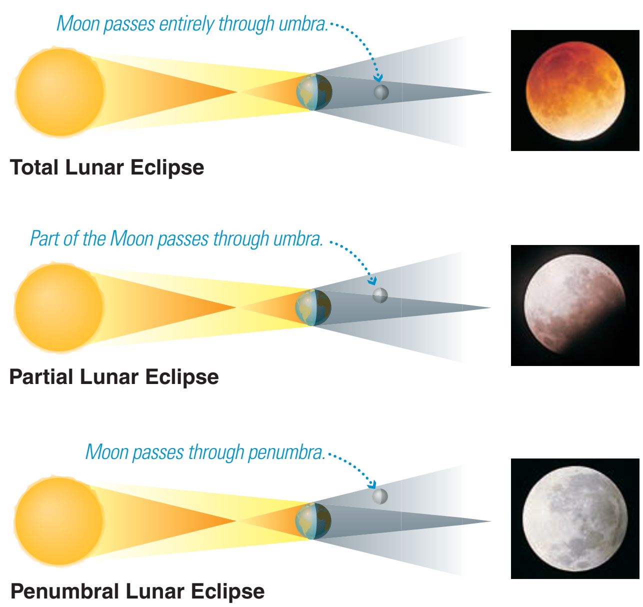


Figure 2.22

The three types of lunar eclipse.

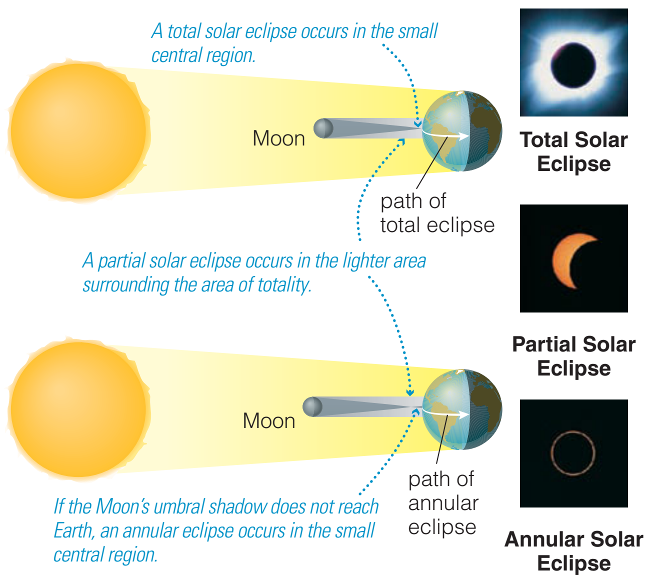


Figure 2.23 MA **interactive figure**

The three types of solar eclipse. The diagrams show the Moon's shadow falling on Earth; note the dark central umbra surrounded by the much lighter penumbra.

Solar Eclipses We can also see three types of solar eclipse (Figure 2.23). If a solar eclipse occurs when the Moon is relatively close to Earth in its orbit, the Moon's umbra touches a small area of Earth's surface (no more than about 270 kilometers in diameter). Within this area you will see a **total solar eclipse**. Surrounding the region of totality is a much larger area (typically about 7000 kilometers in diameter) that falls within the Moon's penumbral shadow. Here you will see a **partial solar eclipse**, in which only part of the Sun is blocked from view. If the eclipse occurs when the Moon is relatively far from Earth, the umbra may not reach Earth's surface at all. In that case, you will see an **annular eclipse**—a ring of sunlight surrounding the moon—from a position directly behind the umbra; again, you will see a partial solar eclipse in the surrounding penumbral shadow.

A total solar eclipse is visible only within the narrow path that the Moon's umbral shadow makes across Earth's surface.

The combination of Earth's rotation and the orbital motion of the Moon causes the Moon's umbral and penumbral shadows to race across the face of Earth at a typical speed of about 1700 kilometers per hour. As a result, the umbral shadow traces a narrow path across Earth, and totality never lasts more than a few minutes in any particular place.

A total solar eclipse is a spectacular sight. It begins when the disk of the Moon first appears to touch the Sun. Over the next couple of hours, the Moon appears to take a larger and larger "bite" out of the Sun. As totality approaches, the sky darkens and temperatures fall. Birds head back to their nests, and crickets begin their nighttime chirping. During the few minutes of totality, the Moon completely blocks the normally visible disk of the Sun, allowing the faint *corona* to be seen (Figure 2.24). The surrounding sky takes on a twilight glow, and planets and bright stars become visible in the daytime. As totality ends, the Sun slowly emerges from behind the Moon over the next couple of hours. However, because your eyes have adapted to the darkness, totality appears to end far more abruptly than it began.

Predicting Eclipses Few phenomena have so inspired and humbled humans throughout the ages as eclipses. For many cultures, eclipses were mystical events associated with fate or the gods, and countless stories and legends surround them. Much of the mystery of eclipses probably stems from the relative difficulty of predicting them.

Figure 2.24

This multiple-exposure photograph shows the progression of a total solar eclipse. Totality (central image) lasts only a few minutes, during which time we can see the faint corona around the outline of the Sun. This photo was taken July 22, 1990, in La Paz, Mexico.

To understand this difficulty, look again at Figure 2.20, which shows two periods during the year—the *eclipse seasons*—in which the nodes of the Moon's orbit are closely aligned with the Sun. If this were the whole story, these periods would always occur 6 months apart and predicting eclipses would be easy. For example, if the eclipse seasons occurred in January and July, we'd always have a solar eclipse at new moon in those months and a lunar eclipse at full moon. Actual eclipse prediction is more difficult than this because of something the figure does not show: The nodes slowly move around the Moon's orbit, so that the alignments actually occur slightly less than 6 months apart (about 173 days apart).

The general pattern of eclipses repeats with the roughly 18-year saros cycle.

The combination of the moving nodes and the $29\frac{1}{2}$-day cycle of lunar phases makes eclipses recur in a cycle of about 18 years $11\frac{1}{3}$ days. This cycle is called the **saros cycle**. Astronomers in many ancient cultures identified the saros cycle and thus could predict *when* eclipses would occur. However, the saros cycle does not account for all the complications involved in predicting eclipses. If a solar eclipse occurred today, the one that would occur 18 years $11\frac{1}{3}$ days from now would not be visible from the same places on Earth and might not be of the same type. For example, one might be total and the other only partial. No ancient culture achieved the ability to predict eclipses in every detail.

Today, we can predict eclipses because we know the precise details of the orbits of Earth and the Moon. Table 2.1 lists upcoming lunar eclipses; notice that, as we expect, eclipses generally come a little less than 6 months apart. Figure 2.25 shows paths of totality for upcoming total solar eclipses (but not for partial or annular eclipses), using color coding to show eclipses that repeat with the saros cycle.

think about it Table 2.1 shows one exception to the "rule" of eclipses coming about 6 months apart: the 2013 eclipses of April 25 and May 25. How can eclipses occur a month apart like this? Should you be surprised that one of these lunar eclipses is penumbral? Explain.

Table 2.1 *Lunar Eclipses 2011–2013**

Date	Type	Where You Can See It
Jun. 15, 2011	total	South America, Europe, Africa, Asia, Australia
Dec. 10, 2011	total	Europe, Africa, Asia, Australia, North America
Jun. 4, 2012	partial	Asia, Australia, Americas
Nov. 28, 2012	penumbral	Europe, Africa, Asia, Australia, North America
Apr. 25, 2013	partial	Europe, Africa, Asia, Australia
May 25, 2013	penumbral	Americas, Africa
Oct. 18, 2013	penumbral	Americas, Europe, Africa, Asia

*Dates are based on Universal Time and hence are those in Greenwich, England, at the time of the eclipse; to see an eclipse, check a news source for the local time and date. Data from NASA's Eclipse Home Page, maintained by Fred Espenak.

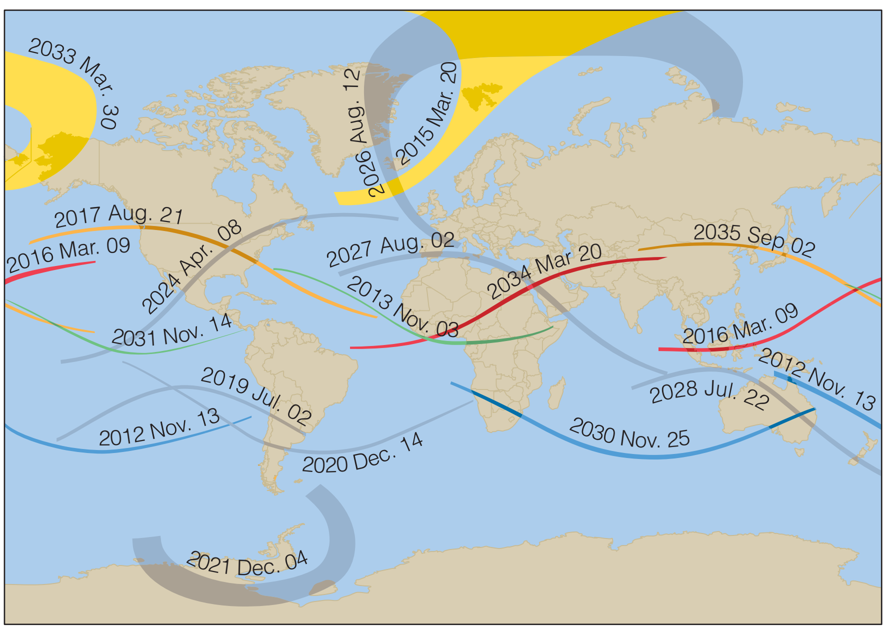


Figure 2.25

This map shows the paths of totality for solar eclipses through 2035. Paths of the same color represent eclipses occurring in successive saros cycles, separated by 18 years 11 days. For example, the 2034 eclipse occurs 18 years 11 days after the 2016 eclipse, both shown in red. (Eclipse predictions by Fred Espenak; see NASA's Eclipse Web site.)

2.4 The Ancient Mystery of the Planets

We've now covered the appearance and motion of the stars, Sun, and Moon in the sky. That leaves us with the planets yet to discuss. As we'll soon see, planetary motion posed an ancient mystery that played a critical role in the development of modern civilization.

Five planets are easy to find with the naked eye: Mercury, Venus, Mars, Jupiter, and Saturn. Mercury is visible infrequently, and only just after sunset or just before sunrise because it is so close to the Sun. Venus often shines brightly in the early evening in the west or before dawn in the east. If you see a very bright "star" in the early evening or early morning, it is probably Venus. Jupiter, when it is visible at night, is the brightest object in the sky besides the Moon and Venus. Mars is often recognizable by its reddish color, though you should check a star chart to make sure you aren't looking at a bright red star. Saturn is also easy to see with the naked eye, but because many stars are just as bright as Saturn, it helps to know where to look. (It also helps to know that planets tend not to twinkle as much as stars.)

• Why was planetary motion so hard to explain?

Over the course of a single night, planets behave like all other objects in the sky—Earth's rotation makes them appear to rise in the east and set in the west. But if you continue to watch the planets night after night, you will notice that their movements among the constellations are quite complex; in fact, the word *planet* comes from the Greek for "wandering star." Instead of moving steadily eastward relative to the stars, like the Sun and Moon, the planets vary substantially in both speed and brightness. Moreover, while the planets *usually* move eastward through the constellations, they occasionally reverse course, moving westward through the zodiac (Figure 2.26). These periods of **apparent retrograde motion** (*retrograde* means "backward") last from a few weeks to a few months, depending on the planet.

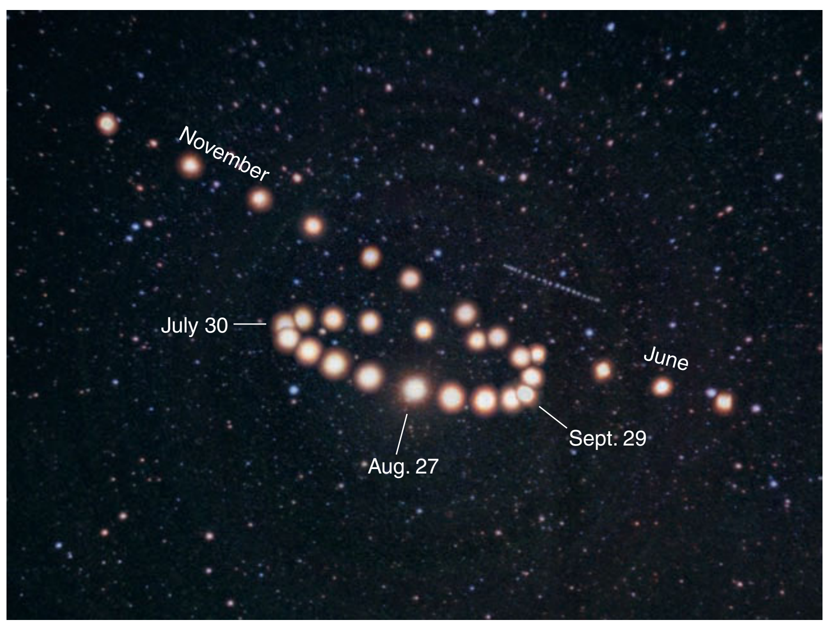
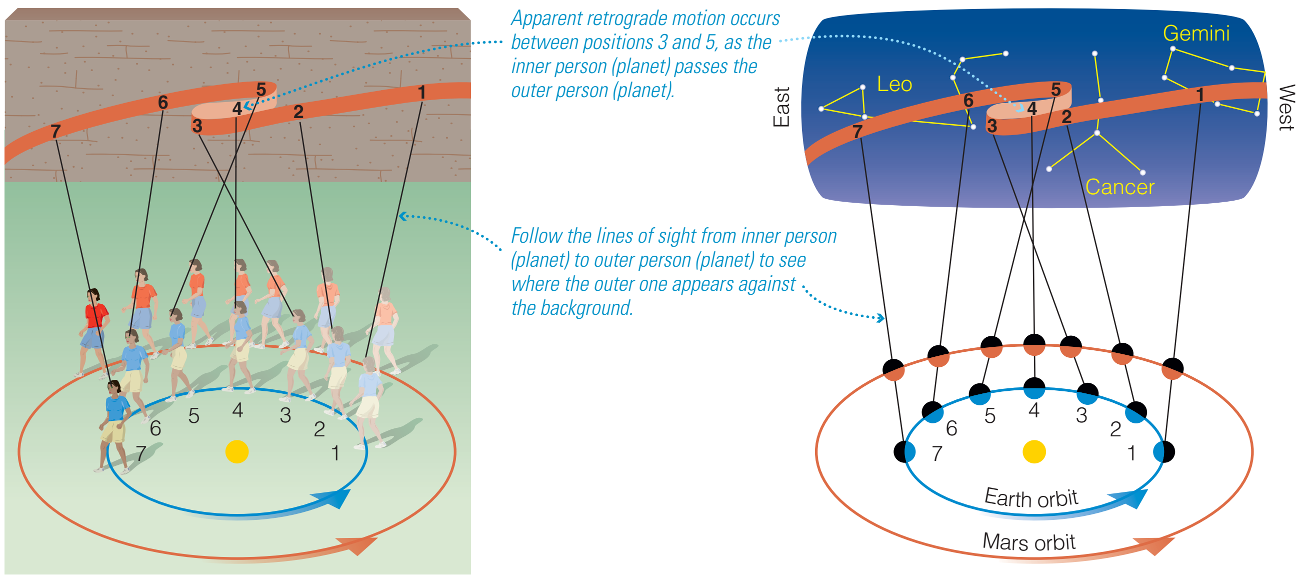


Figure 2.26

This composite of 29 individual photos shows Mars from June through November 2003. Notice that Mars usually moves eastward (left) relative to the stars, but reverses course during its apparent retrograde motion. Note also that Mars is biggest and brightest in the middle of the retrograde loop, because that is where it is closest to Earth in its orbit. (The white dots in a line just right of center are the planet Uranus, which by coincidence was in the same part of the sky.)



a This demonstration shows why planets sometimes seem to go backward relative to distant stars. Watch how your friend (in red) usually appears to move forward against the background of the building in the distance, but appears to move backward as you (in blue) catch up and pass her in your "orbit."

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

Figure 2.27 MA **interactive figure**

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

For ancient people who believed in an Earth-centered universe, apparent retrograde motion was very difficult to explain; after all, what could make planets sometimes turn around and go backward if everything moves in circles around Earth? The ancient Greeks nevertheless came up with some very clever ways to explain it (which we'll study in Chapter 3), but their complex explanations were ultimately proven wrong.

In contrast, apparent retrograde motion has a simple explanation in a Sun-centered solar system. You can demonstrate it for yourself with the help of a friend (Figure 2.27a). Pick a spot in an open area to represent the Sun. You can represent Earth, walking counterclockwise around the Sun, while your friend represents a more distant planet (such as Mars or Jupiter) by walking counterclockwise around the Sun at a greater distance. Your friend should walk more slowly than you, because more distant planets orbit the Sun more slowly. As you walk, watch how your friend appears to move relative to buildings or trees in the distance. Although both of you always walk the same way around the Sun, your friend will appear to move backward against the background during the part of your "orbit" at which you catch up to and pass him or her. To understand the apparent retrograde motions of Mercury and Venus, which are closer to the Sun than is Earth, simply switch places with your friend and repeat the demonstration.

A planet appears to move backward relative to the stars during the period when Earth passes it in its orbit.

This demonstration closely models actual planet motions. For example, because Mars takes about 2 years to orbit the Sun (more precisely, 1.88 years), it covers about half its orbit during the 1 year in which Earth makes a complete orbit. If you trace lines of sight from Earth to Mars from different points in their orbits, you will see that the line of sight usually moves eastward relative to the stars but moves westward during the time when Earth is passing Mars in its orbit (Figure 2.27b).

Like your friend in the demonstration, Mars never actually changes direction. It only *appears* to change direction from our perspective on Earth.

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

If the apparent retrograde motion of the planets is so readily explained by recognizing that Earth orbits the Sun, why wasn't this idea accepted in ancient times? In fact, the idea that Earth goes around the Sun was suggested as early as 260 B.C. by the Greek astronomer Aristarchus. No one knows why Aristarchus proposed a Sun-centered solar system, but the fact that it explains planetary motion so naturally probably played a role. Nevertheless, Aristarchus's contemporaries rejected his idea, and the Sun-centered solar system did not gain wide acceptance until almost 2000 years later.

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

If you now imagine that your two eyes represent Earth at opposite sides of its orbit around the Sun and that your finger represents a relatively nearby star, you have the idea of stellar parallax. Because we view the stars from different places in our orbit at different times of year, nearby stars should *appear* to shift back and forth against the background of more distant stars (Figure 2.28).

The Greeks knew that stellar parallax should occur if Earth orbits the Sun, but they could not detect it.

Because the Greeks believed that all stars lie on the same celestial sphere, they expected to see stellar parallax in a slightly different way. If Earth orbited the Sun, they reasoned, at different times of year we would be closer to different parts of the celestial sphere and would notice changes in the angular separations of stars. However, no matter how hard they searched, they could find no sign of stellar parallax. They concluded that one of the following must be true:

1. Earth orbits the Sun, but the stars are so far away that stellar parallax is not detectable to the naked eye.
2. There is no stellar parallax because Earth remains stationary at the center of the universe.

Aside from notable exceptions such as Aristarchus, the Greeks rejected the correct answer (the first one) because they could not imagine that the stars could be *that* far away. Today, we can detect stellar parallax with the aid of telescopes, providing direct proof that Earth really does orbit the Sun. Careful measurements of stellar parallax also provide the most reliable means of measuring distances to nearby stars **[Section 11.1]**.

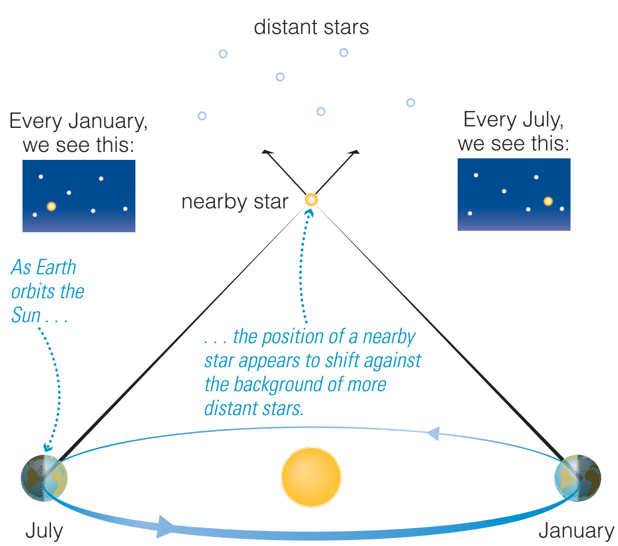


Figure 2.28

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

think about it How far apart are opposite sides of Earth's orbit? How far away are the nearest stars? Using the 1-to-10-billion scale from Chapter 1, describe the challenge of detecting stellar parallax.

The ancient mystery of the planets drove much of the historical debate over Earth's place in the universe. In many ways, the modern technological society we take for granted today can be traced directly to the scientific revolution that began in the quest to explain the strange wanderings of the planets among the stars in our sky. We will turn our attention to this revolution in the next chapter.

the big picture

Putting Chapter 2 into Perspective

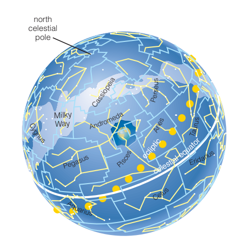
In this chapter, we surveyed the phenomena of our sky. Keep the following "big picture" ideas in mind as you continue your study of astronomy:

- You can enhance your enjoyment of astronomy by observing the sky. The more you learn about the appearance and apparent motions of objects in the sky, the more you will appreciate what you can see in the universe.
- From our vantage point on Earth, it is convenient to imagine that we are at the center of a great celestial sphere—even though we really are on a planet orbiting a star in a vast universe. We can then understand what we see in the local sky by thinking about how the celestial sphere appears from our latitude.
- Most of the phenomena of the sky are relatively easy to observe and understand. The more complex phenomena—particularly eclipses and apparent retrograde motion of the planets—challenged our ancestors for thousands of years. The desire to understand these phenomena helped drive the development of science and technology.

summary of key concepts

2.1 Patterns in the Night Sky

- **What does the universe look like from Earth?**



Stars and other celestial objects appear to lie on a great **celestial sphere** surrounding Earth. We divide the celestial sphere into **constellations** with well-defined borders. From any location on Earth, we see half the celestial sphere at any given time as the dome of our **local sky**, in which the **horizon** is the boundary between Earth and sky, the zenith is the point directly overhead, and the **meridian** runs from due south to due north through the zenith.

- **Why do stars rise and set?**

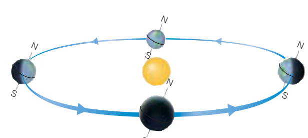
Earth's rotation makes stars appear to circle around Earth each day. A star whose complete circle lies above our horizon is said to be **circumpolar**. Other stars have circles that cross the horizon, so they rise in the east and set in the west each day.

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

The visible constellations vary with time of year because our night sky lies in different directions in space as we orbit the Sun. The constellations vary with **latitude** because your latitude determines the orientation of your horizon relative to the celestial sphere. The sky does not vary with **longitude**.

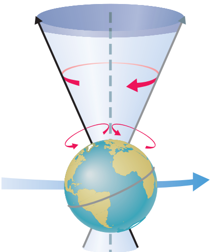
2.2 The Reason for Seasons

- **What causes the seasons?**



The tilt of Earth's axis causes the seasons. The axis points in the same direction throughout the year, so as Earth orbits the Sun, sunlight hits different parts of Earth more directly at different times of year. The **summer** and **winter solstices** are the times during the year when the Northern Hemisphere gets its most and least direct sunlight, respectively. The **spring** and **fall equinoxes** are the two times when both hemispheres get equally direct sunlight.

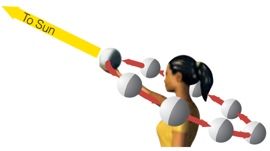
• **How does the orientation of Earth's axis change with time?**



Earth's 26,000-year cycle of **precession** changes the orientation of its axis in space, although the tilt remains about $23\frac{1}{2}°$. The changing orientation of the axis does not affect the pattern of seasons, but it changes the identity of the north star and shifts the locations of the solstices and equinoxes in Earth's orbit.

2.3 The Moon, Our Constant Companion

• **Why do we see phases of the Moon?**



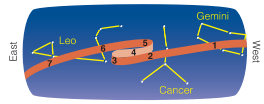
The **phase** of the Moon depends on its position relative to the Sun as it orbits Earth. The half of the Moon facing the Sun is always illuminated while the other half is dark, but from Earth we see varying combinations of the illuminated and dark halves.

• **What causes eclipses?**

We see a **lunar eclipse** when Earth's shadow falls on the Moon and a **solar eclipse** when the Moon blocks our view of the Sun. We do not see an eclipse at every new and full moon because the Moon's orbit is slightly inclined to the ecliptic plane. Eclipses come in different types, depending on where the dark **umbral** and lighter **penumbral** shadows fall.

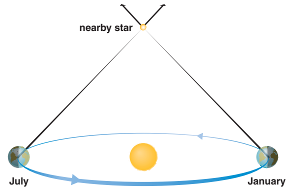
2.4 The Ancient Mystery of the Planets

• **Why was planetary motion so hard to explain?**



Planets generally appear to move eastward relative to the stars over the course of the year, but for weeks or months they reverse course during periods of **apparent retrograde motion**. This motion occurs when Earth passes by (or is passed by) another planet in its orbit, but it posed a major mystery to ancient people who assumed Earth to be at the center of the universe.

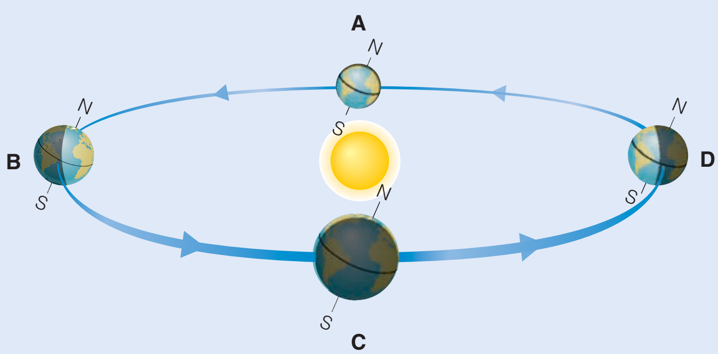
• **Why did the ancient Greeks reject the real explanation for planetary motion?**



The Greeks rejected the idea that Earth goes around the Sun in part because they could not detect **stellar parallax**—slight apparent shifts in stellar positions over the course of the year. To most Greeks, it seemed unlikely that the stars could be so far away as to make parallax undetectable to the naked eye, even though that is, in fact, the case.

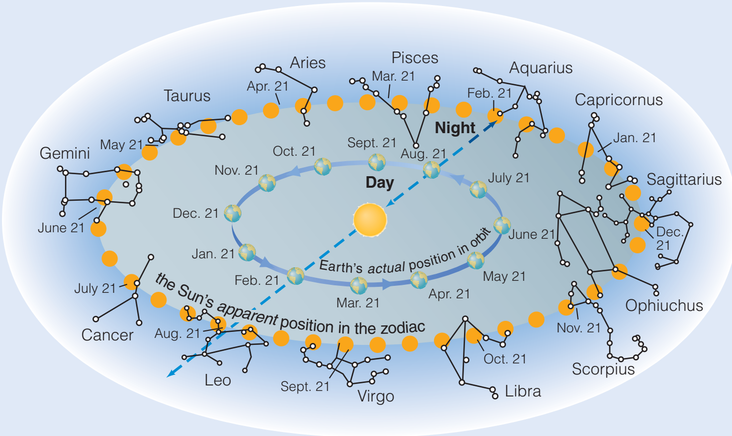
visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 2 Visual Quiz at www.masteringastronomy.com.



The figure above is a typical diagram used to describe Earth's seasons. Use this figure to answer questions 1–5.

1. Which of the four labeled points (A through D) represents the beginning of summer for the Northern Hemisphere?
2. Which of the four labeled points represents the beginning of summer for the Southern Hemisphere?
3. Which of the four labeled points represents the beginning of spring for the Northern Hemisphere?
4. Which of the four labeled points represents the beginning of spring for the Southern Hemisphere?
5. Diagrams like the one shown in the figure are useful for representing seasons, but they can also be misleading because they exaggerate the sizes of Earth and the Sun relative to the orbit. If Earth were correctly scaled relative to the orbit in the figure, how big would it be?
   a. about half the size shown
   b. about 2 millimeters across
   c. about 0.1 millimeter across
   d. microscopic



The figure above (based on Figure 2.12) shows the Sun's path through the constellations of the zodiac. Use this figure to answer questions 6–8.

6. As viewed from Earth, in which zodiac constellation does the Sun appear to be located on April 21?
   a. Leo
   b. Aquarius
   c. Libra
   d. Aries
7. If the date is April 21, what zodiac constellation will be visible on your meridian at midnight?
   a. Leo
   b. Aquarius
   c. Libra
   d. Aries
8. If the date is April 21, what zodiac constellation will you see setting in the west shortly after sunset?
   a. Scorpius
   b. Pisces
   c. Taurus
   d. Virgo

exercises and problems

Mastering ASTRONOMY

For instructor-assigned homework go to www.masteringastronomy.com.

Review Questions

1. What are *constellations*? How did they get their names?
2. Suppose you were making a model of the celestial sphere with a ball. Briefly describe all the things you would need to mark on your celestial sphere.
3. On a clear, dark night, the sky may appear to be "full" of stars. Does this appearance accurately reflect the way stars are distributed in space? Explain.
4. Why does the *local sky* look like a dome? Define *horizon*, *zenith*, and *meridian*. How do we describe the location of an object in the local sky?
5. Explain why we can measure only *angular sizes* and *angular distances* for objects in the sky. What are *arcminutes* and *arcseconds*?
6. What are *circumpolar stars*? Are more stars circumpolar at the North Pole or in the United States? Explain.
7. What are *latitude* and *longitude*? Does the local sky vary with latitude? Does it vary with longitude? Explain.
8. What is the *zodiac*, and why do we see different parts of it at different times of year?
9. Suppose Earth's axis had no tilt. Would we still have seasons? Why or why not?
10. Briefly describe what is special about the summer and winter solstices and the spring and fall equinoxes.
11. What is *precession*, and how does it affect the sky that we see from Earth?
12. Briefly describe the Moon's cycle of *phases*. Can you ever see a full moon at noon? Explain.
13. Suppose you lived on the Sun (and could ignore the heat). Would you still see the Moon go through phases as it orbited Earth? Why or why not?
14. Why don't we see an *eclipse* at every new and full moon? Describe the conditions needed for a *solar* or *lunar eclipse*.
15. What do we mean by the *apparent retrograde motion* of the planets? Why was it difficult for ancient astronomers to explain but is easy for us to explain?
16. What is *stellar parallax*? Briefly describe the role it played in making ancient astronomers believe in an Earth-centered universe.

Test Your Understanding

Does It Make Sense?

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

17. The constellation Orion didn't exist when my grandfather was a child.
18. When I looked into the dark lanes of the Milky Way with my binoculars, I saw what must have been a cluster of distant galaxies.
19. Last night the Moon was so big that it stretched for a mile across the sky.
20. I live in the United States, and during my first trip to Argentina I saw many constellations that I'd never seen before.
21. Last night I saw Jupiter right in the middle of the Big Dipper. (*Hint*: Is the Big Dipper part of the zodiac?)
22. Last night I saw Mars move westward through the sky in its apparent retrograde motion.
23. Although all the known stars appear to rise in the east and set in the west, we might someday discover a star that will appear to rise in the west and set in the east.

24. If Earth's orbit were a perfect circle, we would not have seasons.
25. Because of precession, someday it will be summer everywhere on Earth at the same time.
26. This morning I saw the full moon setting at about the same time the Sun was rising.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

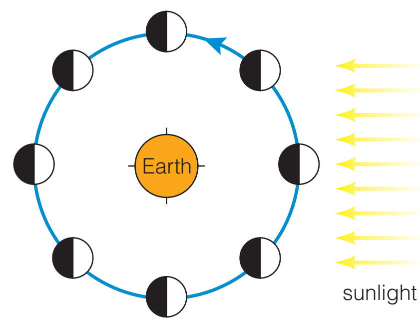
27. Two stars that are in the same constellation (a) must both be part of the same cluster of stars in space. (b) must both have been discovered at about the same time. (c) may actually be very far away from each other.
28. The north celestial pole is 35° above your northern horizon. This tells you that (a) you are at latitude 35°N. (b) you are at longitude 35°E. (c) you are at latitude 35°S.
29. Beijing and Philadelphia have about the same latitude but very different longitudes. Therefore, tonight's night sky in these two places (a) will look about the same. (b) will have completely different sets of constellations. (c) will have partially different sets of constellations.
30. In winter, Earth's axis points toward the star Polaris. In spring, (a) the axis also points toward Polaris. (b) the axis points toward Vega. (c) the axis points toward the Sun.
31. When it is summer in Australia, the season in the United States is (a) winter. (b) summer. (c) spring.
32. If the Sun rises precisely due east, (a) you must be located at Earth's equator. (b) it must be the day of either the spring or fall equinox. (c) it must be the day of the summer solstice.
33. A week after full moon, the Moon's phase is (a) first quarter. (b) third quarter. (c) new.
34. Some type of lunar or solar eclipse (not necessarily a total eclipse) occurs (a) about once every 18 years. (b) about once a month. (c) at least four times a year.
35. If there is going to be a total lunar eclipse tonight, then you know that (a) the Moon's phase is full. (b) the Moon's phase is new. (c) the Moon is unusually close to Earth.
36. When we see Saturn going through a period of apparent retrograde motion, it means (a) Saturn is temporarily moving backward in its orbit of the Sun. (b) Earth is passing Saturn in its orbit, with both planets on the same side of the Sun. (c) Saturn and Earth must be on opposite sides of the Sun.

Process of Science

37. *Earth-Centered or Sun-Centered?* The phenomena discussed in this chapter are all visible to the naked eye and therefore have been known throughout human history, even during the thousands of years when Earth was assumed to be at the center of the universe. For each of the following, decide whether the phenomenon is consistent or inconsistent with a belief in an Earth-centered system. If consistent, describe how. If inconsistent, explain why, and also explain why the inconsistency did not immediately lead people to abandon the Earth-centered model.
    a. The daily paths of stars through the sky
    b. Seasons
    c. Phases of the Moon
    d. Eclipses
    e. Apparent retrograde motion of the planets
38. *Shadow Phases.* Many people incorrectly guess that the phases of the Moon are caused by Earth's shadow falling on the Moon. How would you convince a friend that the phases of the Moon have nothing to do with Earth's shadow? Describe the observations you would use to show that Earth's shadow isn't the cause of phases.

Group Work Exercise

39. *Lunar Phases and Time of Day.* Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Proposer* (proposes explanations to the group), *Skeptic* (points out weaknesses in proposed explanations), and *Moderator* (leads group discussion and makes sure everyone contributes). Then each member of the group should draw a copy of the following diagram, which represents the Moon's orbit as seen from above Earth's North Pole (not to scale):



Discuss and answer the following questions as a group:
    a. How would the Moon appear from Earth at each of the eight Moon positions? Label each one with the corresponding phase.
    b. What time of day corresponds to each of the four tick marks on Earth? Label each tick mark accordingly.
    c. Why doesn't the Moon's phase change during the course of one night? Explain your reasoning.
    d. At what times of day would a full moon be visible to someone standing on Earth? Write down when a full moon rises and explain why it appears to rise at that time.
    e. At what times of day would a third quarter moon be visible to someone standing on Earth? Write down when a third quarter moon sets and explain why it appears to set at that time.
    f. At what times of day would a waxing crescent moon be visible to someone standing on Earth? Write down when a waxing crescent moon rises and explain why it appears to rise at that time.

Investigate Further

Short-Answer/Essay Questions

40. *New Planet.* A planet in another solar system has a circular orbit and an axis tilt of 35°. Would you expect this planet to have seasons? If so, would you expect them to be more extreme than the seasons on Earth? If not, why not?
41. *Your View of the Sky.*
    a. Find your latitude and longitude, and state the source of your information.
    b. Describe the altitude and direction in your local sky at which the north or south celestial pole appears.
    c. Is Polaris a circumpolar star in your sky? Explain.

42. *View from the Moon.* Suppose you lived on the Moon, in which case you would see Earth going through phases in your sky. Assume you live near the center of the face that looks toward Earth.
   a. Suppose you see a full Earth in your sky. What phase of the Moon would people on Earth see? Explain.
   b. Suppose people on Earth see a full moon. What phase would you see for Earth? Explain.
   c. Suppose people on Earth see a waxing gibbous moon. What phase would you see for Earth? Explain.
   d. Suppose people on Earth are viewing a total lunar eclipse. What would you see from your home on the Moon? Explain.
43. *A Farther Moon.* Suppose the distance to the Moon were twice its actual value. Would it still be possible to have a total solar eclipse? Why or why not?
44. *A Smaller Earth.* Suppose Earth were smaller. Would solar eclipses be any different? If so, how? What about lunar eclipses? Explain.
45. *Observing Planetary Motion.* Find out what planets are currently visible in your evening sky. At least once a week, observe the planets and draw a diagram showing the position of each visible planet relative to stars in a zodiac constellation. From week to week, note how the planets are moving relative to the stars. Can you see any of the apparently wandering features of planetary motion? Explain.

Quantitative Problems

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

46. *Arcminutes and Arcseconds.* There are 360° in a full circle.
   a. How many arcminutes are in a full circle?
   b. How many arcseconds are in a full circle?
   c. The Moon's angular size is about $\frac{1}{2}°$. What is this in arcminutes? In arcseconds?
47. *Find the Sun's Diameter.* The Sun has an angular diameter of about 0.5° and an average distance from Earth of about 150 million km. What is the Sun's approximate physical diameter? Compare your answer to the actual value of 1,390,000 km.
48. *Find a Star's Diameter.* The supergiant star Betelgeuse (in the constellation Orion) has a measured angular diameter of 0.044 arcsecond from Earth and a distance from Earth of 427 light-years. What is the actual diameter of Betelgeuse? Compare your answer to the size of our Sun and the Earth–Sun distance.
49. *Eclipse Conditions.* The Moon's precise equatorial diameter is 3476 km, and its orbital distance from Earth varies between 356,400 km and 406,700 km. The Sun's diameter is 1,390,000 km, and its distance from Earth ranges between 147.5 and 152.6 million km.
   a. Find the Moon's angular size at its minimum and maximum distances from Earth.
   b. Find the Sun's angular size at its minimum and maximum distances from Earth.
   c. Based on your answers to (a) and (b), is it possible to have a total solar eclipse when the Moon and Sun are both at their maximum distances? Explain.

Discussion Questions

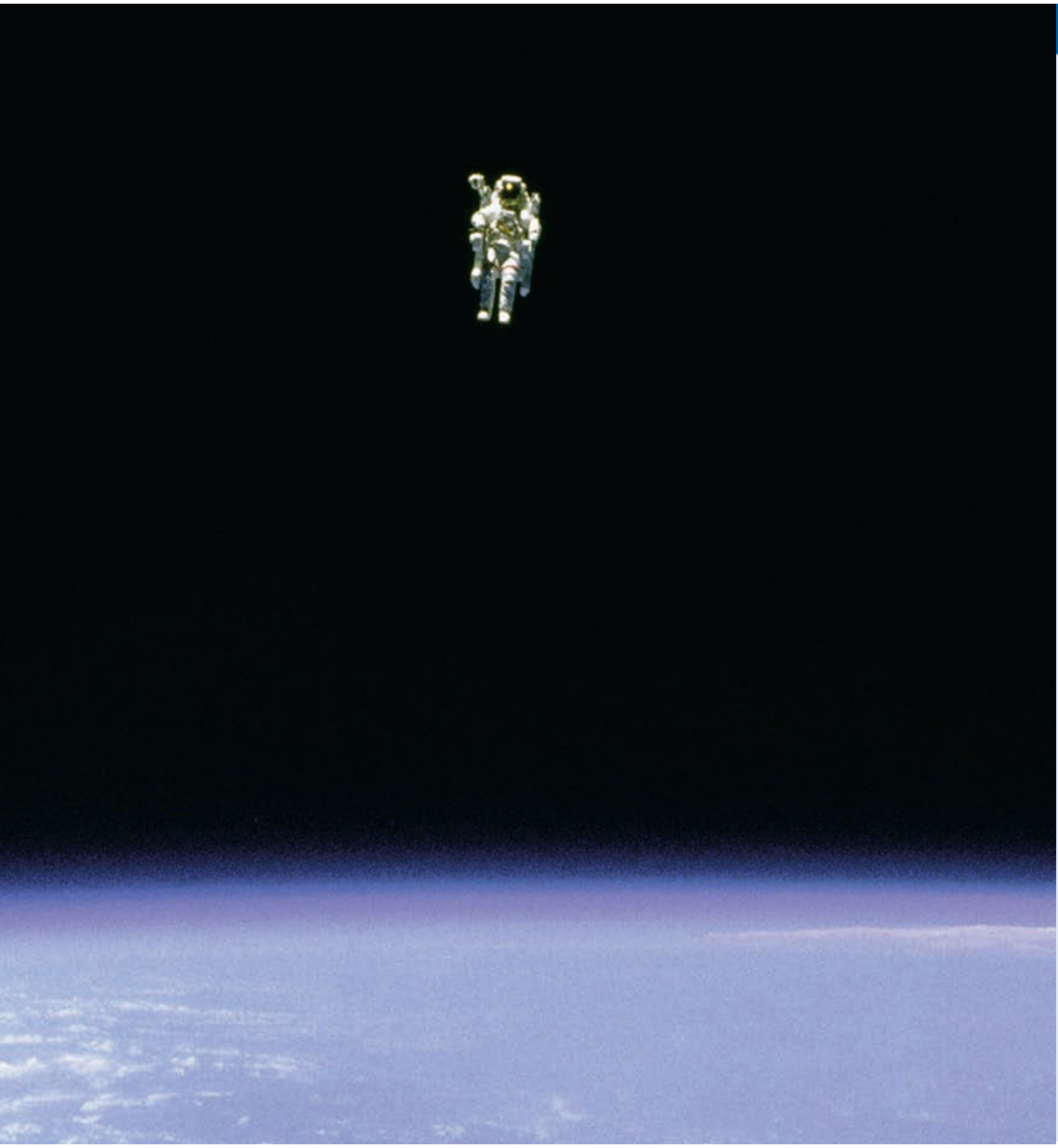
50. *Earth-Centered Language.* Many common phrases reflect the ancient Earth-centered view of our universe. For example, the phrase "the Sun rises each day" implies that the Sun is really moving over Earth. We know that the Sun only *appears* to rise as the rotation of Earth carries us to a place where we can see the Sun in our sky. Identify other common phrases that imply an Earth-centered viewpoint.
51. *Flat Earth Society.* Believe it or not, there is an organization called the Flat Earth Society. Its members hold that Earth is flat and that all indications to the contrary (such as pictures of Earth from space) are fabrications made as part of a conspiracy to hide the truth from the public. Discuss the evidence for a round Earth and how you can check it for yourself. In light of the evidence, is it possible that the Flat Earth Society is correct? Defend your opinion.

Web Projects

52. *Sky Information.* Search the Web for sources of daily information about sky phenomena (such as lunar phases, times of sunrise and sunset, or dates of equinoxes and solstices). Identify and briefly describe your favorite source.
53. *Constellations.* Search the Web for information about the constellations and their mythology. Write a one- to three-page report about one or more constellations.
54. *Upcoming Eclipse.* Find information about an upcoming solar or lunar eclipse. Write a one- to three-page report about how you could best observe the eclipse, including any necessary travel to a viewing site, and what you could expect to see. Bonus: Describe how you could photograph the eclipse.

3

The Science of Astronomy



learning goals

3.1 The Ancient Roots of Science
- In what ways do all humans use scientific thinking?
- How did astronomical observations benefit ancient societies?
- What did ancient civilizations achieve in astronomy?

3.2 Ancient Greek Science
- Why does modern science trace its roots to the Greeks?
- How did the Greeks explain planetary motion?
- How did Islamic scientists preserve and extend Greek science?

3.3 The Copernican Revolution
- How did Copernicus, Tycho, and Kepler challenge the Earth-centered model?
- What are Kepler's three laws of planetary motion?
- How did Galileo solidify the Copernican revolution?

3.4 The Nature of Science
- How can we distinguish science from nonscience?
- What is a scientific theory?

Today we know that Earth is a planet orbiting a rather ordinary star, in a galaxy of more than a hundred billion stars, in an incredibly vast universe. We know that Earth, along with the entire cosmos, is in constant motion. We know that, on the scale of cosmic time, human civilization has existed for only the briefest moment. How did we manage to learn these things?

It wasn't easy. Astronomy is the oldest of the sciences, with roots extending as far back as recorded history allows us to see. But the most impressive advances in knowledge have come in just the past few centuries.

In this chapter, we will trace how modern astronomy grew from its roots in ancient observations, including those of the Greeks. We'll pay special attention to the unfolding of the Copernican revolution, which overturned the ancient belief in an Earth-centered universe and laid the foundation for the rise of our technological civilization. Finally, we'll explore the nature of modern science and the distinction between science and nonscience.

essential preparation

1. What does the universe look like from Earth? [Section 2.1]
2. Why was planetary motion so hard to explain? [Section 2.4]
3. Why did the ancient Greeks reject the real explanation for planetary motion? [Section 2.4]

3.1 The Ancient Roots of Science

A common stereotype holds that scientists walk around in white lab coats and somehow think differently than other people. In reality, scientific thinking is a fundamental part of human nature. In this section, we will trace the roots of science to experiences common to nearly all people and nearly all cultures.

• In what ways do all humans use scientific thinking?

Scientific thinking comes naturally to us. By about a year of age, a baby notices that objects fall to the ground when she drops them. She lets go of a ball—it falls. She pushes a plate of food from her high chair—it falls, too. She continues to drop all kinds of objects, and they all plummet to Earth. Through her powers of observation, the baby learns about the physical world, finding that things fall when they are unsupported. Eventually, she becomes so certain of this fact that, to her parents' delight, she no longer needs to test it continually.

Scientific thinking is based on everyday observations and trial-and-error experiments.

One day somebody gives the baby a helium balloon. She releases it, and to her surprise it rises to the ceiling! Her understanding of nature must be revised. She now knows that the principle "all things fall" does not represent the whole truth, although it still serves her quite well in most situations. It will be years before she learns enough about the atmosphere, the force of gravity, and the concept of density to understand *why* the balloon rises when most other objects fall. For now, she is delighted to observe something new and unexpected.

The baby's experience with falling objects and balloons exemplifies scientific thinking. In essence, it is a way of learning about nature through careful observation and trial-and-error experiments. Rather

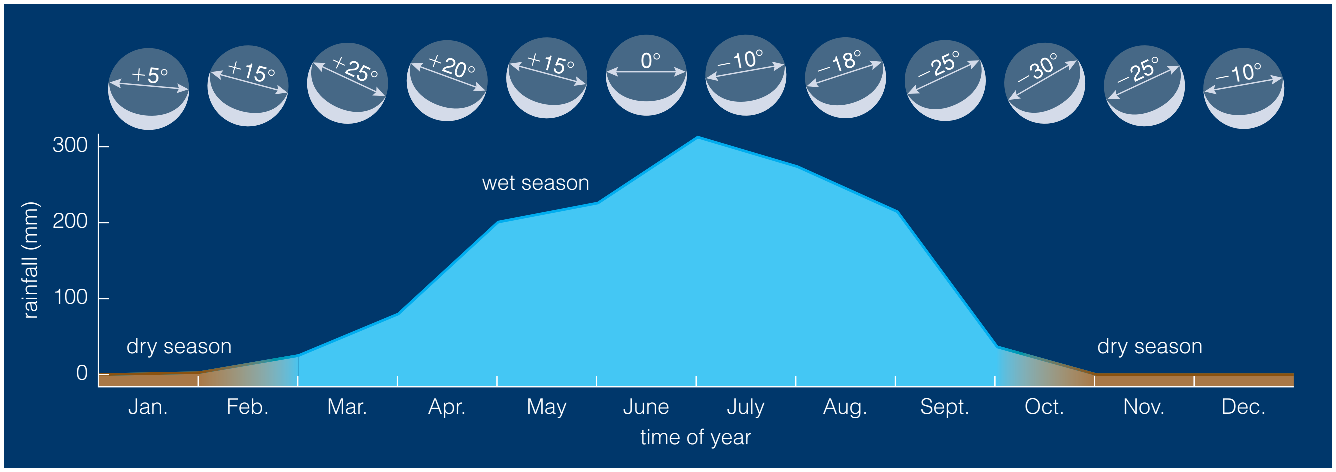


Figure 3.1

Science is rooted in careful observation of the world around us. This diagram shows how central Africans used the orientation of the waxing crescent moon to predict rainfall. The graph depicts the annual rainfall pattern in central Nigeria, and the Moon diagrams show the varying angle of the "horns" of a waxing crescent moon relative to the western horizon. (Adapted from *Ancient Astronomers* by Anthony F. Aveni.)

than thinking differently than other people, modern scientists are trained to organize everyday thinking in a way that makes it easier for them to share their discoveries and use their collective wisdom.

think about it Describe a few cases where you have learned by trial and error—while cooking, participating in sports, fixing something, learning on the job, or in any other situation.

Just as learning to communicate through language, art, or music is a gradual process for a child, the development of science has been a gradual process for humanity. Science in its modern form requires painstaking attention to detail, relentless testing of each piece of information to ensure its reliability, and a willingness to give up old beliefs that are not consistent with observed facts about the physical world. For professional scientists, these demands are the "hard work" part of the job. At heart, professional scientists are like the baby with the balloon, delighted by the unexpected and motivated by those rare moments when they—and all of us—learn something new about the universe.

• How did astronomical observations benefit ancient societies?

We will discuss modern science shortly, but first we will explore how it arose from the observations of ancient peoples. Our exploration begins in central Africa, where people long ago learned to predict the weather with reasonable accuracy by making careful observations of the Moon. Remember that the Moon begins its monthly cycle as a crescent in the western sky just after sunset. Through long traditions of sky watching, central African societies discovered that the orientation of the crescent "horns" relative to the horizon is closely tied to local rainfall patterns (Figure 3.1).

Why did ancient people make such careful and detailed observations of the sky? In part, it was probably to satisfy their inherent curiosity. But astronomy also played a practical role for them. They used the changing positions of the Sun, Moon, and stars to keep track of the time and seasons, crucial skills for people who depended on agriculture. Some cultures even learned to navigate by the Sun and stars.

Table 3.1 *The Seven Days of the Week and the Astronomical Objects They Honor*

In English, the correspondence between astronomical days and objects is obvious only for Sunday, "Moonday," and "Saturnday." You can see some of the other connections in languages such as French and Spanish.

Object	English	French	Spanish
Sun	Sunday	dimanche	domingo
Moon	Monday	lundi	lunes
Mars	Tuesday	mardi	martes
Mercury	Wednesday	mercredi	miércoles
Jupiter	Thursday	jeudi	jueves
Venus	Friday	vendredi	viernes
Saturn	Saturday	samedi	sábado

Modern measures of time come directly from ancient observations of motion in the sky. The length of our day is the time it takes the Sun to make one full circuit of the sky. The length of a month comes from the Moon's cycle of phases **[Section 2.3]**, and our year is based on the cycle of the seasons **[Section 2.2]**. The seven days of the week were named after the seven objects that could be seen with the naked eye and appeared to move among the constellations: the Sun, the Moon, and the five planets recognized in ancient times (Table 3.1).

Ancient people used observations of the sky to keep track of the time and seasons and as an aid in navigation.

• What did ancient civilizations achieve in astronomy?

Nearly all ancient civilizations practiced astronomy at some level. Many built remarkable structures for observing the sky. Let's explore a few of the ways that ancient societies studied the sky.

Determining the Time of Day In the daytime, ancient peoples could tell time by observing the Sun's path through the sky. Many cultures probably used the shadows cast by sticks as simple sundials. The ancient Egyptians built huge obelisks, often decorated in homage to the Sun, that probably also served as simple clocks (Figure 3.2). At night, ancient people could estimate the time from the position and phase of the Moon (see Figure 2.19) or by observing the constellations visible at a particular time of night.

We can trace the origins of our modern clock to ancient Egypt, some 4000 years ago. The Egyptians divided the daylight into 12 equal parts, and we still break the 24-hour day into 12 hours each of A.M. and P.M. The abbreviations *A.M.* and *P.M.* stand for the Latin terms *ante meridiem* and *post meridiem*, respectively, which mean "before the middle of the day" and "after the middle of the day."

Marking the Seasons Many ancient cultures built structures to help them mark the seasons. One of the oldest standing human-made structures served such a purpose: Stonehenge in southern England (Figure 3.3). Stonehenge was both an astronomical device for keeping track of the seasons and a social and religious gathering place.

Among the most spectacular structures used to mark the seasons was the Templo Mayor in the Aztec city of Tenochtitlán, located in modern-day Mexico City (Figure 3.4). Twin temples stood on a flat-topped, 150-foot-high pyramid. From the vantage point of a royal observer watching from the opposite side of the plaza, the Sun rose directly through the notch between the temples on the equinoxes.

Many cultures aligned their buildings with the cardinal directions (north, south, east, and west), enabling them to mark the rising and setting of the Sun relative to the building orientation. Other structures were used to mark the Sun's position on special dates. For example, the ancient Anasazi people carved a 19-turn spiral—known as the *Sun Dagger*—on a vertical cliff face in Chaco Canyon, New Mexico (Figure 3.5). The Sun's rays form a dagger of sunlight that pierces the center of the carved spiral only once each year—at noon on the summer solstice.

Lunar Calendars Some ancient civilizations paid particular attention to lunar phases and used them as the basis for calendars. Some months on a lunar calendar have 29 days and others have 30 days, so that the

Figure 3.2

This ancient Egyptian obelisk, which stands 83 feet tall and weighs 331 tons, resides in St. Peter's Square at the Vatican in Rome. It is one of 21 surviving obelisks from ancient Egypt, most of which are now scattered around the world. Shadows cast by the obelisks may have been used to tell time.

Figure 3.3

The remains of Stonehenge today. It was built in stages from about 2750 B.C. to about 1550 B.C.

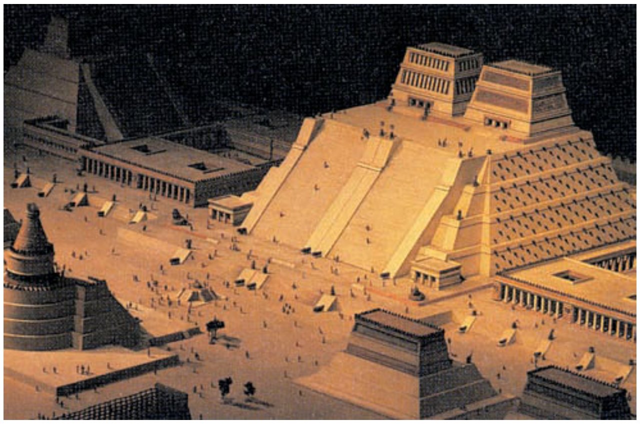


Figure 3.4

This scale model shows the Templo Mayor and the surrounding plaza as they are thought to have looked before the Spanish conquistadores destroyed Aztec civilization. The structure was used to help mark the seasons.

Figure 3.5

The Sun Dagger. Three large slabs of rock in front of the spiral produce patterns of light and shadow that vary throughout the year, forming a dagger of sunlight that pierced the center of the spiral only at noon on the summer solstice. (Unfortunately, within just 12 years of the site's 1977 discovery, the rocks shifted so that the effect no longer occurs; the shifts probably were due to erosion caused by large numbers of visitors.)

average matches the $29\frac{1}{2}$-day lunar cycle. A 12-month lunar calendar has only 354 or 355 days, or about 11 days fewer than a calendar based on the Sun. Such a calendar is still used in the Muslim religion. That is why the month-long fast of Ramadan (the ninth month) begins about 11 days earlier with each subsequent year.

Other lunar calendars remain roughly synchronized with solar calendars by taking advantage of an interesting coincidence: 19 years on a solar calendar is almost precisely 235 months on a lunar calendar. As a result, the lunar phases repeat on the same dates about every 19 years (a pattern known as the *Metonic cycle*). For example, there was a full moon on January 19, 2011, and there will be a full moon 19 years later, on January 19, 2030. Because an ordinary lunar calendar has only $19 \times 12 = 228$ months in a 19-year period, adding 7 extra months (to make 235) can keep the lunar calendar roughly synchronized to the seasons. The Jewish calendar does this by adding a thirteenth month in the third, sixth, eighth, eleventh, fourteenth, seventeenth, and nineteenth years of each 19-year cycle.

Remarkable ancient achievements included accurate calendars, eclipse prediction, navigational tools, and elaborate structures for astronomical observations.

In addition to following the lunar phases, some ancient cultures discovered other lunar cycles. In the Middle East more than 2500 years ago, the Babylonians achieved remarkable success in predicting eclipses, thanks to their recognition of the approximately 18-year saros cycle **[Section 2.3]**. The Mayans of Central America also appear to have been experts at eclipse prediction, but we know few details about their accomplishments because the Spanish conquistadores burned most Mayan writings.

Ancient Structures and Archaeoastronomy

It's easy to establish the astronomical intentions of ancient cultures that left extensive written records, such as the Chinese and the Egyptians. In other cases, however, claims that ancient structures served astronomical purposes can be much more difficult to evaluate.

The study of ancient structures in search of astronomical connections is called *archaeoastronomy*, a word that combines archaeology and astronomy. Scientists engaged in archaeoastronomy usually start by evaluating an ancient structure to see whether it shows any particular astronomical alignments. For example, they may check to see whether an observer in a central location would see particular stars rise above specially marked stones, or whether sunlight enters through a window only on special days like the solstices or equinoxes. However, the mere existence of astronomical alignments is not enough to establish that a structure had an astronomical purpose; the alignments may be coincidental.

Native American Medicine Wheels—stone circles found throughout the northern plains of the United States—offer an example of the difficulty of trying to establish the intentions of ancient builders. In the 1970s, a study of the Big Horn Medicine Wheel in Wyoming (Figure 3.6) seemed to indicate that its 28 "spokes" were aligned with the rise and set of particular stars. However, later research showed that the original study had failed to take into account the motion of stars as they rise above the horizon and the way the atmosphere affects the visibility of stars at the latitude of Big Horn. In reality the spokes do *not* show any special alignments with bright stars. Moreover, if Medicine Wheels really did serve an astronomical purpose, we'd expect all of them to have been built with consistent alignments—but that is not the case.

In some cases, scientists can use other clues to establish the intentions of ancient builders. For example, lodges built by the Pawnee people in Kansas feature strategically placed holes for observing the passage of constellations that figure prominently in Pawnee folklore. The correspondence between the folklore and the structural features provides a strong case for deliberate intent rather than coincidence. Similarly, traditions of the Inca Empire of South America held that its rulers were descendents of the Sun and therefore demanded that movements of the Sun be watched closely. This fact supports the idea that astronomical alignments in Inca cities and ceremonial centers, such as the World Heritage Site of Machu Picchu (Figure 3.7), were deliberate rather than accidental.

A different type of evidence makes a convincing case for the astronomical sophistication of ancient Polynesians, who lived and traveled among the many islands of the mid- and South Pacific. Navigation was crucial to survival, because the next island in a journey usually was too distant to be seen. The most esteemed position in Polynesian culture was that of the Navigator, a person who had acquired the knowledge necessary to navigate great distances among the islands. Navigators used a combination of detailed knowledge of astronomy and of the patterns of waves and swells around different islands (Figure 3.8).

Figure 3.6

The Big Horn Medicine Wheel in Wyoming. A study once claimed that its "spokes" have astronomically significant alignments, but later research showed the claim was in error—making this a good example of how science adapts as new data come to light.

Figure 3.7

The World Heritage Site of Machu Picchu has structures aligned with sunrise at the winter and summer solstices.

Figure 3.8

A Micronesian stick chart, an instrument used by Polynesian Navigators to represent swell patterns around islands.

3.2 Ancient Greek Science

Before a structure such as Stonehenge or the Templo Mayor could be built, careful observations had to be made and repeated over and over to ensure their accuracy. Careful, repeatable observations also underlie modern science. Elements of modern science were therefore present in many early human cultures. If the circumstances of history had been different, almost any culture might have been the first to develop what we consider to be modern science. In the end, however, history takes only one of countless possible paths. The path that led to modern science emerged from the ancient civilizations of the Mediterranean and the Middle East—especially from ancient Greece.

Greece gradually rose as a power in the Middle East beginning around 800 B.C. and was well-established by about 500 B.C. Its geographical location placed it at a crossroads for travelers, merchants, and armies from northern Africa, Asia, and Europe. Building on the diverse ideas brought forth by the meeting of these many cultures, ancient Greek philosophers soon began their efforts to move human understanding of nature from the mythological to the rational. Their ideas spread widely with the conquests of Alexander the Great (356–323 B.C.), who had been personally tutored by Aristotle and had a keen interest in science. Alexander founded the city of Alexandria in Egypt, and shortly after his death the city commenced work on a great research center and library. The Library of Alexandria (Figure 3.9) opened in about 300 B.C. and remained the world's preeminent center of research for some 700 years. At its peak, it may have held as many as a half million books, handwritten on papyrus scrolls. Most of these scrolls were ultimately burned, their contents lost forever.

think about it Estimate the number of books you're likely to read in your lifetime and compare this number to the half million books once housed in the Library of Alexandria. Can you think of other ways to put into perspective the loss of ancient wisdom resulting from the destruction of the Library of Alexandria?

a This rendering shows an artist's reconstruction of how the Great Hall may have looked in the ancient Library of Alexandria.

b A similar rendering to (a), this time showing a scroll room in the ancient library.

c The New Library of Alexandria, Egypt, which opened in 2003.

Figure 3.9

The ancient Library of Alexandria thrived for some 700 years, starting in about 300 B.C.

• Why does modern science trace its roots to the Greeks?

Greek philosophers developed at least three major innovations that helped pave the way for modern science. First, they developed a tradition of trying to understand nature without relying on supernatural explanations, and of working communally to debate and challenge each other's ideas. Second, the Greeks used mathematics to give precision to their ideas, which allowed them to explore the implications of new ideas in much greater depth than would have otherwise been possible. Third, while much of their philosophical activity consisted of subtle debates grounded only in thought and was not scientific in the modern sense, the Greeks also saw the power of reasoning from observations. They understood that an explanation could not be right if it disagreed with observed facts.

The Greeks developed models of nature that aimed to explain and predict observed phenomena.

Perhaps most important, the Greeks combined all three innovations to create **models** of nature, a practice that is still central to modern science. Scientific models differ somewhat from the models you may be familiar with in everyday life. In our daily lives, we tend to think of models as miniature physical representations, such as model cars or airplanes. In contrast, a scientific model is a conceptual representation created to explain and predict observed phenomena. For example, a model of Earth's climate uses logic and mathematics to represent what we know about how the climate works. Its purpose is to explain and predict climate changes, such as the changes that may occur with global warming. Just as a model airplane does not faithfully represent every aspect of a real airplane, a scientific model may not fully explain all our observations of nature. Nevertheless, even the failings of a scientific model can be useful, because they often point the way toward building a better model.

In astronomy, the Greeks constructed conceptual models of the universe in an attempt to explain what they observed in the sky, an effort that quickly led them past simplistic ideas of a flat Earth under a dome-shaped sky to a far more sophisticated view of the cosmos. We do not know precisely when other Greeks first began to think that Earth is round, but this idea was being taught as early as about 500 B.C. by the famous mathematician Pythagoras (c. 560–480 B.C.). He and his followers envisioned Earth as a sphere floating at the center of the celestial sphere. More than a century later, Aristotle cited observations of Earth's

common Misconceptions

Columbus and a Flat Earth

A widespread myth gives credit to Columbus for learning that Earth is round, but knowledge of Earth's shape predated Columbus by nearly 2000 years. Not only were scholars of Columbus's time well aware that Earth is round, but they even knew its approximate size: Earth's circumference was first measured in about 240 B.C. by the Greek scientist Eratosthenes. In fact, a likely reason why Columbus had so much difficulty finding a sponsor for his voyages was that he tried to argue a point on which he was dead wrong: He claimed the distance by sea from western Europe to eastern Asia to be much less than the scholars knew it to be. Indeed, when he finally found a patron in Spain and left on his journey, he was so woefully underprepared that the voyage would almost certainly have ended in disaster if the Americas hadn't stood in his way.

curved shadow on the Moon during lunar eclipses as evidence for a spherical Earth. Thus, Greek philosophers adopted a **geocentric model** of the universe (recall that **geocentric** means "Earth-centered"), with a spherical Earth at the center of a great celestial sphere.

• How did the Greeks explain planetary motion?

Greek philosophers quickly realized that there had to be more to the heavens than just a single sphere surrounding Earth. To account for the fact that the Sun and Moon each move gradually eastward through the constellations, the Greeks added separate spheres for them, with these spheres turning at different rates from the sphere of the stars. The planets also move relative to the stars, so the Greeks added additional spheres for each planet (Figure 3.10).

The difficulty with this model was that it made it hard to explain the apparent retrograde motion of the planets **[Section 2.4]**. You might guess that the Greeks would simply have allowed the planetary spheres to sometimes turn forward and sometimes turn backward relative to the sphere of the stars, but they did not because it would have violated their deeply held belief in "heavenly perfection." According to this idea, enunciated most clearly by Plato, heavenly objects could move only in perfect circles. But how could the planets sometimes go backward in our sky if they were moving in perfect circles?

One potential answer would have been to discard the geocentric model and replace it with a Sun-centered model, since such a model gives a simple and natural explanation for apparent retrograde motion (see Figure 2.27). While such a model was indeed proposed by Aristarchus in about 260 B.C., it never gained much support in ancient times—in part because of the lack of detectable stellar parallax **[Section 2.4]**, but also because Aristotle and others developed (incorrect) ideas about physics that required having Earth at the center of the universe.

The Greeks came up with a number of ingenious ideas for explaining planetary motion while preserving Earth's central position and the idea that heavenly objects move in perfect circles. These ideas were refined for centuries and reached their culmination in the work of Claudius Ptolemy (c. A.D. 100–170; pronounced *tol-e-mee*). We refer to Ptolemy's model as the **Ptolemaic model** to distinguish it from earlier geocentric models.

In the Ptolemaic model, each planet moved on a small circle whose center moved around Earth on a larger circle.

The essence of the Ptolemaic model was that each planet moves on a small circle whose center moves around Earth on a larger circle (Figure 3.11). (The small circle is called an *epicycle*, and the larger circle is called a *deferent*.) A planet following this circle-upon-circle motion traces a loop as seen from Earth, with the backward portion of the loop mimicking apparent retrograde motion. However, to make his model agree well with observations, Ptolemy had to include a number of other complexities, such as positioning some of the large circles slightly off-center from Earth. As a result, the full Ptolemaic model was mathematically quite complex, and using it to predict planetary positions required long and tedious calculations. Many centuries later, while supervising computations based on the Ptolemaic model, the Spanish monarch Alphonso X (1221–1284) is said to have complained, "If I had been present at the creation, I would have recommended a simpler design for the universe."

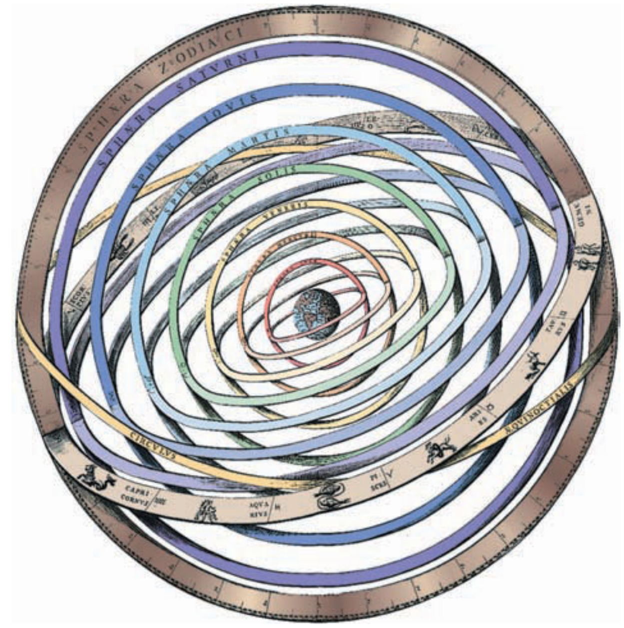


Figure 3.10

This model represents the Greek idea of the heavenly spheres (c. 400 B.C.). Earth is a sphere that rests in the center. The Moon, the Sun, and the planets each have their own spheres. The outermost sphere holds the stars.

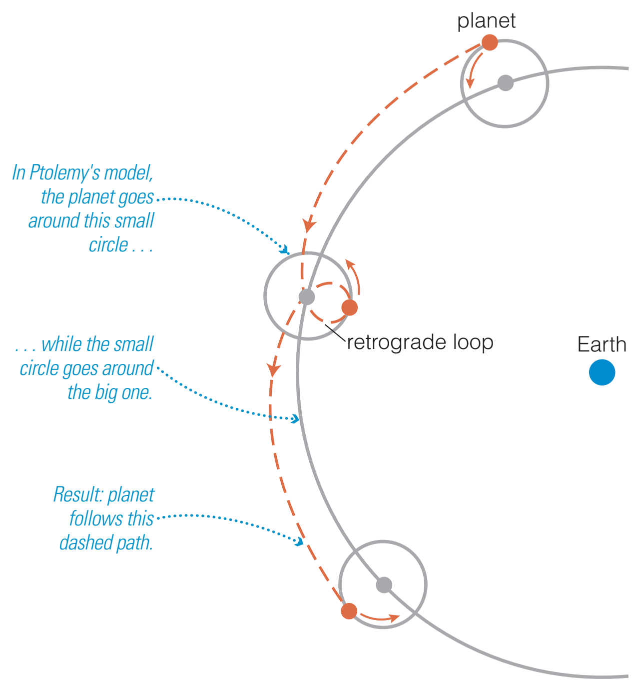


Figure 3.11 MA interactive figure

This diagram shows how the Ptolemaic model accounted for apparent retrograde motion. Each planet is assumed to move around a small circle that turns upon a larger circle. The resulting path (dashed) includes a loop in which the planet goes backward as seen from Earth.

cosmic Calculations 3.1

Eratosthenes Measures Earth

The first accurate estimate of Earth's circumference was made by the Greek scientist Eratosthenes in about 240 B.C. Eratosthenes knew that the Sun passed directly overhead in the Egyptian city of Syene (modern-day Aswan) on the summer solstice but that on the same day the Sun came only within 7° of the zenith in the city of Alexandria. He concluded that Alexandria must be 7° of latitude north of Syene (see figure), making the north-south distance between the two cities $\frac{7}{360}$ of Earth's circumference.

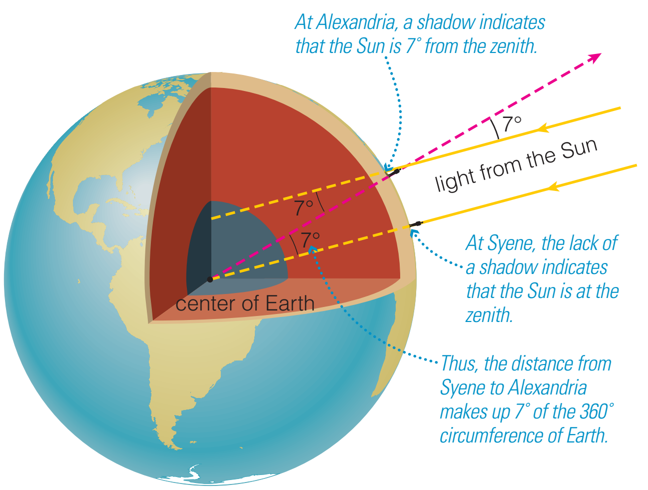
Eratosthenes estimated the north-south distance between Syene and Alexandria to be 5000 stadia (the *stadium* was a Greek unit of distance), which meant

$$\frac{7}{360} \times \text{Earth's circumference} = 5000 \text{ stadia}$$

Multiplying both sides by $\frac{360}{7}$ gives us

$$\text{Earth's circumference} = \frac{360}{7} \times 5000 \text{ stadia} \approx 250{,}000 \text{ stadia}$$

Based on the actual sizes of Greek stadiums, we estimate that stadia must have been about $\frac{1}{6}$ km each, making Eratosthenes' estimate about $\frac{250{,}000}{6} = 42{,}000$ km—remarkably close to the actual value of just over 40,000 km.



This diagram shows how Eratosthenes concluded that the north-south distance from Syene to Alexandria is $\frac{7}{360}$ of Earth's circumference.

Despite its complexity, the Ptolemaic model proved remarkably successful: It could correctly forecast future planetary positions to within a few degrees of arc, which is about the angular extent of your hand held at arm's length against the sky. This was sufficiently accurate to keep the model in use for the next 1500 years. When Ptolemy's book describing the model was translated by Arabic scholars around A.D. 800, they gave it the title *Almagest*, derived from words meaning "the greatest compilation."

• How did Islamic scientists preserve and extend Greek science?

Much of Greek knowledge was lost with the destruction of the Library of Alexandria. That which survived was preserved primarily thanks to the rise of a new center of intellectual inquiry in Baghdad (in present-day Iraq). While European civilization fell into the period of intellectual decline known as the Dark Ages, scholars of the new religion of Islam sought knowledge of mathematics and astronomy in hopes of better understanding the wisdom of Allah. During the eighth and ninth centuries A.D., scholars working in the Muslim empire translated and thereby saved many ancient Greek works.

Around A.D. 800, the Islamic leader Al-Mamun (A.D. 786–833) established a "House of Wisdom" in Baghdad with a mission much like that of the destroyed Library of Alexandria. Using the translated Greek scientific manuscripts as building blocks, scholars in Baghdad developed the mathematics of algebra and many new instruments and techniques for astronomical observation. Most of the official names of constellations and stars come from Arabic because of the work of these scholars. If you look at a star chart, you will see that the names of many bright stars begin with *al* (e.g., Aldebaran, Algol), which simply means "the" in Arabic.

Islamic scholars preserved and extended ancient Greek scholarship, and their work helped ignite the European Renaissance.

The Islamic world of the Middle Ages was in frequent contact with Hindu scholars from India, who in turn brought knowledge of ideas and discoveries from China. Hence, the intellectual center in Baghdad achieved a synthesis of the surviving work of the ancient Greeks and that of the Indians and the Chinese. The accumulated knowledge of the Arabs spread throughout the Byzantine empire (part of the former Roman empire). When the Byzantine capital of Constantinople (modern-day Istanbul) fell to the Turks in 1453, many Eastern scholars headed west to Europe, carrying with them the knowledge that helped ignite the European Renaissance.

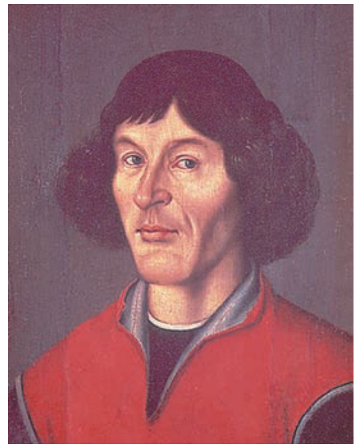
3.3 The Copernican Revolution

The Greeks and other ancient peoples developed many important scientific ideas, but what we now think of as science arose during the European Renaissance. Within a half century after the fall of Constantinople, Polish scientist Nicholas Copernicus (1473–1543) began the work that ultimately overturned the Earth-centered Ptolemaic model.

• How did Copernicus, Tycho, and Kepler challenge the Earth-centered model?

The new ideas introduced by Copernicus fundamentally changed the way we perceive our place in the universe. The story of this dramatic change, known as the **Copernican revolution**, is in many ways the story of the origin of modern science. It is also the story of several key personalities, beginning with Copernicus himself.

Copernicus Copernicus was born in Torún, Poland, on February 19, 1473. He began studying astronomy in his late teens, and soon learned that tables of planetary motion based on the Ptolemaic model had been growing increasingly inaccurate. He therefore began a quest to find a better way to predict planetary positions.



Copernicus (1473–1543)

Copernicus was aware of and adopted Aristarchus's ancient Sun-centered idea, probably because it offered such a simple explanation for the apparent retrograde motion of the planets. But he went beyond Aristarchus in working out mathematical details of the model. In the process, Copernicus discovered simple geometric relationships that allowed him to calculate each planet's orbital period around the Sun and its relative distance from the Sun in terms of Earth–Sun distance. The model's success in providing a geometric layout for the solar system further convinced him that the Sun-centered idea must be correct.

Despite his own confidence in the model, Copernicus was hesitant to publish his work, fearing that the idea of a moving Earth would be considered absurd. However, he discussed his system with other scholars, including high-ranking officials of the Church, who urged him to publish a book. Copernicus saw the first printed copy of his book, *De Revolutionibus Orbium Coelestium* ("Concerning the Revolutions of the Heavenly Spheres"), on the day he died—May 24, 1543.

Copernicus's Sun-centered model had the right general ideas, but its predictions were not substantially better than those of Ptolemy's Earth-centered model.

Publication of the book spread the Sun-centered idea widely, and many scholars were drawn to its aesthetic advantages. Nevertheless, the Copernican model gained relatively few converts over the next 50 years, for a good reason: It didn't work all that well. The primary problem was that while Copernicus had been willing to overturn Earth's central place in the cosmos, he had held fast to the ancient belief that heavenly motion must occur in perfect circles. This incorrect assumption forced him to add numerous complexities to his system (including circles on circles much like those used by Ptolemy) to get it to make decent predictions. In the end, his complete model was no more accurate and no less complex than the Ptolemaic model, and few people were willing to throw out thousands of years of tradition for a new model that worked just as poorly as the old one.

Tycho Brahe (1546–1601)

Tycho Part of the difficulty faced by astronomers who sought to improve either the Ptolemaic model or the Copernican model was a lack of quality data. The telescope had not yet been invented, and existing naked-eye observations were not very accurate. Better data were needed, and they were provided by the Danish nobleman Tycho Brahe (1546–1601), usually known simply as Tycho (pronounced "tie-koe").

Tycho was an eccentric genius who once lost part of his nose in a sword fight with another student over who was the better mathematician.

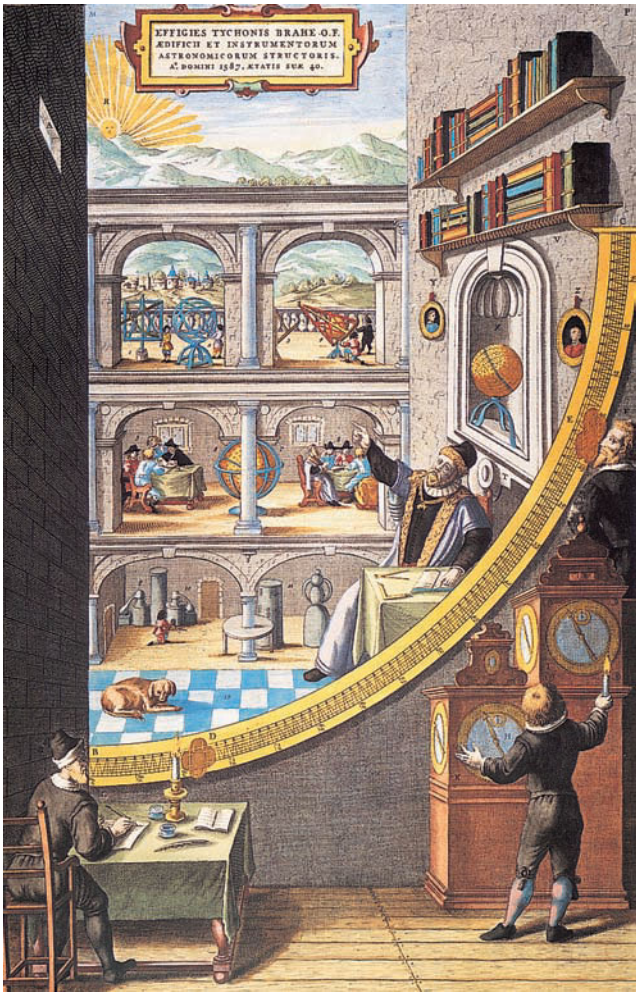


Figure 3.12

Tycho Brahe in his naked-eye observatory, which worked much like a giant protractor. He could sit and observe a planet through the rectangular hole in the wall as an assistant used a sliding marker to measure the angle on the protractor.

In 1563, Tycho decided to observe a widely anticipated alignment of Jupiter and Saturn. To his surprise, the alignment occurred nearly 2 days later than the date Copernicus had predicted. Resolving to improve the state of astronomical prediction, he set about compiling careful observations of stellar and planetary positions in the sky.

Tycho's fame grew after he observed what he called a *nova*, meaning "new star," in 1572 and proved that it was much farther away than the Moon. (Today, we know that Tycho saw a *supernova*—the explosion of a distant star **[Section 12.3]**.) In 1577, Tycho observed a comet and proved that it too lay in the realm of the heavens. Others, including Aristotle, had argued that comets were phenomena of Earth's atmosphere. King Frederick II of Denmark decided to sponsor Tycho's ongoing work, providing him with money to build an unparalleled observatory for naked-eye observations (Figure 3.12). After Frederick II died in 1588, Tycho moved to Prague, where his work was supported by German emperor Rudolf II.

Tycho's accurate naked-eye observations provided the data needed to improve the Copernican system.

Over a period of three decades, Tycho and his assistants compiled naked-eye observations accurate to within less than 1 arcminute—less than the thickness of a fingernail viewed at arm's length. Despite the quality of his observations, Tycho never succeeded in coming up with a satisfying explanation for planetary motion. He was convinced that the *planets* must orbit the Sun, but his inability to detect stellar parallax **[Section 2.4]** led him to conclude that Earth must remain stationary. He therefore advocated a model in which the Sun orbits Earth while all other planets orbit the Sun. Few people took this model seriously.

Kepler Tycho failed to explain the motions of the planets satisfactorily, but he succeeded in finding someone who could: In 1600, he hired the young German astronomer Johannes Kepler (1571–1630). Kepler and Tycho had a strained relationship, but Tycho recognized the talent of his young apprentice. In 1601, as he lay on his deathbed, Tycho begged Kepler to find a system that would make sense of his observations so "that it may not appear I have lived in vain."

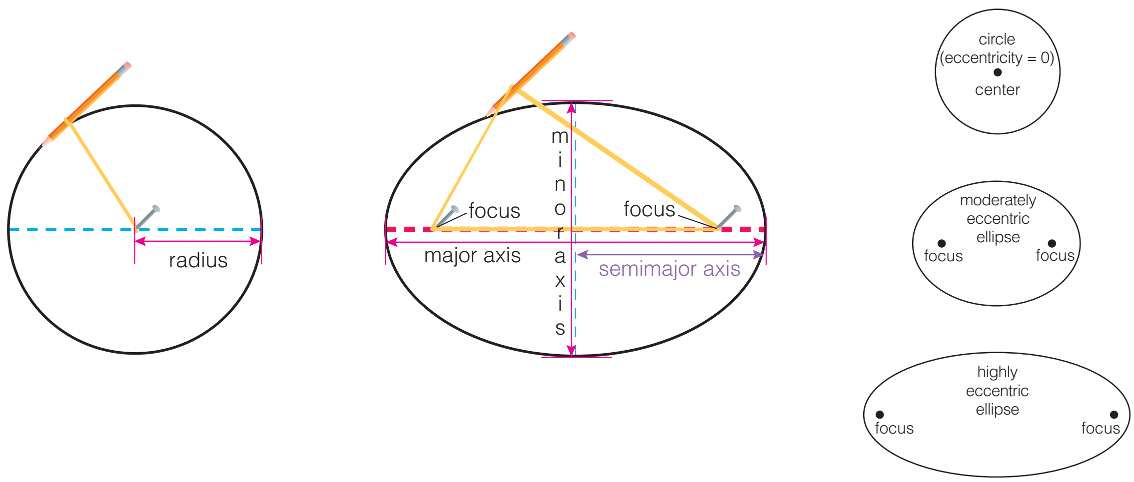
Kepler was deeply religious and believed that understanding the geometry of the heavens would bring him closer to God. Like Copernicus, he believed that planetary orbits should be perfect circles, so he worked diligently to match circular motions to Tycho's data. After years of effort, he found a set of circular orbits that matched most of Tycho's observations quite well. Even in the worst cases, which were for the planet Mars, Kepler's predicted positions differed from Tycho's observations by only about 8 arcminutes.

Kepler surely was tempted to ignore these discrepancies and attribute them to errors by Tycho. After all, 8 arcminutes is barely one-fourth the angular diameter of the full moon. But Kepler trusted Tycho's careful work. The small discrepancies finally led Kepler to abandon the idea of circular orbits—and to find the correct solution to the ancient riddle of planetary motion. About this event, Kepler wrote:

> *If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy.*

Johannes Kepler (1571–1630)

Kepler's key discovery was that planetary orbits are not circles but instead are a special type of oval called an **ellipse**. You can draw a circle by putting a pencil on the end of a string, tacking the string to a board, and pulling the pencil around (Figure 3.13a). Drawing an ellipse is similar,



a Drawing a circle with a string of fixed length.

b Drawing an ellipse with a string of fixed length.

c Eccentricity describes how much an ellipse deviates from a perfect circle.

Figure 3.13 MA **interactive figure**

An ellipse is a special type of oval. These diagrams show how an ellipse differs from a circle and how different ellipses vary in their eccentricity.

except that you must stretch the string around *two* tacks (Figure 3.13b). The locations of the two tacks are called the **foci** (singular, **focus**) of the ellipse. The long axis of the ellipse is called its *major axis*, each half of which is called a **semimajor axis**; as we'll see shortly, the length of the semimajor axis is particularly important in astronomy. The short axis is called the *minor axis*. By altering the distance between the two foci while keeping the length of string the same, you can draw ellipses of varying **eccentricity**, a quantity that describes the amount by which an ellipse is stretched out compared to a perfect circle (Figure 3.13c). A circle is an ellipse with zero eccentricity, and greater eccentricity means a more elongated ellipse.

By using elliptical orbits, Kepler created a Sun-centered model that predicted planetary positions with outstanding accuracy.

Kepler's decision to trust the data over his preconceived beliefs marked an important transition point in the history of science. Once he abandoned perfect circles in favor of ellipses, Kepler soon came up with a model that could predict planetary positions with far greater accuracy than Ptolemy's Earth-centered model. Kepler's model withstood the test of time and became accepted not only as a model of nature but also as a deep, underlying truth about planetary motion.

MA Orbits and Kepler's Laws Tutorial, Lessons 2–4

• What are Kepler's three laws of planetary motion?

Kepler summarized his discoveries with three simple laws that we now call **Kepler's laws of planetary motion**. He published the first two laws in 1609 and the third in 1619.

Kepler's first law: The orbit of each planet about the Sun is an ellipse with the Sun at one focus.

Kepler's first law tells us that the orbit of each planet about the Sun is an ellipse with the Sun at one focus (Figure 3.14). (There is nothing at the other focus.) In essence, this law tells us that a planet's distance from the Sun varies during its orbit. It is closest at the point

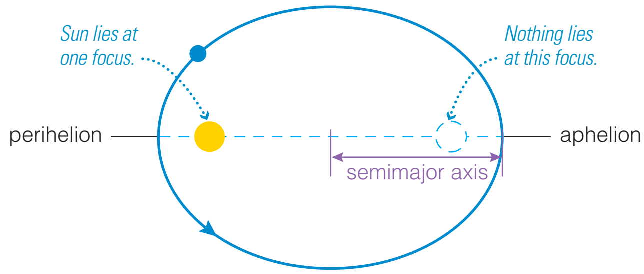


Figure 3.14 MA interactive figure

Kepler's first law: The orbit of each planet about the Sun is an ellipse with the Sun at one focus. (The eccentricity shown here is exaggerated compared to the actual eccentricities of the planets.)

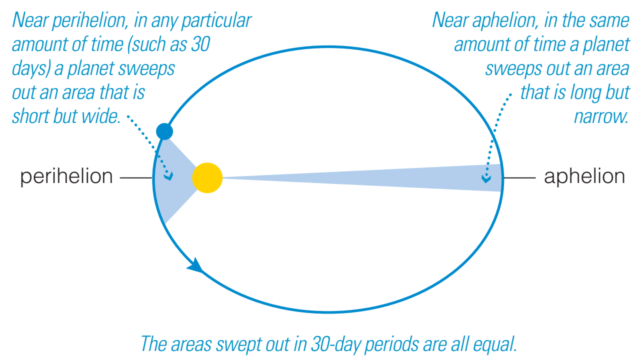


Figure 3.15 MA interactive figure

Kepler's second law: As a planet moves around its orbit, an imaginary line connecting it to the Sun sweeps out equal areas (the shaded regions) in equal times.

cosmic Calculations 3.2

Kepler's Third Law

When Kepler discovered his third law ($p^2 = a^3$), he knew only that it applied to the orbits of planets about the Sun. In fact, it applies to any orbiting object as long as the following two conditions are met:

1. The object orbits the Sun *or* another star of precisely the same mass.
2. We use units of *years* for the orbital period and *AU* for the orbital distance.

(Newton extended the law to *all* orbiting objects; see Cosmic Calculations 4.1.)

Example 1: The largest asteroid, Ceres, orbits the Sun at an average distance (semimajor axis) of 2.77 AU. What is its orbital period?

Solution: Both conditions are met, so we solve Kepler's third law for the orbital period p and substitute the given orbital distance, $a = 2.77$ AU:

$$p^2 = a^3 \quad \Rightarrow \quad p = \sqrt{a^3} = \sqrt{2.77^3} = 4.6$$

Ceres has an orbital period of 4.6 years.

Example 2: A planet is discovered orbiting every 3 months around a star of the same mass as our Sun. What is the planet's average orbital distance?

Solution: The first condition is met, and we can satisfy the second by converting the orbital period from months to years: $p = 3$ months $= 0.25$ year. We now solve Kepler's third law for the average distance a:

$$p^2 = a^3 \quad \Rightarrow \quad a = \sqrt[3]{p^2} = \sqrt[3]{0.25^2} = 0.40$$

The planet orbits its star at an average distance of 0.40 AU, which is nearly the same as Mercury's average distance from the Sun.

called **perihelion** (from the Greek for "near the Sun") and farthest at the point called **aphelion** (from the Greek for "away from the Sun"). The *average* of a planet's perihelion and aphelion distances is the length of its *semimajor axis*. We will refer to this simply as the planet's average distance from the Sun.

Kepler's second law: As a planet moves around its orbit, it sweeps out equal areas in equal times.

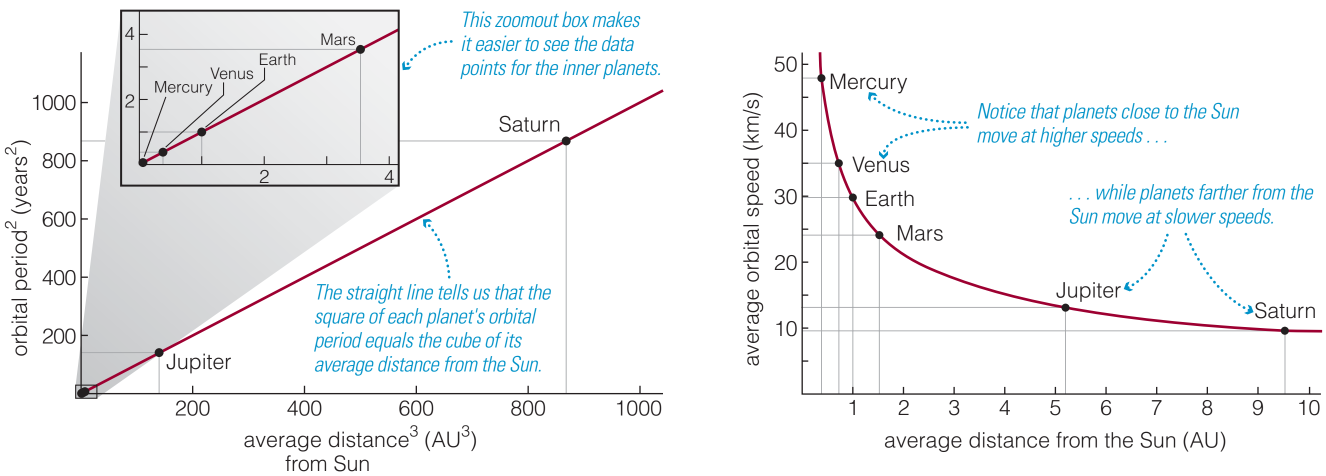
Kepler's second law states that as a planet moves around its orbit, it sweeps out equal areas in equal times. As shown in Figure 3.15, this means the planet moves a greater distance when it is near perihelion than it does in the same amount of time near aphelion. That is, the planet travels faster when it is nearer to the Sun and slower when it is farther from the Sun.

Kepler's third law: More distant planets orbit the Sun at slower average speeds, obeying the precise mathematical relationship $p^2 = a^3$.

Kepler's third law tells us that more distant planets orbit the Sun at slower average speeds, obeying a precise mathematical relationship (Figure 3.16). The relationship is written $p^2 = a^3$, where p is the planet's orbital period in years and a is its average distance from the Sun in astronomical units. Figure 3.16a shows the $p^2 = a^3$ law graphically. Notice that the square of each planet's orbital period (p^2) is indeed equal to the cube of its average distance from the Sun (a^3). Because Kepler's third law relates a planet's orbital distance to its orbital time (period), we can use the law to calculate a planet's average orbital speed. Figure 3.16b shows the result, confirming that more distant planets orbit the Sun more slowly.

think about it Suppose a comet has an orbit that brings it quite close to the Sun at its perihelion and beyond Mars at its aphelion, but with an average distance (semimajor axis) of 1 AU. According to Kepler's laws, how long would the comet take to complete each orbit of the Sun? Would it spend most of its time close to the Sun, far from the Sun, or somewhere in between? Explain.

The fact that more distant planets move more slowly led Kepler to suggest that planetary motion might be the result of a force from the Sun. He did not know the nature of the force, but others worked to discover it. The mystery was finally solved by Isaac Newton, who explained planetary motion and Kepler's laws as consequences of gravity [Section 4.4].



a This graph shows that Kepler's third law ($p^2 = a^3$) does indeed hold true; for simplicity, the graph shows only the planets known in Kepler's time.

b This graph, based on Kepler's third law and modern values of planetary distances, shows that more distant planets orbit the Sun more slowly.

Figure 3.16

Graphs based on Kepler's third law.

• How did Galileo solidify the Copernican revolution?

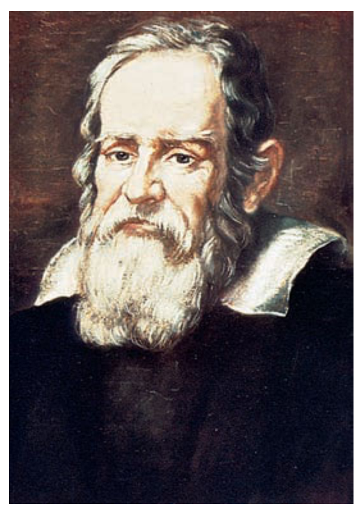
The success of Kepler's laws in matching Tycho's data provided strong evidence in favor of Copernicus's placement of the Sun at the center of the solar system. Nevertheless, many scientists still voiced reasonable objections to the Copernican view. There were three basic objections, all rooted in the 2000-year-old beliefs of Aristotle and other ancient Greeks.

- First, Aristotle had held that Earth could not be moving because, if it were, objects such as birds, falling stones, and clouds would be left behind as Earth moved along its way.
- Second, the idea of noncircular orbits contradicted Aristotle's claim that the heavens—the realm of the Sun, Moon, planets, and stars—must be perfect and unchanging.
- Third, no one had detected the stellar parallax that should occur if Earth orbits the Sun.

Galileo Galilei (1564–1642), usually known by his first name, answered all three objections.

Galileo defused the first objection with experiments that almost single-handedly overturned the Aristotelian view of physics. In particular, he used experiments with rolling balls to demonstrate that a moving object remains in motion *unless* a force acts to stop it (an idea now codified in Newton's first law of motion **[Section 4.2]**). This insight explained why objects that share Earth's motion through space—such as birds, falling stones, and clouds—should *stay* with Earth rather than falling behind as Aristotle had argued. This same idea explains why passengers stay with a moving airplane even when they leave their seats.

Tycho's supernova and comet observations already had challenged the validity of the second objection by showing that the heavens could change. Galileo shattered the idea of heavenly perfection after he built a telescope in late 1609. (The telescope was patented in 1608 by Hans Lippershey, but Galileo's was much more powerful.) Through his telescope, Galileo saw sunspots on the Sun, which were considered "imperfections" at the time. He also used his telescope to prove that the



Galileo (1564–1642)

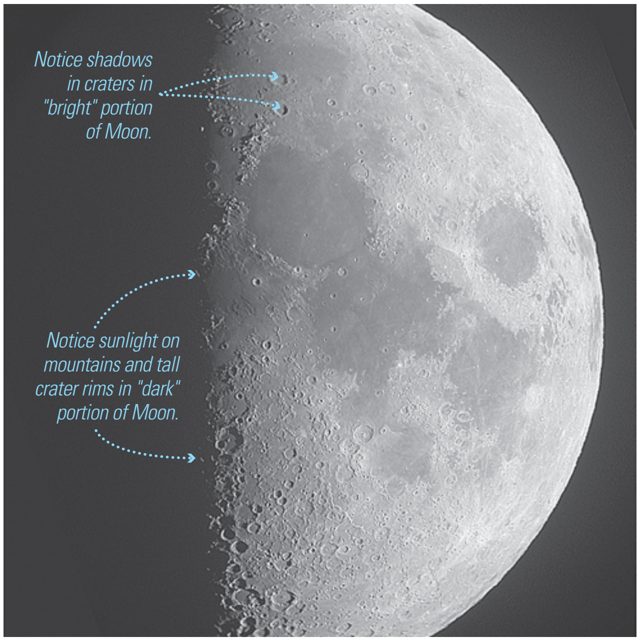


Figure 3.17

The shadows cast by mountains and crater rims near the dividing line between the light and dark portions of the lunar face prove that the Moon's surface is not perfectly smooth.

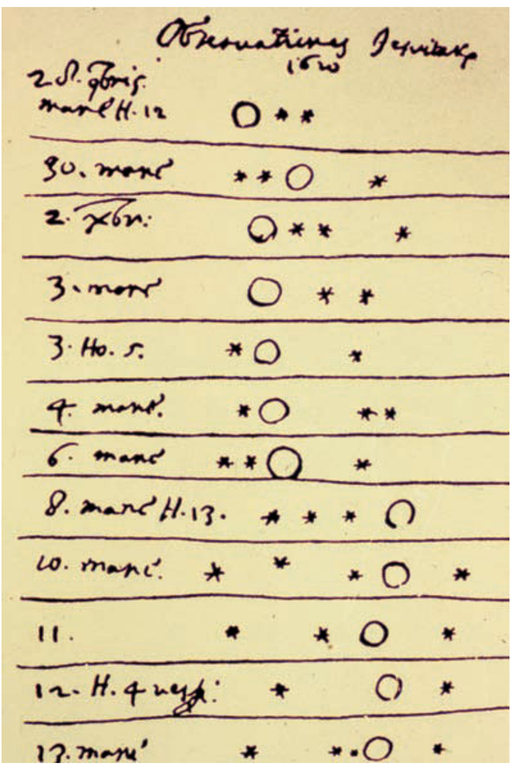


Figure 3.18

A page from Galileo's notebook written in 1610. His sketches show four "stars" near Jupiter (the circle) but in different positions at different times (and sometimes hidden from view). Galileo soon realized that the "stars" were actually moons orbiting Jupiter.

Moon has mountains and valleys like the "imperfect" Earth by noticing the shadows cast near the dividing line between the light and dark portions of the lunar face (Figure 3.17). If the heavens were in fact not perfect, then the idea of elliptical orbits (as opposed to "perfect" circles) was not so objectionable.

Galileo's experiments and telescopic observations overcame remaining scientific objections to the Copernican idea, sealing the case for the Sun-centered solar system.

The third objection—the absence of observable stellar parallax—had been of particular concern to Tycho. Based on his estimates of the distances of stars, Tycho believed that his naked-eye observations were sufficiently precise to detect stellar parallax if Earth did in fact orbit the Sun. Refuting Tycho's argument required showing that the stars were more distant than Tycho had thought and therefore too distant for him to have observed stellar parallax. Although Galileo didn't actually prove this fact, he provided strong evidence in its favor. For example, he saw with his telescope that the Milky Way resolved into countless individual stars. This discovery helped him argue that the stars were far more numerous and more distant than Tycho had believed.

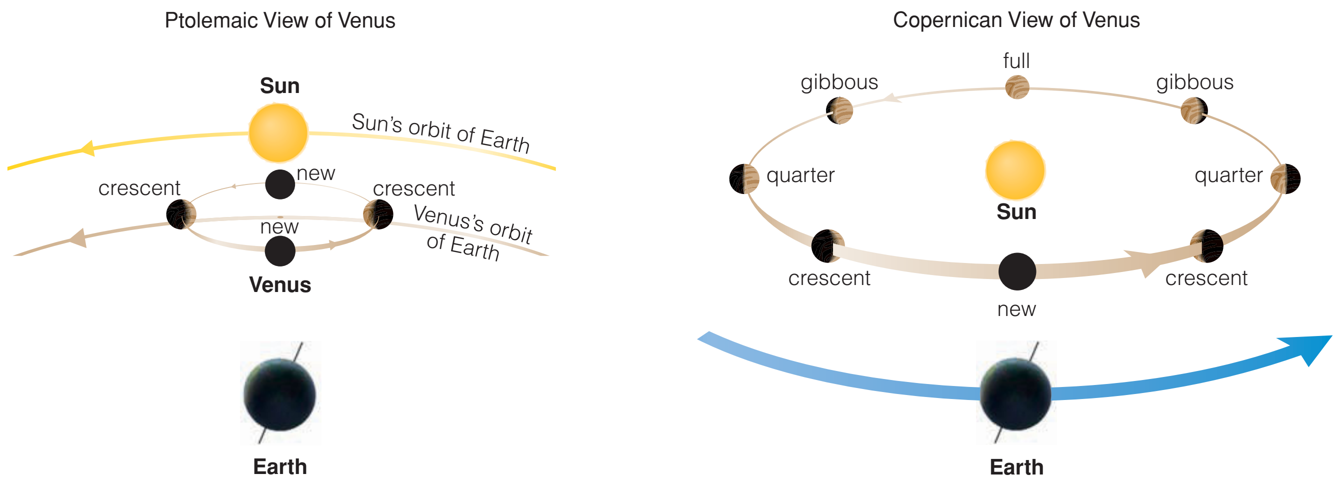
In hindsight, the final nails in the coffin of the Earth-centered model came with two of Galileo's earliest discoveries through the telescope. First, he observed four moons clearly orbiting Jupiter, *not* Earth (Figure 3.18). Soon thereafter, he observed that Venus goes through phases in a way that proved that it must orbit the Sun and not Earth (Figure 3.19).

Although we now recognize that Galileo won the day, the story was more complex in his own time, when Catholic Church doctrine still held Earth to be the center of the universe. On June 22, 1633, Galileo was brought before a Church inquisition in Rome and ordered to recant his claim that Earth orbits the Sun. Nearly 70 years old and fearing for his life, Galileo did as ordered. His life was spared. However, legend has it that as he rose from his knees he whispered under his breath, *Eppur si muove*—Italian for "And yet it moves." (Given the likely consequences if Church officials had heard him say this, most historians doubt the legend.)

The Church did not formally vindicate Galileo until 1992, but Church officials gave up the argument long before that: In 1757, all works backing the idea of a Sun-centered solar system were removed from the Church's Index of banned books. Today, Catholic scientists are at the forefront of much astronomical research, and official Church teachings are compatible not only with Earth's planetary status but also with the theories of the Big Bang and the subsequent evolution of the cosmos and of life.

3.4 The Nature of Science

The story of how our ancestors gradually figured out the basic architecture of the cosmos exhibits many features of what we now consider "good science." For example, we have seen how models were formulated and tested against observations and were modified or replaced when they failed those tests. The story also illustrates some classic mistakes, such as the apparent failure of anyone before Kepler to question the belief that orbits must be circles. The ultimate success of the Copernican revolution led scientists, philosophers, and theologians to reassess the various modes of thinking that played a role in the 2000-year process of discovering Earth's place in the universe. Let's examine how the principles of modern science emerged from the lessons learned in the Copernican revolution.



a In the Ptolemaic model, Venus orbits Earth, moving around a smaller circle on its larger orbital circle; the center of the smaller circle lies on the Earth–Sun line. If this view were correct, Venus's phases would range only from new to crescent.

b In reality, Venus orbits the Sun, so from Earth we can see it in many different phases. This is just what Galileo observed, allowing him to prove that Venus orbits the Sun.

Figure 3.19 MA interactive figure

Galileo's telescopic observations of Venus proved that it orbits the Sun rather than Earth.

• How can we distinguish science from nonscience?

It's surprisingly difficult to define the term *science* precisely. The word comes from the Latin *scientia*, meaning "knowledge," but not all knowledge is science. For example, you may know what music you like best, but your musical taste is not a result of scientific study.

Approaches to Science One reason science is difficult to define is that not all science works in the same way. For example, you've probably heard it said that science is supposed to proceed according to something called the "scientific method." As an idealized illustration of this method, consider what you would do if your flashlight suddenly stopped working. In hopes of fixing the flashlight, you might *hypothesize* that its batteries have died. This type of tentative explanation, or **hypothesis**, is sometimes called an *educated guess*—in this case, it is "educated" because you already know that flashlights need batteries. Your hypothesis allows you to make a simple prediction: If you replace the batteries with new ones, the flashlight should work. You can test this prediction by replacing the batteries. If the flashlight now works, you've confirmed your hypothesis. If it doesn't, you must revise or discard your hypothesis, perhaps in favor of some other one that you can also test (such as that the bulb is burned out). Figure 3.20 illustrates the basic flow of this process.

The scientific method is a useful idealization of scientific thinking, but science rarely progresses in such an orderly way.

The scientific method can be a useful idealization, but real science rarely progresses in such an orderly way. Scientific progress often begins with someone going out and looking at nature in a general way, rather than by conducting a careful set of experiments. For example, Galileo wasn't looking for anything in particular when he pointed his telescope at the sky and made his first startling discoveries. Furthermore, scientists are human beings, and their intuition and personal beliefs inevitably influence their work. Copernicus, for example, adopted the idea that Earth orbits the Sun not because he had carefully tested it but because he believed it made more sense than the prevailing view of an Earth-centered universe. While his intuition guided

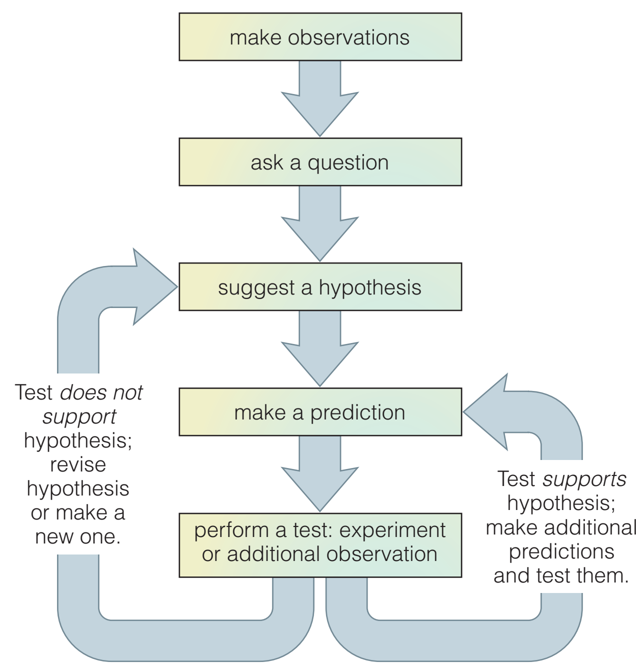


Figure 3.20

This diagram illustrates what we often call the *scientific method*.

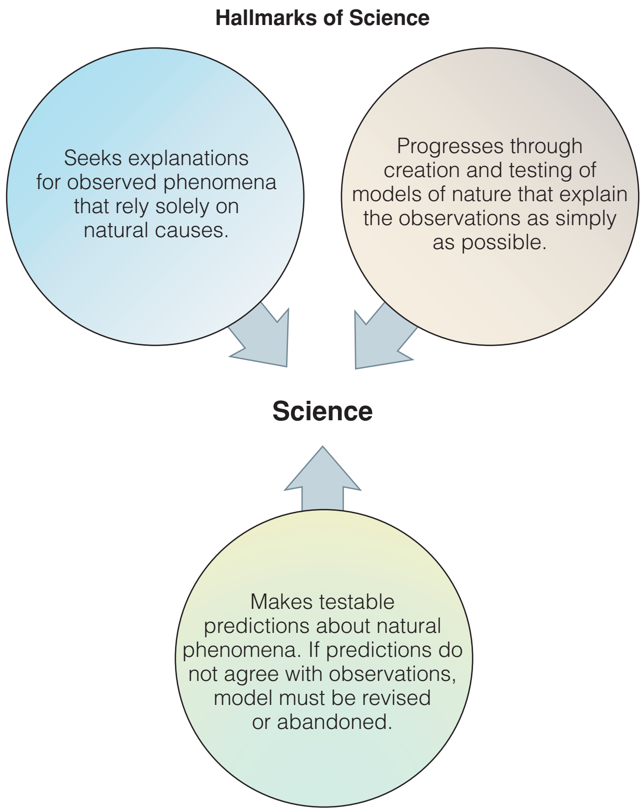


Figure 3.21

Hallmarks of science.

him to the right general idea, he erred in the specifics because he still held Plato's ancient belief that heavenly motion must be in perfect circles.

Given that the idealized scientific method is an overly simplistic characterization of science, how can we tell what is science and what is not? To answer this question, we must look a little deeper at the distinguishing characteristics of scientific thinking.

Hallmarks of Science One way to define scientific thinking is to list the criteria that scientists use when they judge competing models of nature. Historians and philosophers of science have examined (and continue to examine) this issue in great depth, and different experts express different viewpoints on the details. Nevertheless, everything we now consider to be science shares the following three basic characteristics, which we will refer to as the "hallmarks" of science (Figure 3.21):

- Modern science seeks explanations for observed phenomena that rely solely on natural causes.
- Science progresses through the creation and testing of models of nature that explain the observations as simply as possible.
- A scientific model must make testable predictions about natural phenomena that would force us to revise or abandon the model if the predictions do not agree with observations.

Science seeks to explain observed phenomena using testable models of nature that explain the observations as simply as possible.

Each of these hallmarks is evident in the story of the Copernican revolution. The first shows up in the way Tycho's careful measurements of planetary motion motivated Kepler to come up with a better explanation for those motions. The second is evident in the way several competing models were compared and tested, most notably those of Ptolemy, Copernicus, and Kepler. We see the third in the fact that each model could make precise predictions about the future motions of the Sun, Moon, planets, and stars in our sky. When a model's predictions failed, the model was modified or ultimately discarded. Kepler's model gained acceptance in large part because its predictions were so much better than those of thePtolemaic model in matching Tycho's observations. Figure 3.22 (pages 74–75) summarizes the Copernican revolution and how it illustrates the hallmarks of science.

Occam's Razor The criterion of simplicity in the second hallmark deserves further explanation. Remember that the original model of Copernicus did *not* match the data noticeably better than Ptolemy's model. If scientists had judged Copernicus's model solely on the accuracy of its predictions, they might have rejected it immediately. However, many scientists found elements of the Copernican model appealing, such as its simple explanation for apparent retrograde motion. They therefore kept the model alive until Kepler found a way to make it work.

In fact, if agreement with data were the sole criterion for judgment, we could imagine a modern-day Ptolemy adding millions or billions of additional circles to the geocentric model in an effort to improve its agreement with observations. A sufficiently complex geocentric model could in principle reproduce the observations with almost perfect accuracy—but it still would not convince us that Earth is the center of the universe. We would still choose the Copernican view over the geocentric view because its predictions would be just as accurate while arising from a much simpler model of nature. The idea that scientists should prefer the simpler of two models that agree equally well with observations is called *Occam's razor*, after the medieval scholar William of Occam (1285–1349).

Verifiable Observations The third hallmark of science forces us to face the question of what counts as an "observation" against which a prediction can be tested. Consider the claim that aliens are visiting Earth in UFOs. Proponents of this claim say that thousands of eyewitness observations of UFO encounters provide evidence that it is true. But do these personal testimonials count as *scientific* evidence? On the surface, the answer isn't obvious, because all scientific studies involve eyewitness accounts on some level. For example, only a handful of scientists have personally made detailed tests of Einstein's theory of relativity, and it is their personal reports of the results that have convinced other scientists of the theory's validity. However, there's an important difference between personal testimony about a scientific test and an observation of a UFO: The first can be verified by anyone, at least in principle, while the second cannot.

Understanding this difference is crucial to understanding what counts as science and what does not. Even though you may never have conducted a test of Einstein's theory of relativity yourself, there's nothing stopping you from doing so. It might require several years of study before you have the necessary background to conduct the test, but you could then confirm the results reported by other scientists. In other words, while you may currently be trusting the eyewitness testimony of scientists, you always have the option of verifying their testimony for yourself.

In contrast, there is no way for you to verify someone's eyewitness account of a UFO. Moreover, scientific studies of eyewitness testimony show it to be notoriously unreliable, because different eyewitnesses often disagree on what they saw even immediately after an event has occurred. As time passes, memories of the event may change further. In some cases in which memory has been checked against reality, people have reported vivid memories of events that never happened at all. This explains something that virtually all of us have experienced: disagreements with a friend about who did what and when. Since both people cannot be right in such cases, at least one person must have a memory that differs from reality.

Because of its demonstrated unreliability, eyewitness testimony alone should *never* be used as evidence in science, no matter who reports it or how many people offer similar testimony. It can be used in support of a scientific model only when it is backed up by independently verifiable evidence that anyone could in principle check. (For much the same reason, eyewitness testimony is usually insufficient for a conviction in criminal court; other evidence, such as motive, is required.)

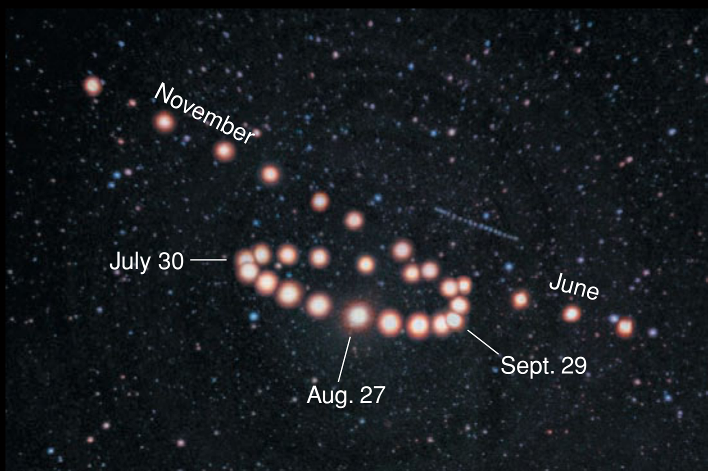
Objectivity in Science It's important to realize that science is not the only valid way of seeking knowledge. For example, suppose you are shopping for a car, learning to play drums, or pondering the meaning of life. In each case, you might make observations, exercise logic, and test hypotheses. Yet these pursuits clearly are not science, because they are not directed at developing testable explanations for observed natural phenomena. As long as nonscientific searches for knowledge make no claims about how the natural world works, they do not conflict with science.

The boundaries between science and nonscience are sometimes blurry. We generally think of science as being objective, meaning that all people should be able to find the same answers to scientific questions. However, there is a difference between the overall objectivity of science and the objectivity of individual scientists.

cosmic**Context** • # Figure 3.22. The Copernican Revolution

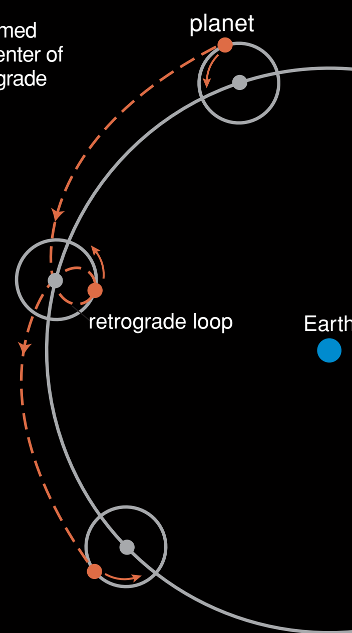
Ancient Earth-centered models of the universe easily explained the simple motions of the Sun and Moon through our sky, but had difficulty explaining the more complicated motions of the planets. The quest to understand planetary motions ultimately led to a revolution in our thinking about Earth's place in the universe that illustrates the process of science. This figure summarizes the major steps in that process.

1 Night by night, planets usually move from west to east relative to the stars. However, during periods of *apparent retrograde motion,* they reverse direction for a few weeks to months [Section 2.4]. The ancient Greeks knew that any credible model of the solar system had to explain these observations.



This composite photo shows the apparent retrograde motion of Mars.

2 Most ancient Greek thinkers assumed that Earth remained fixed at the center of the solar system. To explain retrograde motion, they therefore added a complicated scheme of circles moving upon circles to their Earth-centered model. However, at least some Greeks,such as Aristarchus, preferred a Sun-centered model, which offered a simpler explanation for retrograde motion.



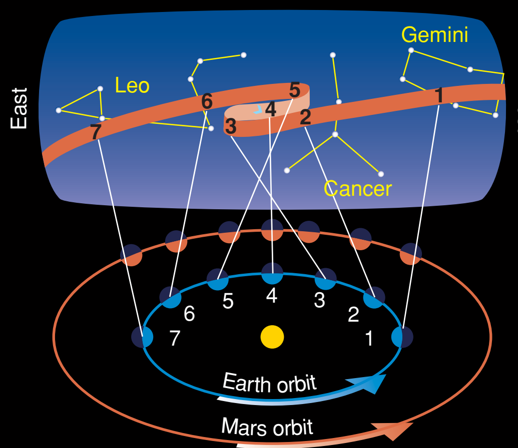
The Greek geocentric model explained apparent retrograde motion by having planets move around Earth on small circles that turned on larger circles.

HALLMARK OF SCIENCE **A scientific model must seek explanations for observed phenomena that rely solely on natural causes.** The ancient Greeks used geometry to explain their observations of planetary motion.

(Left page)
A schematic map of the universe from 1539 with Earth at the center and the Sun (Solis) orbiting it between Venus (Veneris) and Mars (Martis).

(Right page)
A page from Copercnicus's De Revolutionibus, *published in 1543, showing the Sun (Sol) at the center and Earth (Terra) orbiting between Venus and Mars.*

3 By the time of Copernicus (1473–1543), predictions based on the Earth-centered model had become noticeably inaccurate. Hoping for improvement, Copernicus revived the Sun-centered idea. He did not succeed in making substantially better predictions because he retained the ancient belief that planets must move in perfect circles, but he inspired a revolution continued over the next century by Tycho, Kepler, and Galileo.



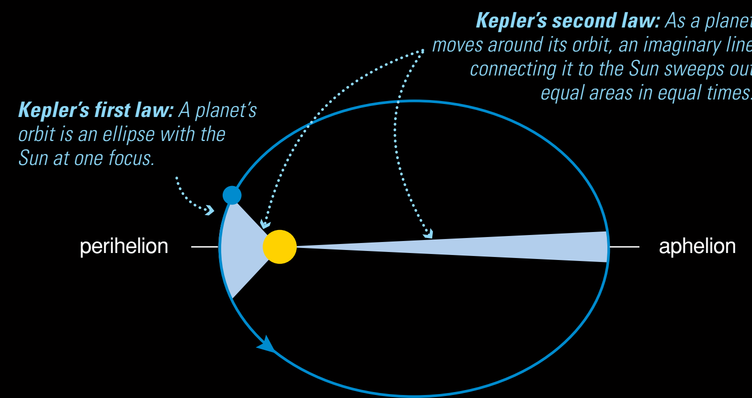
Apparent retrograde motion is simply explained in a Sun-centered system. Notice how Mars appears to change direction as Earth moves past it.

HALLMARK OF SCIENCE **Science progresses through creation and testing of models of nature that explain the observations as simply as possible.** Copernicus developed a Sun-centered model in hopes of explaining observations better than the more complicated Earth-centered model.

NICOLAI COPERNICI

quo terram cum orbe lunari tanquam epicyclo contineri
us. Quinto loco Venus nono menſe reducitur. Sextum
locum Mercurius tenet, octuaginta dierum ſpacio circũ
s. In medio uero omnium reſidet Sol. Quis enim in hoc

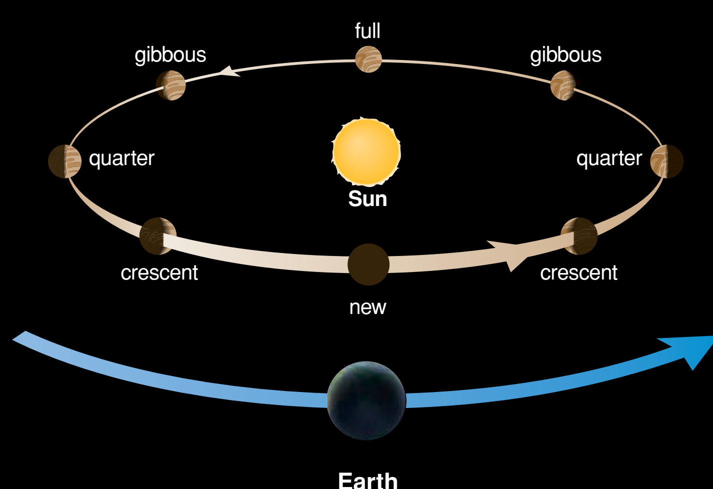
4 Tycho exposed flaws in both the ancient Greek and Copernican models by observing planetary motions with unprecedented accuracy. His observations led to Kepler's breakthrough insight that planetary orbits are elliptical, not circular, and enabled Kepler to develop his three laws of planetary motion.



Kepler's third law: *More distant planets orbit at slower average speeds, obeying* $p^2 = a^3$.

HALLMARK OF SCIENCE **A scientific model makes testable predictions about natural phenomena. If predictions do not agree with observations, the model must be revised or abandoned.** Kepler could not make his model agree with observations until he abandoned the belief that planets move in perfect circles.

5 Galileo's experiments and telescopic observations overcame remaining scientific objections to the Sun-centered model. Together, Galileo's discoveries and the success of Kepler's laws in predicting planetary motion overthrew the Earth-centered model once and for all.



With his telescope, Galileo saw phases of Venus that are consistent only with the idea that Venus orbits the Sun rather than Earth.

Science is practiced by human beings, and individual scientists may bring their personal biases and beliefs to their scientific work. For example, most scientists choose their research projects based on personal interests rather than on some objective formula. In extreme cases, scientists have been known to cheat—either deliberately or subconsciously—to obtain a result they desire. In one famous case that occurred a little over a century ago, astronomer Percival Lowell claimed to see a network of artificial canals in blurry telescopic images of Mars, leading him to conclude that there was a great Martian civilization. But no such canals actually exist, so Lowell must have allowed his beliefs about extraterrestrial life to influence the way he interpreted what he saw—in essence, a form of cheating, though probably not intentional.

Bias can sometimes show up even in the thinking of the scientific community as a whole. Some valid ideas may not be considered by any scientist because they fall too far outside the general patterns of thought, or **paradigm**, of the time. Einstein's theory of relativity is an example. Many scientists in the decades before Einstein had gleaned hints of the theory but did not investigate them, at least in part because they seemed too outlandish.

Individual scientists inevitably carry personal biases into their work, but the collective action of many scientists should ultimately make science objective.

The beauty of science is that it encourages continued testing by many people. Even if personal biases affect some results, tests by others should eventually uncover the mistakes. Similarly, if a new idea is correct but falls outside the accepted paradigm, sufficient testing and verification of the idea should eventually force a paradigm shift. In that sense, *science ultimately provides a means of bringing people to agreement*, at least on topics that can be subjected to scientific study.

• What is a scientific theory?

The most successful scientific models explain a wide variety of observations in terms of just a few general principles. When a powerful yet simple model makes predictions that survive repeated and varied testing, scientists elevate its status and call it a **theory**. Some famous examples are Isaac Newton's theory of gravity, Charles Darwin's theory of evolution, and Albert Einstein's theory of relativity.

Note that the scientific meaning of the word *theory* is quite different from its everyday meaning, in which we equate a theory more closely with speculation or a hypothesis. For example, someone might get a new idea and say, "I have a new theory about why people enjoy the beach." Without the support of a broad range of evidence that others have tested and confirmed, this "theory" is really only a guess. In contrast, Newton's theory of gravity qualifies as a scientific theory because it uses simple physical principles to explain many observations and experiments.

A scientific theory is a simple yet powerful model whose predictions have been borne out by repeated and varied testing.

Despite its success in explaining observed phenomena, a scientific theory can never be proved true beyond all doubt, because future observations may disagree with its predictions. However, anything that qualifies as a scientific theory must be supported by a large, compelling body of evidence.

common Misconceptions

Eggs on the Equinox

One of the hallmarks of science holds that you needn't take scientific claims on faith. In principle, at least, you can always test them for yourself. Consider the claim, repeated in news reports every year, that the spring equinox is the only day on which you can balance an egg on its end. Many people believe this claim, but you'll be immediately skeptical if you think about the nature of the spring equinox. The equinox is merely a point in time at which sunlight strikes both hemispheres equally (see Figure 2.13). It's difficult to see how sunlight could affect an attempt to balance eggs (especially if the eggs are indoors), and there is no difference in the strength of either Earth's gravity or the Sun's gravity on that day compared to any other day.

More important, you can test this claim directly. It's not easy to balance an egg on its end, but with practice you can do it on any day of the year, not just on the spring equinox. Not all scientific claims are so easy to test for yourself, but the basic lesson should be clear: Before you accept any scientific claim, you should demand at least a reasonable explanation of the evidence that backs it up.

In this sense, a scientific theory is not at all like a hypothesis or any other type of guess. We are free to change a hypothesis at any time, because it has not yet been carefully tested. In contrast, we can discard or replace a scientific theory only if we have an alternate way of explaining the evidence that supports it.

Again, the theories of Newton and Einstein offer good examples. A vast body of evidence supports Newton's theory of gravity, but by the late 1800s scientists had begun to discover cases where its predictions did not perfectly match observations. These discrepancies were explained only when Einstein developed his general theory of relativity, which was able to match the observations. Still, the many successes of Newton's theory could not be ignored, and Einstein's theory would not have gained acceptance if it had not been able to explain these successes equally well. It did, and that is why we now view Einstein's theory as a broader theory of gravity than Newton's theory. Some scientists today are seeking a theory of gravity that will go beyond Einstein's. If any new theory ever gains acceptance, it will have to match all the successes of Einstein's theory as well as work in new realms where Einstein's theory does not.

think about it When people claim that something is "only a theory," what do you think they mean? Does this meaning of "theory" agree with the definition of a theory in science? Do scientists always use the word *theory* in its "scientific" sense? Explain.

special**Topic:** | Astrology

ALTHOUGH THE TERMS *astrology* and *astronomy* sound very similar, today they describe very different practices. In ancient times, however, astrology and astronomy often went hand in hand, and astrology played an important role in the historical development of astronomy. Indeed, astronomers and astrologers were usually one and the same.

The basic tenet of astrology is that human events are influenced by the apparent positions of the Sun, Moon, and planets among the stars in our sky. The origins of this idea are easy to understand. The position of the Sun in the sky clearly influences our lives—it determines the seasons and hence the times of planting and harvesting, of warmth and cold, and of daylight and darkness. Similarly, the Moon determines the tides, and the cycle of lunar phases coincides with many biological cycles. Because the planets also appear to move among the stars, it seemed reasonable to imagine that planets also influence our lives, even if these influences were much more difficult to discover.

Ancient astrologers hoped that they might learn *how* the positions of the Sun, Moon, and planets influence our lives. They charted the skies, seeking correlations with events on Earth. For example, if an earthquake occurred when Saturn was entering the constellation of Leo, might Saturn's position have caused the earthquake? If the king became ill when Mars was in Gemini and the first-quarter moon was in Scorpio, might it mean another tragedy for the king when this particular alignment of the Moon and Mars next recurred? Ancient astrologers thought that the patterns of influence eventually would become clear and they would then be able to forecast human events with the same reliability with which observations of the Sun could forecast the coming of spring.

This hope was never realized. Although many astrologers still attempt to predict future events, scientific tests have shown that their predictions come true no more often than would be expected by pure chance. Moreover, in light of our current understanding of the universe, the original ideas behind astrology no longer make sense. For example, today we use ideas of gravity and energy to explain the influences of the Sun and the Moon, and these same ideas tell us that the planets are too far from Earth to have a similar influence.

Of course, many people continue to practice astrology, perhaps because of its ancient and rich traditions. Scientifically, we cannot say anything about such traditions, because traditions are not testable predictions. But if you want to understand the latest discoveries about the cosmos, you'll need a science that can be tested and refined—and astrology fails to meet these requirements.

the big picture

Putting Chapter 3 into Perspective

In this chapter, we focused on the scientific principles through which we have learned so much about the universe. Key "big picture" concepts from this chapter include the following:

- The basic ingredients of scientific thinking—careful observation and trial-and-error testing—are a part of everyone's experience. Modern science simply provides a way of organizing this everyday thinking to facilitate the learning and sharing of new knowledge.
- Although our understanding of the universe is growing rapidly today, each new piece of knowledge builds on ideas that came before.
- The Copernican revolution, which overthrew the ancient Greek belief in an Earth-centered universe, did not occur instantaneously. It unfolded over a period of more than a century, during which many of the characteristics of modern science first appeared.
- Science exhibits several key features that distinguish it from non-science and that in principle allow anyone to come to the same conclusions when studying a scientific question.

summary of key concepts

3.1 The Ancient Roots of Science

- **In what ways do all humans use scientific thinking?**

Scientific thinking relies on the same type of trial-and-error thinking that we use in our everyday lives, but done in a carefully organized way.

- **How did astronomical observations benefit ancient societies?**

Ancient cultures used astronomical observations to help them keep track of time and the seasons, crucial skills for people who depended on agriculture for survival, as well as to aid them in navigation.

- **What did ancient civilizations achieve in astronomy?**

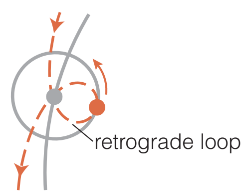
Ancient astronomers were accomplished observers who learned to tell the time of day and the time of year, to track cycles of the Moon, and to observe planets and stars. Many ancient structures aided in astronomical observations.

3.2 Ancient Greek Science

- **Why does modern science trace its roots to the Greeks?**

The Greeks developed **models** of nature and emphasized the importance of having the predictions of those models agree with observations of nature.

- **How did the Greeks explain planetary motion?**



The Greek **geocentric model** reached its culmination with the **Ptolemaic model**, which explained apparent retrograde motion by having each planet move on a small circle whose center moves around Earth on a larger circle.

- **How did Islamic scientists preserve and extend Greek science?**

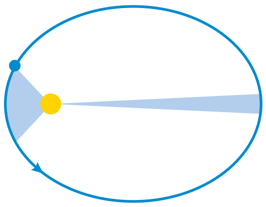
While Europe was in its Dark Ages, Islamic scholars preserved and extended ancient Greek knowledge. After the fall of Constantinople, some of these scholars moved west to Europe, where their knowledge helped ignite the Renaissance.

3.3 The Copernican Revolution

- **How did Copernicus, Tycho, and Kepler challenge the Earth-centered model?**

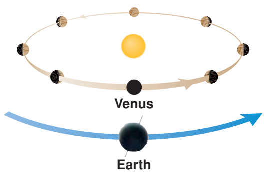
Copernicus created a Sun-centered model of the solar system designed to replace the Ptolemaic model, but it was no more accurate than Ptolemy's because Copernicus still used perfect circles. Tycho's accurate, naked-eye observations provided the data needed to improve on Copernicus's model. Kepler developed a model of planetary motion that fit Tycho's data.

• **What are Kepler's three laws of planetary motion?**



(1) The orbit of each planet is an ellipse with the Sun at one focus. (2) As a planet moves around its orbit, it sweeps out equal areas in equal times. (3) More distant planets orbit the Sun at slower average speeds, obeying the precise mathematical relationship $p^2 = a^3$.

• **How did Galileo solidify the Copernican revolution?**



Galileo's experiments and telescopic observations overcame remaining objections to the Copernican idea of Earth as a planet orbiting the Sun. Although not everyone accepted his results immediately, in hindsight we see that Galileo sealed the case for the Sun-centered solar system.

3.4 The Nature of Science

• **How can we distinguish science from nonscience?**

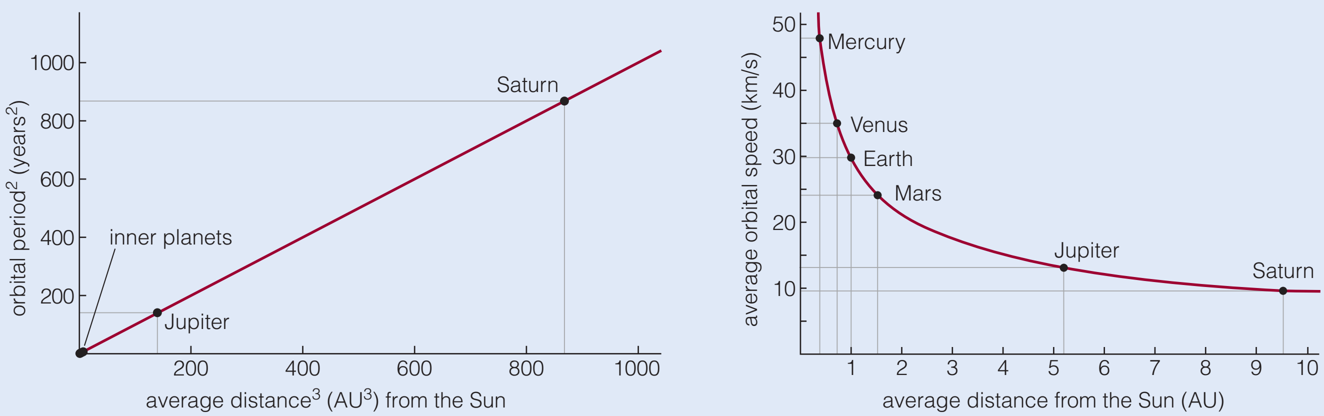
Science generally exhibits three hallmarks: (1) Modern science seeks explanations for observed phenomena that rely solely on natural causes. (2) Science progresses through the creation and testing of models of nature that explain the observations as simply as possible. (3) A scientific model must make testable predictions about natural phenomena that would force us to revise or abandon the model if the predictions do not agree with observations.

• **What is a scientific theory?**

A scientific **theory** is a simple yet powerful model that explains a wide variety of observations using just a few general principles, and that has survived repeated and varied testing.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 3 Visual Quiz at www.masteringastronomy.com.



a

b

Study the two graphs above, based on Figure 3.16. Use the information in the graphs to answer the following questions.

1. Approximately how fast is Jupiter orbiting the Sun?
   a. cannot be determined from the information provided
   b. 20 km/s
   c. 10 km/s
   d. a little less than 15 km/s
2. An asteroid with an average orbital distance of 2 AU will orbit the Sun at an average speed that is ____________.
   a. a little slower than the orbital speed of Mars
   b. a little faster than the orbital speed of Mars
   c. the same as the orbital speed of Mars
3. Uranus, not shown on the graph, orbits about 19 AU from the Sun. Based on the graph, its approximate orbital speed is between about ____________.
   a. 20 and 25 km/s b. 15 and 20 km/s
   c. 10 and 15 km/s d. 5 and 10 km/s
4. Kepler's third law is often stated as $p^2 = a^3$. The value a^3 for a planet is shown on ______________.
   a. the horizontal axis of Figure a
   b. the vertical axis of Figure a
   c. the horizontal axis of Figure b
   d. the vertical axis of Figure b
5. On Figure a, you can see Kepler's third law ($p^2 = a^3$) from the fact that ______________.
   a. the data fall on a straight line
   b. the axes are labeled with values for p^2 and a^3
   c. the planet names are labeled on the graph

Continued

6. Suppose Figure a showed a planet on the red line directly above a value of 1000 AU^3 along the horizontal axis. On the vertical axis, this planet would be at ____________.
   a. 1000 $years^2$ b. 1000^2 $years^2$
   c. $\sqrt{1000}$ $years^2$ d. 100 years

7. How far does the planet in question 6 orbit from the Sun?
   a. 10 AU
   b. 100 AU
   c. 1000 AU
   d. $\sqrt{1000}$ AU

exercises and problems

Mastering ASTRONOMY

For instructor-assigned homework go to www.masteringastronomy.com.

Review Questions

1. In what way is scientific thinking natural to all of us? How does modern science differ from this everyday type of thinking?
2. Why did ancient peoples study astronomy? Describe an astronomical achievement of at least three ancient cultures.
3. How are the names of the days of the week related to astronomical objects?
4. What is a lunar calendar? Are lunar calendars still used today?
5. What do we mean by a *model* in science? Briefly summarize the Greek *geocentric model*.
6. What do we mean by the *Ptolemaic model?* How did this model account for the apparent retrograde motion of planets in our sky?
7. What was the *Copernican revolution*, and how did it change the human view of the universe?
8. Why wasn't the Copernican model immediately accepted? Describe the roles of Tycho, Kepler, and Galileo in the eventual triumph of the Sun-centered model.
9. What is an *ellipse?* Define the *focus* and the *eccentricity* of an ellipse. Why are ellipses important in astronomy?
10. State each of *Kepler's laws of planetary motion*. Describe the meaning of each law in a way that anyone could understand.
11. Describe the three hallmarks of science and explain how we can see them in the Copernican revolution. What is *Occam's razor?* Why doesn't science accept personal testimony as evidence?
12. What is the difference between a *hypothesis* and a *theory* in science?

Test Your Understanding

Science or Nonscience?

Each of the following statements makes some type of claim. Decide in each case whether the claim could be evaluated scientifically or whether it falls into the realm of nonscience. Explain clearly; not all of these have definitive answers, so your explanation is more important than your chosen answer.

13. The Yankees are the best baseball team of all time.
14. Several kilometers below its surface, Jupiter's moon Europa has an ocean of liquid water.
15. My house is haunted by ghosts who make the creaking noises I hear each night.
16. There is no liquid water on the surface of Mars today.
17. Dogs are smarter than cats.
18. Children born when Jupiter is in the constellation Taurus are more likely to be musicians than other children.
19. Aliens can manipulate time so that they can abduct and perform experiments on people who never realize they were taken.
20. Newton's law of gravity works as well for explaining the orbits of planets around other stars as it does for explaining the orbits of planets in our own solar system.
21. God created the laws of motion that were discovered by Newton.
22. A huge fleet of alien spacecraft will land on Earth and introduce an era of peace and prosperity on January 1, 2020.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

23. In the Greek geocentric model, the retrograde motion of a planet occurs when (a) Earth is about to pass the planet in its orbit around the Sun. (b) the planet actually goes backward in its orbit around Earth. (c) the planet is aligned with the Moon in our sky.
24. Which of the following was *not* a major advantage of Copernicus's Sun-centered model over the Ptolemaic model? (a) It made significantly better predictions of planetary positions in our sky. (b) It offered a more natural explanation for the apparent retrograde motion of planets in our sky. (c) It allowed calculation of the orbital periods and distances of the planets.
25. When we say that a planet has a highly eccentric orbit, we mean that (a) it is spiraling in toward the Sun. (b) its orbit is an ellipse with the Sun at one focus. (c) in some parts of its orbit it is much closer to the Sun than in other parts.
26. Earth is closer to the Sun in January than in July. Therefore, in accord with Kepler's second law, (a) Earth travels faster in its orbit around the Sun in July than in January. (b) Earth travels faster in its orbit around the Sun in January than in July. (c) it is summer in January and winter in July.
27. According to Kepler's third law, (a) Mercury travels fastest in the part of its orbit in which it is closest to the Sun. (b) Jupiter orbits the Sun at a faster speed than Saturn. (c) all the planets have nearly circular orbits.
28. Tycho Brahe's contribution to astronomy included (a) inventing the telescope. (b) proving that Earth orbits the Sun. (c) collecting data that enabled Kepler to discover the laws of planetary motion.
29. Galileo's contribution to astronomy included (a) discovering the laws of planetary motion. (b) discovering the law of gravity. (c) making observations and conducting experiments that dispelled scientific objections to the Sun-centered model.
30. Which of the following is *not* true about scientific progress? (a) Science progresses through the creation and testing of models of nature. (b) Science advances only through the scientific method. (c) Science avoids explanations that invoke the supernatural.
31. Which of the following is *not* true about a scientific theory? (a) A theory must explain a wide range of observations or experiments.

(b) Even the strongest theories can never be proved true beyond all doubt. (c) A theory is essentially an educated guess.

32. When Einstein's theory of gravity (general relativity) gained acceptance, it demonstrated that Newton's theory had been (a) wrong. (b) incomplete. (c) really only a guess.

Process of Science

33. *What Makes It Science?* Choose a single idea in the modern view of the cosmos discussed in Chapter 1, such as "The universe is expanding," or "We are made from elements manufactured by stars," or "The Sun orbits the center of the Milky Way Galaxy once every 230 million years."
    a. Describe how this idea reflects each of the three hallmarks of science, discussing how it is based on observations, how our understanding of it depends on a model, and how that model is testable.
    b. No matter how strongly the evidence may support a scientific idea, we can never be certain beyond all doubt that the idea is true. Describe an observation that might cause us to call the idea you chose into question. Then briefly discuss whether you think that, overall, the idea is likely or unlikely to hold up to future observations. Defend your opinion.
34. *Earth's Shape.* It took thousands of years for humans to deduce that Earth is spherical. For each of the following alternative models of Earth's shape, identify one or more observations that you could make for yourself and that would invalidate the model.
    a. A flat Earth
    b. A cylindrical Earth (which was actually proposed by the Greek philosopher Anaximander (c. 610–546 B.C.))
    c. A football-shaped Earth

Group Work Exercise

35. *Galileo on Trial.* In this exercise, you will debate the evidence presented by Galileo in favor of the idea that Earth orbits the Sun. Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Galileo* (argues in favor of the idea that Earth orbits the Sun), *Prosecutor* (argues against the idea that Earth orbits the Sun), and *Moderator* (leads group discussion and makes sure the debate remains civil). Then consider each of the following three pieces of evidence:
    a. observations of mountains and valleys on the Moon
    b. observations of moons orbiting Jupiter
    c. observations of the phases of Venus

    Galileo should explain why the evidence indicates that Earth orbits the Sun, and the *Prosecutor* should present a rebuttal. After the discussion, the *Scribe* and *Moderator* should decide whether the evidence is convincing beyond a reasonable doubt, somewhat convincing, or not convincing, and write down their verdict, along with an explanation of their reasoning.

Investigate Further

Short-Answer/Essay Questions

36. *Copernican Players.* Using a bulleted list format, make a one-page "executive summary" of the major roles that Copernicus, Tycho, Kepler, and Galileo played in overturning the ancient belief in an Earth-centered universe.
37. *Influence on History.* Based on what you have learned about the Copernican revolution, write a one- to two-page essay about how you believe it altered the course of human history.
38. *Cultural Astronomy.* Choose a particular culture of interest to you, and research the astronomical knowledge and accomplishments of that culture. Write a two- to three-page summary of your findings.

Quantitative Problems

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

39. *Method of Eratosthenes.* You are an astronomer on planet Nearth, which orbits a distant star. It has recently been accepted that Nearth is spherical in shape, though no one knows its size. One day, while studying in the library of Alectown, you learn that on the equinox your sun is directly overhead in the city of Nyene, located 1000 km due north of you. On the equinox, you go outside in Alectown and observe that the altitude of your sun is 80°. What is the circumference of Nearth? (*Hint:* Apply the technique used by Eratosthenes to measure Earth's circumference.)
40. *Eris Orbit.* The recently discovered Eris orbits the Sun every 560 years. What is its average distance (semimajor axis) from the Sun? How does its average distance compare to that of Pluto?
41. *Halley Orbit.* Halley's comet orbits the Sun every 76.0 years and has an orbital eccentricity of 0.97.
    a. Find its average distance (semimajor axis).
    b. Halley's orbit is a very eccentric (stretched-out) ellipse, so that at perihelion it is only about 90 million km from the Sun, compared to more than 5 billion km at aphelion. Does Halley's comet spend most of its time near its perihelion distance, its aphelion distance, or halfway in between? Explain.

Discussion Questions

42. *The Impact of Science.* The modern world is filled with ideas, knowledge, and technology that developed through science and application of the scientific method. Discuss some of these things and how they affect our lives. Which of these impacts do you think are positive? Which are negative? Overall, do you think science has benefited the human race? Defend your opinion.
43. *The Importance of Ancient Astronomy.* Why was astronomy important to people in ancient times? Discuss both the practical importance of astronomy and the importance it may have had for religious or other traditions. Which do you think was more important in the development of ancient astronomy, its practical or its philosophical role? Defend your opinion.
44. *Astronomy and Astrology.* Why do you think astrology remains so popular around the world even though it has failed all scientific tests of its validity? Do you think this popularity has any social consequences? Defend your opinions.

Web Projects

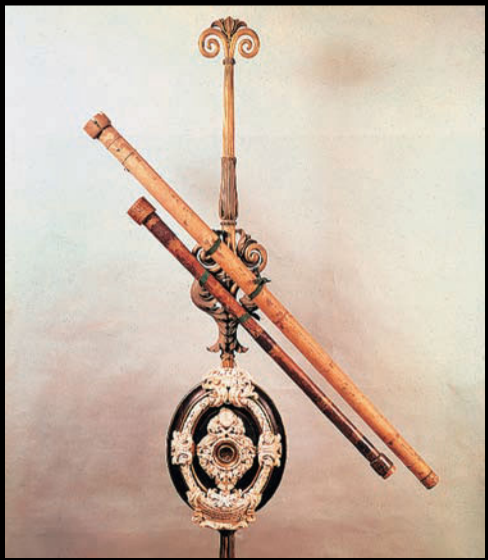
45. *The Ptolemaic Model.* This chapter gives only a very brief description of Ptolemy's model of the universe. Investigate this model in greater depth. Using diagrams and text as needed, create a two- to three-page description of the model.
46. *The Galileo Affair.* In recent years, the Roman Catholic Church has devoted a lot of resources to learning more about the trial of Galileo and to understanding past actions of the Church in the Galilean case. Learn more about these studies, and write a two- to three-page report about the current Vatican view of the case.
47. *Science or Pseudoscience.* Choose a pseudoscientific claim related to astronomy; learn more about it and about how scientists have debunked it. (A good starting point is the Bad Astronomy Web site: www.badastronomy.com.) Write a short summary of your findings.

Part I at a Glance. Our Expanding Perspective

Our perspective on the universe has changed dramatically throughout human history. This timeline summarizes some of the key discoveries that have shaped our modern perspective.

Stonehenge

Earth-centered model of the universe



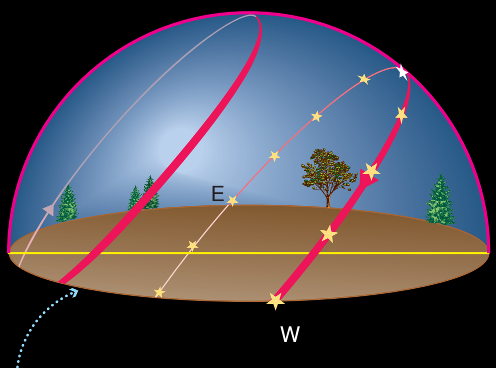
Galileo's telescope

< 2500 B.C. | 400 B.C. – 170 A.D. | 1543–1648 A.D.

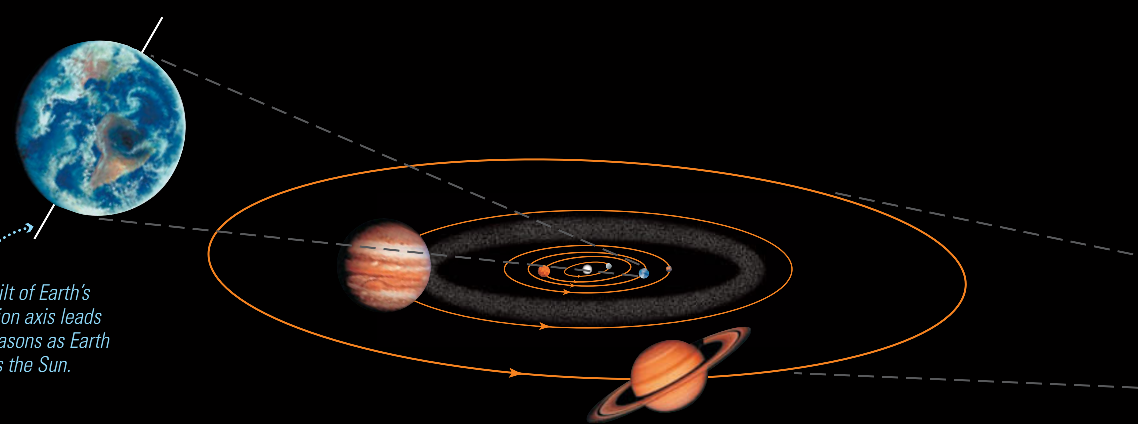
1. Ancient civilizations recognized patterns in the motion of the Sun, Moon, planets, and stars through our sky. They also noticed connections between what they saw in the sky and our lives on Earth, such as the cycles of seasons and of tides [Section 3.1].

2. The ancient Greeks tried to explain observed motions of the Sun, Moon, and planets using a model with Earth at the center, surrounded by spheres in the heavens. The model explained many phenomena well, but could explain the apparent retrograde motion of the planets only with the addition of many complex features—and even then, its predictions were not especially accurate [Section 3.2].

3. Copernicus suggested that Earth is a planet orbiting the Sun. The Sun-centered model explained apparent retrograde motion simply, though it made accurate predictions only after Kepler discovered his three laws of planetary motion. Galileo's telescopic observations confirmed the Sun-centered model, and revealed that the universe contains far more stars than had been previously imagined [Section 3.3].



Earth's rotation around its axis leads to the daily east-to-west motions of objects in the sky.



The tilt of Earth's rotation axis leads to seasons as Earth orbits the Sun.

Planets are much smaller than the Sun. At a scale of 1 to 10 billion, the Sun is the size of a grapefruit, Earth is the size of a ball point of a pen, and the distance between them is about 15 meters.


Yerkes Observatory


Edwin Hubble at the Mt. Wilson telescope


Hubble Space Telescope

1838–1920 A.D.

4. Larger telescopes and photography made it possible to measure the parallax of stars, offering direct proof that Earth really does orbit the Sun and showing that even the nearest stars are light-years away. We learned that our Sun is a fairly ordinary star in the Milky Way [Section 2.4, 11.1].

1924–1929 A.D.

5. Edwin Hubble measured the distances of galaxies, showing that they lay far beyond the bounds of the Milky Way and proving that the universe is far larger than our own galaxy. He also discovered that more distant galaxies are moving away from us faster, telling us that the entire universe is expanding and suggesting that it began in an event we call the Big Bang [Section 1.3, 15.2].

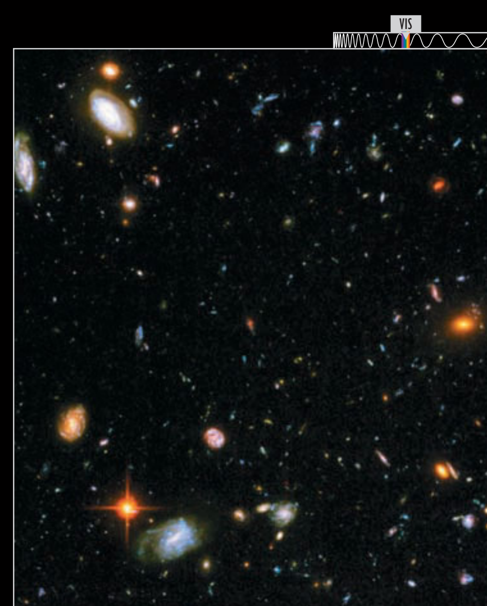
1990 A.D.–present

6. Improved measurements of galactic distances and the rate of expansion have shown that the universe is about 14 billion years old. These measurements have also revealed still unexplained surprises, including evidence for the existence of mysterious dark matter and dark energy [Section 1.3, 16.1].

Distances between stars are enormous. At a scale of 1 to 10 billion, you can hold the Sun in your hand, but the nearest stars are thousands of kilometers away.


Our solar system is located about 28,000 light-years from the center of the Milky Way Galaxy.

The Milky Way Galaxy contains over 100 billion stars.



The observable universe contains over 100 billion galaxies.

4

Making Sense of the Universe

Understanding Motion, Energy, and Gravity

learning goals

4.1 Describing Motion: Examples from Daily Life
- How do we describe motion?
- How is mass different from weight?

4.2 Newton's Laws of Motion
- How did Newton change our view of the universe?
- What are Newton's three laws of motion?

4.3 Conservation Laws in Astronomy
- What keeps a planet rotating and orbiting the Sun?
- Where do objects get their energy?

4.4 The Force of Gravity
- What determines the strength of gravity?
- How does Newton's law of gravity extend Kepler's laws?
- How do gravity and energy allow us to understand orbits?
- How does gravity cause tides?

The history of the universe is essentially a story about the interplay between matter and energy since the beginning of time. Interactions between matter and energy began in the Big Bang and continue today in everything from the microscopic jiggling of atoms to gargantuan collisions of galaxies. Understanding the universe therefore depends on becoming familiar with how matter responds to the ebb and flow of energy.

You might guess that it would be difficult to understand the many interactions that shape the universe, because they occur on so many different size scales. However, we now know that just a few physical laws govern the movements of everything from atoms to galaxies. The Copernican revolution spurred the discovery of these laws, and Galileo deduced some of them from his experiments. But it was Sir Isaac Newton who put all of the pieces together into a simple system of laws describing both motion and gravity.

In this chapter, we'll discuss the laws that govern motion and energy, including Newton's laws of motion, the laws of conservation of angular momentum and of energy, and the universal law of gravitation. Understanding these laws will enable you to make sense of many of the wide-ranging phenomena you will encounter as you study astronomy.

essential preparation

1. How is Earth moving in our solar system? [Section 1.3]
2. How did Copernicus, Tycho, and Kepler challenge the Earth-centered model? [Section 3.3]
3. What are Kepler's three laws of planetary motion? [Section 3.3]

4.1 Describing Motion: Examples from Daily Life

We all have experience with motion and a natural intuition as to what motion is, but in science we need to define our ideas and terms precisely. In this section, we'll use examples from everyday life to explore some of the fundamental ideas of motion.

• How do we describe motion?

You are probably familiar with the terms used to describe motion in science—terms such as *velocity, acceleration,* and *momentum*. However, their scientific definitions may differ subtly from those you use in casual conversation. Let's investigate the precise meanings of these terms.

Speed, Velocity, and Acceleration A car provides a good illustration of the three basic terms that we use to describe motion:

- The **speed** of the car tells us how far it will go in a certain amount of time. For example, "100 kilometers per hour" (about 60 miles per hour) is a speed, and it tells us that the car will cover a distance of 100 kilometers if it is driven at this speed for an hour.
- The **velocity** of the car tells us both its speed and direction. For example, "100 kilometers per hour going due north" describes a velocity.

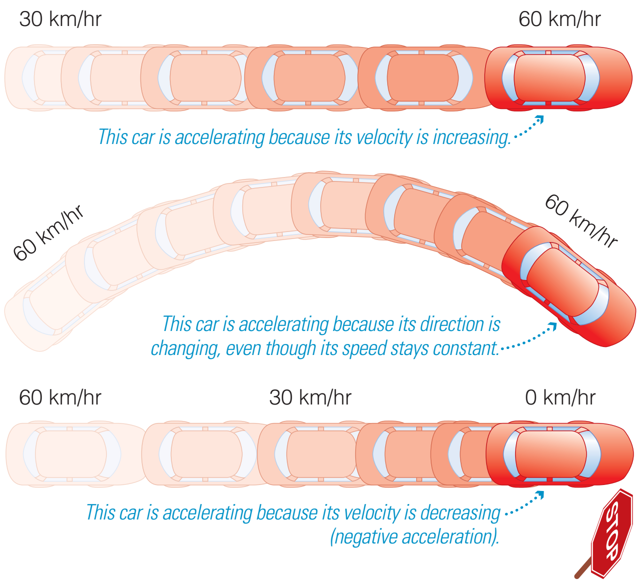


Figure 4.1

Speeding up, turning, and slowing down are all examples of acceleration.

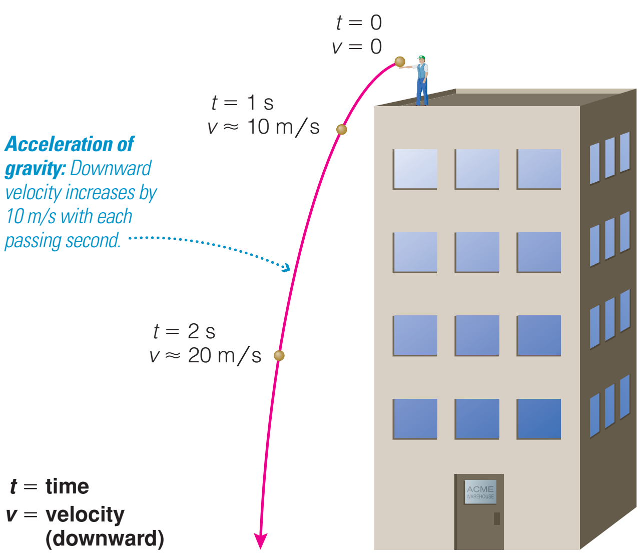


Figure 4.2

On Earth, gravity causes an unsupported object to accelerate downward at about 10 m/s^2, which means its downward velocity increases by about 10 m/s with each passing second. (Gravity does not affect horizontal velocity.)

- The car has an **acceleration** if its velocity is changing in any way, whether in speed or direction or both.

You are undoubtedly familiar with the term *acceleration* as it applies to increasing speed. In science, we also say that you are accelerating when you slow down or turn (Figure 4.1). Slowing occurs when acceleration is in a direction opposite to the motion. In this case, we say that your acceleration is negative, causing your velocity to decrease. Turning changes your velocity because it changes the direction in which you are moving, so turning is a form of acceleration even if your speed remains constant.

An object is accelerating if either its speed or its direction is changing.

You can often feel the effects of acceleration. For example, as you speed up in a car, you feel yourself being pushed back into your seat. As you slow down, you feel yourself being pulled forward. As you drive around a curve, you feel yourself being pushed away from the direction of your turn. In contrast, you don't feel such effects when moving at *constant velocity*. That is why you don't feel any sensation of motion when you're traveling in an airplane on a smooth flight.

The Acceleration of Gravity One of the most important types of acceleration is the acceleration caused by gravity. In a legendary experiment in which he supposedly dropped weights from the Leaning Tower of Pisa, Galileo demonstrated that gravity accelerates all objects by the same amount, regardless of their mass. This fact may be surprising because it seems to contradict everyday experience: A feather floats gently to the ground, while a rock plummets. However, air resistance causes this difference in acceleration. If you dropped a feather and a rock on the Moon, where there is no air, both would fall at exactly the same rate.

see it for yourself Find a piece of paper and a small rock. Hold both at the same height and let them go at the same instant. The rock, of course, hits the ground first. Next, crumple the paper into a small ball and repeat the experiment. What happens? Explain how this experiment suggests that gravity accelerates all objects by the same amount.

The acceleration of a falling object is called the **acceleration of gravity**, abbreviated g. On Earth, the acceleration of gravity causes falling objects to fall faster by 9.8 meters per second (m/s), or about 10 m/s, with each passing second. For example, suppose you drop a rock from a tall building. At the moment you let it go, its speed is 0 m/s. After 1 second, the rock will be falling downward at about 10 m/s. After 2 seconds, it will be falling at about 20 m/s. In the absence of air resistance, its speed will continue to increase by about 10 m/s each second until it hits the ground (Figure 4.2). We therefore say that the acceleration of gravity is about 10 *meters per second per second*, or 10 *meters per second squared*, which we write as 10 m/s^2 (more precisely, $g = 9.8$ m/s^2).

Momentum and Force The concepts of speed, velocity, and acceleration describe how an individual object moves, but most of the interesting phenomena we see in the universe result from interactions between objects. We need two additional concepts to describe these interactions:

- An object's **momentum** is the product of its mass and its velocity; that is, momentum = mass × velocity.

- The only way to change an object's momentum is to apply a **force** to it.

We can understand these concepts by considering the effects of collisions. Imagine that you're stopped in your car at a red light when a bug flying at a velocity of 30 km/hr due south slams into your windshield. What will happen to your car? Not much, except perhaps a bit of a mess on your windshield. Next, imagine that a 2-ton truck runs the red light and hits you head-on with the same velocity as the bug. Clearly, the truck will cause far more damage. We can understand why by considering the momentum and force in each collision.

Before the collisions, the truck's much greater mass means it has far more momentum than the bug, even though both the truck and the bug are moving with the same velocity. During the collisions, the bug and the truck each transfer some of their momentum to your car. The bug has very little momentum to give to your car, so it does not exert much of a force. In contrast, the truck imparts enough of its momentum to cause a dramatic and sudden change in your car's momentum. You feel this sudden change in momentum as a force, and it can do great damage to you and your car.

The mere presence of a force does not always cause a change in momentum. For example, a moving car is always affected by forces of air resistance and friction with the road—forces that will slow your car if you take your foot off the gas pedal. However, you can maintain a constant velocity, and hence constant momentum, if you step on the gas pedal hard enough to overcome the slowing effects of these forces.

In fact, forces of some kind are always present, such as the force of gravity or the electromagnetic forces acting between atoms. The **net force** (or *overall force*) acting on an object represents the combined effect of all the individual forces put together. There is no net force on your car when you are driving at constant velocity, because the force generated by the engine to turn the wheels precisely offsets the forces of air resistance and road friction. A change in momentum occurs only when the net force is not zero.

An object must accelerate whenever a net force acts on it.

Changing an object's momentum means changing its velocity, as long as its mass remains constant. A net force that is not zero therefore causes an object to accelerate. Conversely, whenever an object accelerates, a net force must be causing the acceleration. That is why you feel forces (pushing you forward, backward, or to the side) when you accelerate in your car. We can use the same ideas to understand many astronomical processes. For example, planets are always accelerating as they orbit the Sun, because their direction of travel constantly changes as they go around their orbits. We can therefore conclude that some force must be causing this acceleration. As we'll discuss shortly, Isaac Newton identified this force as gravity.

• How is mass different from weight?

In daily life, we usually think of *mass* as something you can measure with a bathroom scale, but technically the scale measures your *weight,* not your mass. The distinction between mass and weight rarely matters when we are talking about objects on Earth, but it is very important in astronomy:

- Your **mass** is the amount of matter in your body.

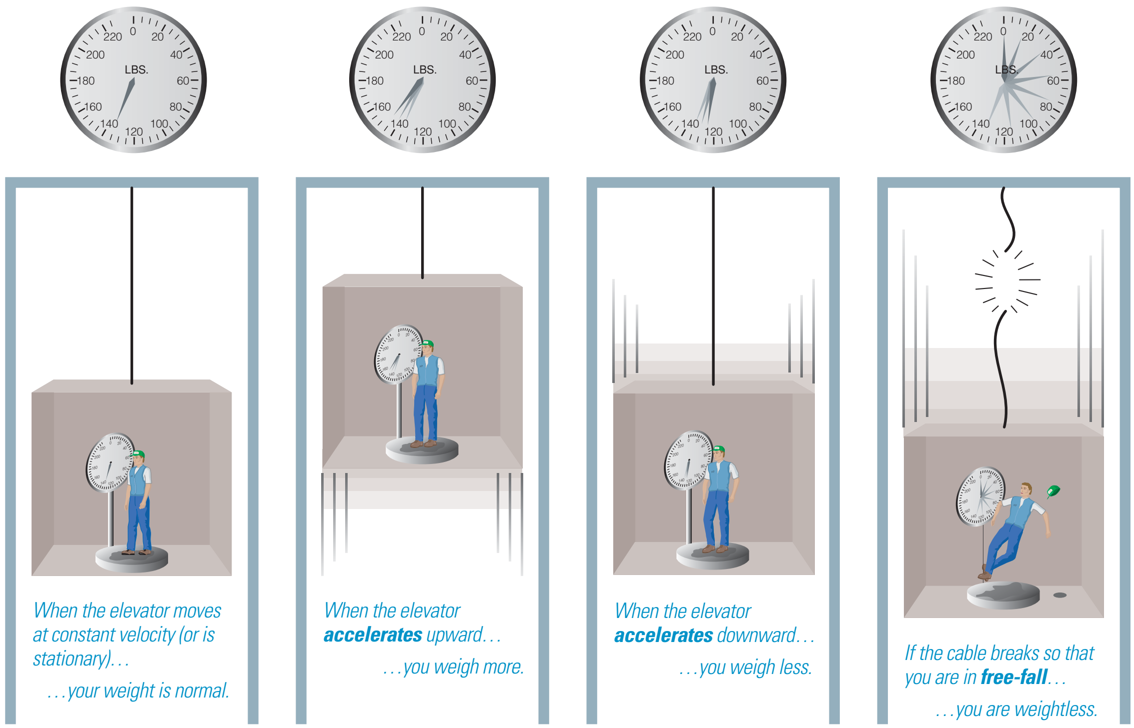


Figure 4.3 MA interactive figure

Mass is not the same as weight. The man's mass never changes, but his weight is different when the elevator accelerates.

- Your **weight** (or **apparent weight***) is the *force* that a scale measures when you stand on it; that is, weight depends both on your mass and on the forces (including gravity) acting on your mass.

To understand the difference between mass and weight, imagine standing on a scale in an elevator (Figure 4.3). Your mass will be the same no matter how the elevator moves, but your weight can vary. When the elevator is stationary or moving at constant velocity, the scale reads your "normal" weight. When the elevator accelerates upward, the floor exerts a greater force than it does when you are at rest. You feel heavier, and the scale verifies your greater weight. When the elevator accelerates downward, the floor and the scale exert a weaker force on you, so the scale registers less weight. Note that the scale shows a weight different from your "normal" weight only when the elevator is *accelerating*, not when it is going up or down at constant speed.

see it for yourself Find a small bathroom scale and take it with you on an elevator ride. How does your weight change when the elevator accelerates upward or downward? Does it change when the elevator is moving at constant speed? Explain your observations.

Your mass is the same no matter where you are, but your weight can vary.

Your mass therefore depends only on the amount of matter in your body and is the same anywhere, but your weight can vary because the forces acting on you can vary. For example, your mass would be the same on the Moon as on Earth, but you would weigh less on the Moon because of its weaker gravity.

*Some physics texts distinguish between "true weight," which is due only to gravity, and "apparent weight," which also depends on other forces (as in an elevator). In this book, the word *weight* means "apparent weight."

Free-Fall and Weightlessness Now consider what happens if the elevator cable breaks (see the last frame in Figure 4.3). The elevator and you are suddenly in **free-fall**—falling without any resistance to slow you down. The floor drops away at the same rate that you fall, allowing you to "float" freely above it, and the scale reads zero because you are no longer held to it. In other words, your free-fall has made you **weightless**.

In fact, you are in free-fall whenever there's nothing to *prevent* you from falling. For example, you are in free-fall when you jump off a chair or spring from a diving board or trampoline. Surprising as it may seem, you have therefore experienced weightlessness many times in your life. You can experience it right now simply by jumping off your chair—though your weightlessness lasts for only a very short time until you hit the ground.

Weightlessness in Space You've probably seen videos of astronauts floating weightlessly in the Space Shuttle or the Space Station. But why are they weightless? Many people guess that there's no gravity in space, but that's not true. After all, it is gravity that makes the Space Shuttle and the Space Station orbit Earth. Astronauts are weightless for the same reason you are weightless when you jump off a chair: They are in free-fall.

People or objects are weightless whenever they are falling freely, and astronauts in orbit are weightless because they are in a constant state of free-fall.

Astronauts are weightless the entire time they orbit Earth because they are in a *constant state of free-fall*. To understand this idea, imagine a tower that reaches all the way to the Space Station's orbit, about 350 kilometers above Earth (Figure 4.4). If you stepped off the tower, you would fall downward, remaining weightless until you hit the ground (or until air resistance had a noticeable effect on you). Now, imagine that instead of stepping off the tower, you ran and jumped out of the tower. You'd still fall to the ground, but because of your forward motion you'd land a short distance away from the base of the tower.

The faster you ran out of the tower, the farther you'd go before landing. If you could somehow run fast enough—about 28,000 km/hr (17,000 mi/hr) at the orbital altitude of the Space Station—a very interesting thing would happen: By the time gravity had pulled you downward as far as the length of the tower, you'd already have moved far enough around Earth that you'd no longer be going down at all. Instead, you'd be just as high above Earth as you'd been all along, but a good portion of the way around the world. In other words, you'd be orbiting Earth.

The Space Shuttle, the Space Station, and all other orbiting objects stay in orbit because they are constantly "falling around" Earth. Their constant state of free-fall makes these spacecraft and everything in them weightless.

MA Motion and Gravity Tutorial, Lesson 1

4.2 Newton's Laws of Motion

The complexity of motion in daily life might lead you to guess that the laws governing motion would also be complex. For example, if you watch a falling piece of paper waft lazily to the ground, you'll see it rock back and forth in a seemingly unpredictable pattern. However, the complexity of this motion arises because the paper is affected by a variety of

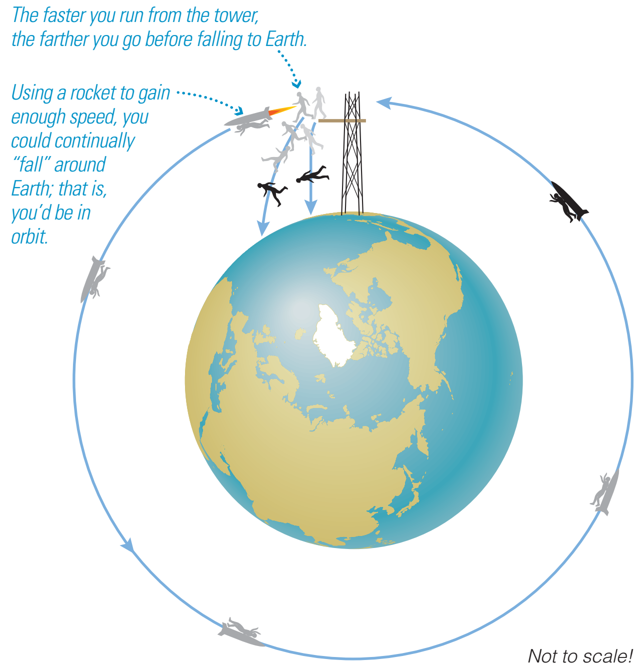


Figure 4.4 MA interactive figure

This figure explains why astronauts are weightless and float freely in space. It shows that if you could leap from a tall tower with enough speed (with the aid of a rocket), you could travel forward so fast that you'd orbit Earth. You'd then be in a constant state of free-fall, which means you'd be weightless. Note: On the scale shown here, the tower extends far higher than the Space Station's orbit; the rocket orientation assumes that it rotates once with each orbit, as is the case for the Space Shuttle. (Adapted from *Space Station Science* by Marianne Dyson.)

common Misconceptions

No Gravity in Space?

If you ask people why astronauts are weightless in space, one of the most common answers is "There is no gravity in space." But you can usually convince people that this answer is wrong by following up with another simple question: Why does the Moon orbit Earth? Most people know that the Moon orbits Earth because of gravity, proving that there is gravity in space. In fact, at the altitude of the Space Station's orbit, the acceleration of gravity is scarcely less than it is on Earth's surface.

The real reason astronauts are weightless is that they are in a constant state of free-fall. Imagine being an astronaut. You'd have the sensation of free-fall—just as when you jump from a diving board—the entire time you were in orbit. This constant falling sensation makes most astronauts sick to their stomachs when they first experience weightlessness. Fortunately, they quickly get used to the sensation, which allows them to work hard and enjoy the view.

Sir Isaac Newton (1642–1727)

forces, including gravity and the changing forces caused by air currents. If you could analyze the forces individually, you'd find that each force affects the paper's motion in a simple, predictable way. Sir Isaac Newton (1642–1727) discovered the remarkably simple laws that govern motion.

• How did Newton change our view of the universe?

Newton was born in Lincolnshire, England, on Christmas Day in 1642. He had a difficult childhood and showed few signs of unusual talent. He attended Trinity College at Cambridge, where he earned his keep by performing menial labor, such as cleaning the boots and bathrooms of wealthier students and waiting on their tables.

The plague hit Cambridge shortly after Newton graduated, and he returned home. By his own account, he experienced a moment of inspiration in 1666 when he saw an apple fall to the ground. He suddenly realized that the gravity making the apple fall was the same force that held the Moon in orbit around Earth. In that moment, Newton shattered the remaining vestiges of the Aristotelian view of the world, which for centuries had been accepted as unquestioned truth.

Aristotle had made many claims about the physics of motion, using his ideas to support his belief in an Earth-centered cosmos. He had also maintained that the heavens were totally distinct from Earth, so that physical laws on Earth did not apply to heavenly motion. By the time Newton saw the apple fall, the Copernican revolution had displaced Earth from a central position, and Galileo's experiments had shown that the laws of physics were not what Aristotle had believed.

Newton showed that the same physical laws that operate on Earth also operate in the heavens.

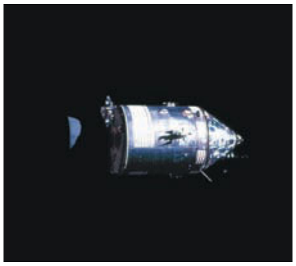
Newton's sudden insight delivered the final blow to Aristotle's physics. When Newton realized that gravity operated in the heavens as well as on Earth, he eliminated Aristotle's distinction between the two realms. For the first time in history, the heavens and Earth were brought together as one *universe*. Newton's insight also heralded the birth of the modern science of *astrophysics* (although the term wasn't coined until much later). Astrophysics applies physical laws discovered on Earth to phenomena throughout the cosmos.

Over the next 20 years, Newton's work completely revolutionized mathematics and science. He quantified the laws of motion and gravity, conducted crucial experiments regarding the nature of light, built the first reflecting telescopes, and invented the mathematics of calculus. We'll discuss his laws of motion in the rest of this section, and later in the chapter we'll turn our attention to Newton's discoveries about gravity.

• What are Newton's three laws of motion?

Newton published the laws of motion and gravity in 1687, in his book *Philosophiae Naturalis Principia Mathematica* ("Mathematical Principles of Natural Philosophy"), usually called *Principia*. He enumerated three laws that apply to all motion, what we now call **Newton's laws of motion**. These laws govern the motion of everything from our daily movements here on Earth to the movements of planets, stars, and galaxies throughout the universe. Figure 4.5 summarizes the three laws.

Newton's first law of motion:
An object moves at constant velocity unless a net force acts to change its speed or direction.



Example: *A spaceship needs no fuel to keep moving in space.*

Newton's second law of motion:
Force = mass × acceleration

Example: *A baseball accelerates as the pitcher applies a force by moving his arm. (Once the ball is released, the force from the pitcher's arm ceases, and the ball's path changes only because of the forces of gravity and air resistance.)*

Newton's third law of motion:
For any force, there is always an equal and opposite reaction force.

Example: *A rocket is propelled upward by a force equal and opposite to the force with which gas is expelled out its back.*

Figure 4.5

Newton's three laws of motion.

Newton's First Law Newton's first law of motion states that in the absence of a net force, an object will move with constant velocity. Objects at rest (velocity = 0) tend to remain at rest, and objects in motion tend to remain in motion with no change in either their speed or their direction.

Newton's first law: An object moves at constant velocity if there is no net force acting upon it.

The idea that an object at rest should remain at rest is rather obvious: A car parked on a flat street won't suddenly start moving for no reason. But what if the car is traveling along a flat, straight road? Newton's first law says that the car should keep going at the same speed forever *unless* a force acts to slow it down. You know that the car eventually will come to a stop if you take your foot off the gas pedal, so one or more forces must be stopping the car—in this case, forces arising from friction and air resistance. If the car were in space, and therefore unaffected by friction or air, it would keep moving forever (though gravity would eventually alter its speed and direction). That is why interplanetary spacecraft need no fuel to keep going after they are launched into space, and why astronomical objects don't need fuel to travel through the universe.

Newton's first law also explains why you don't feel any sensation of motion when you're traveling in an airplane on a smooth flight. As long as the plane is traveling at constant velocity, no net force is acting on it or on you. Therefore, you feel no different from the way you would feel at rest. You can walk around the cabin, play catch with someone, or relax and go to sleep just as though you were "at rest" on the ground.

Newton's Second Law Newton's second law of motion tells us what happens to an object when a net force *is* present. We have already seen that a net force will change an object's momentum, accelerating it in the direction of the force. Newton's second law quantifies this relationship, telling us that the amount of the acceleration depends on the object's mass and the strength of the net force. We usually write this law as an equation: force = mass × acceleration, or $F = ma$ for short.

This law explains why you can throw a baseball farther than you can throw a shot in the shot put. The force your arm delivers to both the baseball and the shot equals the product of mass and acceleration. Because the mass of the shot is greater than that of the baseball, the same force from your arm gives the shot a smaller acceleration. Because of its smaller acceleration, the shot leaves your hand with less speed than the baseball and therefore travels a shorter distance before hitting the ground.

Newton's second law: Force = mass × acceleration ($F = ma$).

Newton's second law also explains why large planets such as Jupiter have a greater effect on asteroids and comets than small planets such as Earth **[Section 9.4]**. Because Jupiter is much more massive than Earth, it exerts a stronger gravitational force on passing asteroids and therefore sends them scattering with a greater acceleration.

Newton's Third Law Think for a moment about standing still on the ground. Your weight exerts a downward force; if this force were acting alone, Newton's second law would demand that you accelerate downward. The fact that you are not falling means there must be no *net* force acting on you, which is possible only if the ground is exerting an upward force on you that precisely offsets the downward force you exert on the ground. The fact that the downward force you exert on the ground is offset by an equal and opposite force that pushes upward on you is one example of Newton's third law of motion, which tells us that every force is always paired with an equal and opposite reaction force. This law is very important in astronomy, because it tells us that objects always attract *each other* through gravity. For example, your body always exerts a gravitational force on Earth identical to the force that Earth exerts on you, except that it acts in the opposite direction. Of course, the same force means a much greater acceleration for you than for Earth (because your mass is so much smaller than Earth's), which is why you fall toward Earth when you jump off a chair, rather than Earth falling toward you.

Newton's third law: For any force, there is always an equal and opposite reaction force.

Newton's third law also explains how a rocket works: A rocket engine generates a force that drives hot gas out the back, which creates an equal and opposite force that propels the rocket forward.

common Misconceptions

What Makes a Rocket Launch?

If you've ever watched a rocket launch, it's easy to see why many people believe that the rocket "pushes off" the ground. In fact, the ground has nothing to do with the rocket launch. The rocket's launch is explained by Newton's third law of motion. To balance the force driving gas out the back of the rocket, an equal and opposite force must propel the rocket forward. Rockets can be launched horizontally as well as vertically, and a rocket can be "launched" in space (for example, from a space station) with no need for a solid surface to push off from.

4.3 Conservation Laws in Astronomy

Newton's laws of motion are easy to state, but they may seem a bit arbitrary. Why, for example, should every force be opposed by an equal and opposite reaction force? In the centuries since Newton first stated his laws, we have learned that they are not arbitrary at all, but instead reflect deeper aspects of nature known as *conservation laws*.

Consider what happens when two objects collide. Newton's second law tells us that object 1 exerts a force that will change the momentum of object 2. At the same time, Newton's third law tells us that object 2 exerts an equal and opposite force on object 1—which means that object 1's momentum changes by precisely the same amount as object 2's momentum, but in the opposite direction. The total combined momentum of objects 1 and 2 remains the same both before and after the collision. We say that the total momentum of the colliding objects is conserved, reflecting a principle that we call *conservation of momentum*. In essence, the law of conservation of momentum tells us that the total momentum of all interacting objects always stays the same. An individual object can gain or lose momentum only when a force causes it to exchange momentum with another object.

Conservation of momentum is one of several important conservation laws that underlie Newton's laws of motion and other physical laws in the universe. Two other conservation laws are especially important in astronomy. They go by the names *conservation of angular momentum* and *conservation of energy*. Let's see how these important laws work.

• What keeps a planet rotating and orbiting the Sun?

Perhaps you've wondered how Earth manages to keep rotating and going around the Sun day after day and year after year. The answer relies on a special type of momentum that we use to describe objects turning in circles or going around curves. This special type of "circling momentum" is called **angular momentum**. (The term *angular* arises because a circle turns through an *angle* of 360°.)

Conservation of angular momentum: An object's angular momentum cannot change unless it transfers angular momentum to or from another object.

The **law of conservation of angular momentum** tells us that total angular momentum can never change. An individual object can change its angular momentum only by transferring some angular momentum to or from another object.

Consider Earth's orbit around the Sun. A simple formula tells us Earth's angular momentum at any point in its orbit:

$$\text{angular momentum} = m \times v \times r$$

where m is Earth's mass, v is its speed (or velocity) around the orbit, and r is the "radius" of the orbit, by which we mean Earth's distance from the Sun (Figure 4.6). Because there are no objects around to give or take angular momentum from Earth as it orbits the Sun, Earth's orbital angular momentum must always stay the same. This explains two key facts about Earth's orbit:

1. Earth needs no fuel or push of any kind to keep orbiting the Sun—it will keep orbiting as long as nothing comes along to take angular momentum away.
2. Because Earth's angular momentum at any point in its orbit depends on the product of its speed and orbital radius (distance from the Sun), Earth's orbital speed must be faster when it is nearer to the Sun (and the radius is smaller) and slower when it is farther from the Sun (and the radius is larger).

The second fact is just what Kepler's second law of planetary motion states **[Section 3.3]**. That is, the law of conservation of angular momentum tells us *why* Kepler's law is true.

The same idea explains why Earth keeps rotating. As long as Earth isn't transferring any of the angular momentum of its rotation to another object, it keeps rotating at the same rate. (In fact, Earth is very gradually transferring some of its rotational angular momentum to the Moon, and as a result Earth's rotation is gradually slowing down; see Special Topic, page 103.)

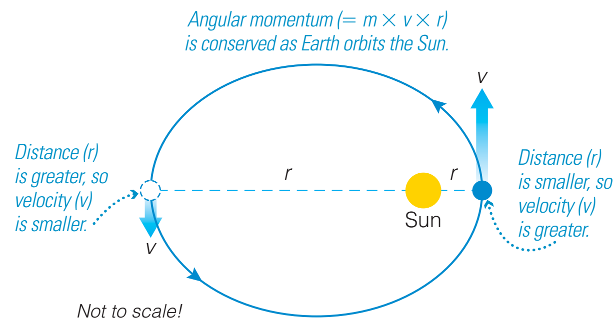


Figure 4.6

Earth's angular momentum always stays the same as it orbits the Sun, so it moves faster when it is closer to the Sun and slower when it is farther from the Sun. It needs no fuel to keep orbiting because no forces are acting in a way that could change its angular momentum.

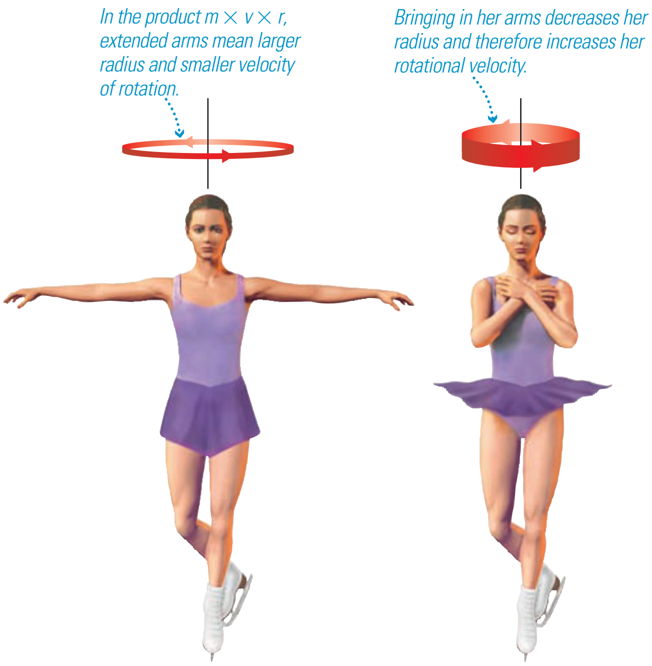


Figure 4.7

A spinning skater conserves angular momentum.

Conservation of angular momentum also explains why we see so many spinning disks in the universe, such as the disks of galaxies like the Milky Way and disks of material orbiting young stars. The idea is easy to illustrate with an ice skater spinning in place (Figure 4.7). Because there is so little friction on ice, the angular momentum of the ice skater remains essentially constant. When she pulls in her extended arms, she decreases her radius—which means her velocity of rotation must increase. Stars and galaxies are both born from clouds of gas that start out much larger in size. These clouds almost inevitably have some small net rotation, though it may be imperceptible. Like the spinning skater as she pulls in her arms, these clouds must spin faster as gravity makes them shrink in size. (We'll discuss why the clouds also flatten into disks in Chapter 6.)

Earth is not exchanging substantial angular momentum with any other object, so its rotation rate and orbit must stay about the same.

think about it How does conservation of angular momentum explain the spiraling of water going down a drain?

MA Energy Tutorial, Lesson 1

• Where do objects get their energy?

The **law of conservation of energy** tells us that, like momentum and angular momentum, energy cannot appear out of nowhere or disappear into nothingness. Objects can gain or lose energy only by exchanging energy with other objects. Because of this law, the story of the universe is a story of the interplay of energy and matter: All actions involve exchanges of energy or the conversion of energy from one form to another.

Throughout the rest of this book, we'll see numerous cases in which we can understand astronomical processes simply by studying how energy is transformed and exchanged. For example, we'll see that planetary interiors cool with time only because they radiate energy into space, and that the Sun became hot because of energy released by the gas that formed it. By applying the laws of conservation of angular momentum and conservation of energy, we can understand almost every major process that occurs in the universe.

Conservation of energy: Energy can be transferred from one object to another or transformed from one type to another, but the total amount of energy is always conserved.

Figure 4.8

The three basic categories of energy. Energy can be converted from one form to another, but it can never be created or destroyed, an idea embodied in the law of conservation of energy.

Basic Types of Energy Before we can fully understand the law of conservation of energy, we need to know exactly what energy is. In essence, energy is what makes matter move. Because this statement is so broad, we often distinguish between many different types of energy. For example, we talk about the energy we get from the food we eat, the energy that makes our cars go, and the energy put out by a light bulb. Fortunately, scientists have found a way to classify all these various types of energy into just three major categories (Figure 4.8):

- Energy of motion, or **kinetic energy** (*kinetic* comes from a Greek word meaning "motion"). Falling rocks, orbiting planets, and the molecules moving in the air are all examples of objects with kinetic energy.

- Energy carried by light, or **radiative energy** (the word *radiation* is often used as a synonym for *light*). All light carries energy, which is why light can cause changes in matter. For example, light can alter molecules in our eyes—thereby allowing us to see—or warm the surface of a planet.
- Stored energy, or **potential energy**, which might later be converted into kinetic or radiative energy. For example, a rock perched on a ledge has *gravitational* potential energy because it will fall if it slips off the edge, and gasoline contains *chemical* potential energy that can be converted into the kinetic energy of a moving car.

There are three basic categories of energy: energy of motion (kinetic), energy of light (radiative), and stored energy (potential).

Regardless of which type of energy we are dealing with, we can measure the amount of energy with the same standard units. For Americans, the most familiar units of energy are *Calories*, which are shown on food labels to tell us how much energy our bodies can draw from the food. A typical adult needs about 2500 Calories of energy from food each day. In science, the standard unit of energy is the **joule**. One food Calorie is equivalent to about 4184 joules, so the 2500 Calories used daily by a typical adult is equivalent to about 10 million joules. Table 4.1 compares various energies in joules.

Table 4.1 *Energy Comparisons*

Item	Energy (joules)
Energy of sunlight at Earth (per square meter per second)	1.3×10^3
Energy from metabolism of a candy bar	1×10^6
Energy needed to walk for 1 hour	1×10^6
Kinetic energy of a car going 60 mi/hr	1×10^6
Daily food energy need of average adult	1×10^7
Energy released by burning 1 liter of oil	1.2×10^7
Thermal energy of parked car	1×10^8
Energy released by fission of 1 kilogram of uranium-235	5.6×10^{13}
Energy released by fusion of hydrogen in 1 liter of water	7×10^{13}
Energy released by 1-megaton H-bomb	4×10^{15}
Energy released by major earthquake (magnitude 8.0)	2.5×10^{16}
Annual U.S. energy consumption	10^{20}
Annual energy generation of Sun	10^{34}
Energy released by a supernova	$10^{44} - 10^{46}$

Thermal Energy—The Kinetic Energy of Many Particles

Although there are only three major categories of energy, we sometimes divide them into various subcategories. In astronomy, the most important subcategory of kinetic energy is **thermal energy**, which represents the collective kinetic energy of the many individual particles (atoms and molecules) moving randomly within a substance like a rock or the air or the gas within a distant star. In such cases, it is much easier to talk about the thermal energy of the object rather than about the kinetic energies of its billions upon billions of individual particles.

Thermal energy gets its name because it is related to temperature, but temperature and thermal energy are not quite the same thing. Thermal energy measures the *total* kinetic energy of all the randomly moving particles in a substance, while **temperature** measures the *average* kinetic energy of the particles. For a particular object, a higher temperature simply means that the particles on average have more kinetic energy and hence are moving faster (Figure 4.9). You're probably familiar with temperatures measured on the *Fahrenheit* or *Celsius* scale, but in science we often use the **Kelvin** temperature scale (Figure 4.10). The Kelvin scale does not have negative temperatures, because it starts from the coldest possible temperature, known as *absolute zero* (0 K), at which there are no random motions at all.

Thermal energy is the total kinetic energy of many individual particles.

Thermal energy depends on temperature, because a higher average kinetic energy for the particles in a substance must also lead to a higher total energy. But thermal energy also depends on the number and density of the particles, as you can see by imagining that you quickly thrust your arm in and out of a hot oven and a pot of boiling water. The air in a hot oven is much hotter in temperature than the water boiling in a pot (typically 400°F for the oven versus 212°F for boiling water). However, the boiling water would scald your arm almost instantly, while you can safely put your arm into the oven air for a few seconds. The reason for this difference is

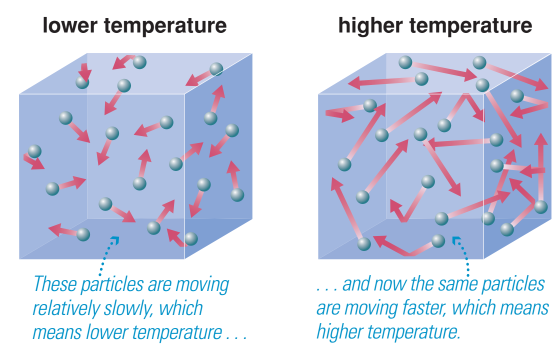


Figure 4.9

Temperature is a measure of the average kinetic energy of the particles (atoms and molecules) in a substance. Longer arrows represent faster speeds.

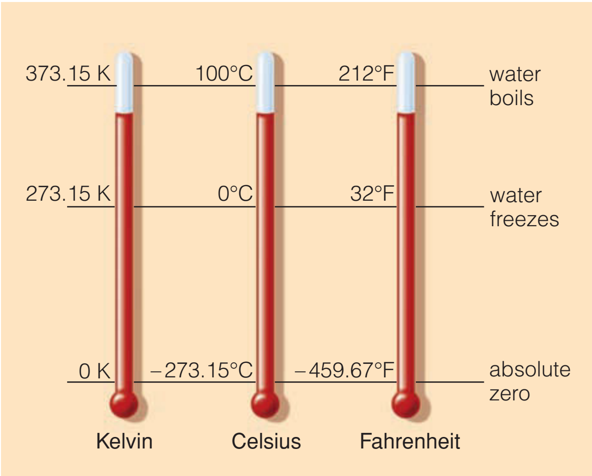


Figure 4.10

Three common temperature scales: Kelvin, Celsius, and Fahrenheit. Scientists generally prefer the Kelvin scale. (The degree symbol ° is not usually used with the Kelvin scale.)

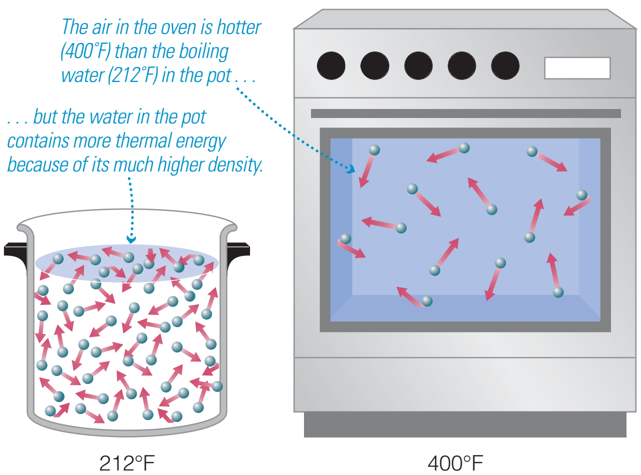


Figure 4.11

Thermal energy depends on both the temperature and the density of a substance.

density (Figure 4.11). If air or water is hotter than your body, molecules striking your skin transfer thermal energy to molecules in your arm. The higher temperature in the oven means that the air molecules strike your skin harder, on average, than the molecules in the boiling water. However, because the *density* of water is so much higher than the density of air (meaning water has far more molecules in the same amount of space), many more molecules strike your skin each second in the water. While each individual molecule that strikes your skin transfers a little less energy in the boiling water than in the oven, the sheer number of molecules hitting you in the water means that more thermal energy is transferred to your arm. That is why boiling water causes a burn almost instantly.

think about it In air or water that is colder than your body temperature, thermal energy is transferred from you to the surrounding cold air or water. Use this fact to explain why falling into a 32°F (0°C) lake is much more dangerous than standing naked outside on a 32°F day.

Potential Energy in Astronomy Many types of potential energy are important in astronomy, but two are particularly important: *gravitational potential energy* and the potential energy of mass itself, or *mass-energy*.

An object's gravitational potential energy increases when it moves higher and decreases when it moves lower.

An object's **gravitational potential energy** depends on its mass and how far it can fall as a result of gravity. An object has more gravitational potential energy when it is higher and less when it is lower. For example, if you throw a ball up into the air, it has more potential energy when it is high up than it does near the ground. Because energy must be conserved during the ball's flight, the ball's kinetic energy increases when its gravitational potential energy decreases, and vice versa (Figure 4.12a). That is why the ball travels fastest (has the most kinetic energy) when it is closest to the ground, where it has the least gravitational potential energy. The higher it is, the more gravitational potential energy it has and the slower the ball travels (less kinetic energy).

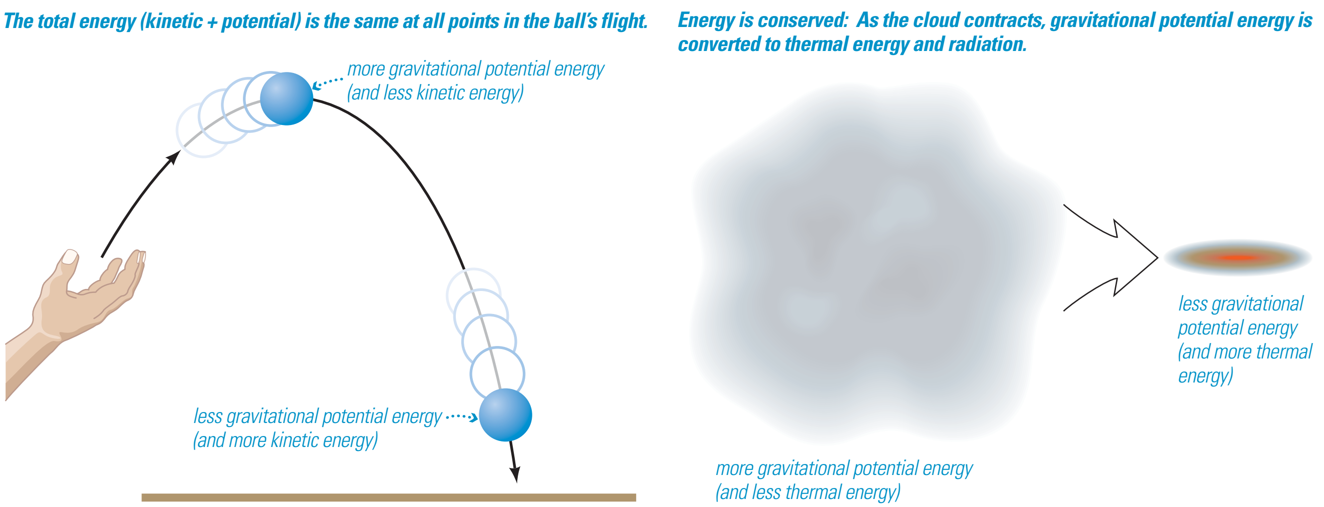
The same general idea explains how stars become hot (Figure 4.12b). Before a star forms, its matter is spread out in a large, cold cloud of gas. Most of the individual gas particles are far from the center of this large cloud and therefore have a lot of gravitational potential energy. The particles lose gravitational potential energy as the cloud contracts under its own gravity, and this "lost" potential energy ultimately gets converted into thermal energy, making the center of the cloud hot.

Einstein discovered that mass itself is a form of potential energy, often called **mass-energy**. The amount of potential energy contained in mass is described by Einstein's famous equation

$$E = mc^2$$

Mass itself is a form of potential energy, as described by Einstein's equation $E = mc^2$.

where E is the amount of potential energy, m is the mass of the object, and c is the speed of light. This equation tells us that a small amount of mass contains a huge amount of energy. For example, the energy released by a 1-megaton H-bomb comes from converting only about 0.1 kilogram of mass (about 3 ounces—a quarter of a can of soda) into energy (Figure 4.13). The Sun generates energy by converting a tiny



a The ball has more gravitational potential energy when it is high up than when it is near the ground.

b A cloud of interstellar gas can contract due to its own gravity. It has more gravitational potential energy when it is spread out than when it shrinks in size.

Figure 4.12

Two examples of gravitational potential energy.

fraction of its mass into energy through a similar process of nuclear fusion **[Section 10.2]**.

Just as Einstein's formula tells us that mass can be converted into other forms of energy, it also tells us that energy can be transformed into mass. This process is especially important in understanding what we think happened during the early moments in the history of the universe, when some of the energy of the Big Bang turned into the mass from which all objects, including us, are made **[Section 17.1]**. Scientists also use this idea to search for undiscovered particles of matter, using large machines called *particle accelerators* to create subatomic particles from energy.

Conservation of Energy We have seen that energy comes in three basic categories—kinetic, radiative, and potential—and explored several subcategories that are especially important in astronomy: thermal energy, gravitational potential energy, and mass-energy. Now we are ready to return to the question of where objects get their energy. Because energy cannot be created or destroyed, objects always get their energy from other objects. Ultimately, we can always trace an object's energy back to the Big Bang **[Section 1.1]**, the beginning of the universe in which all matter and energy is thought to have come into existence.

The energy of any object can be traced back to the origin of the universe in the Big Bang.

For example, imagine that you've thrown a baseball. It is moving, so it has kinetic energy. Where did this kinetic energy come from? The baseball got its kinetic energy from the motion of your arm as you threw it. Your arm, in turn, got its kinetic energy from the release of chemical potential energy stored in your muscle tissues. Your muscles got this energy from the chemical potential energy stored in the foods you ate. The energy stored in the foods came from sunlight, which plants convert into chemical potential energy through photosynthesis. The radiative energy of the Sun was generated through the process of nuclear fusion, which releases some of the mass-energy stored in the Sun's supply of hydrogen. The mass-energy stored in the hydrogen came from the birth of the universe in the Big Bang. After you throw the ball, its kinetic energy will ultimately be transferred to molecules in the air or

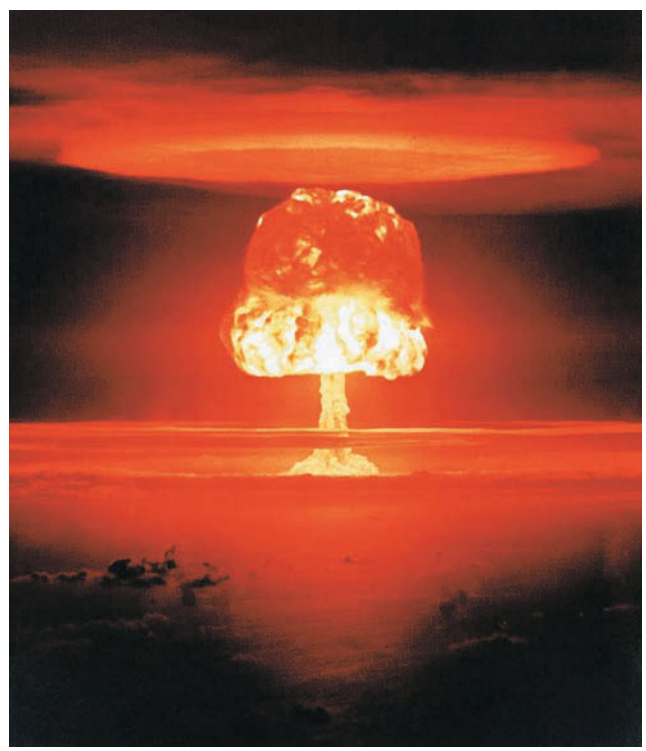


Figure 4.13

The energy released by this H-bomb comes from converting only about 0.1 kilogram of mass into energy in accordance with the formula $E = mc^2$.

ground. According to present understanding, the total energy content of the universe was determined in the Big Bang. It remains the same today and will stay the same in the future.

4.4 The Force of Gravity

Newton's laws of motion describe how objects in the universe move in response to forces. The laws of conservation of momentum, angular momentum, and energy offer an alternative and often simpler way of thinking about what happens when a force causes some change in the motion of one or more objects. However, we cannot fully understand motion unless we also understand the forces that lead to changes in motion. In astronomy, the most important force is gravity, which governs virtually all large-scale motion in the universe.

Motion and Gravity Tutorial, Lesson 2

• What determines the strength of gravity?

Isaac Newton discovered the basic law that describes how gravity works. Newton expressed the force of gravity mathematically with his **universal law of gravitation**. Three simple statements summarize this law:

- Every mass attracts every other mass through the force called *gravity*.
- The strength of the gravitational force attracting any two objects is *directly proportional* to the product of their masses. For example, doubling the mass of *one* object doubles the force of gravity between the two objects.
- The strength of gravity between two objects decreases with the *square* of the distance between their centers. We therefore say that the gravitational force follows an **inverse square law**. For example, doubling the distance between two objects weakens the force of gravity by a factor of 2^2, or 4.

Doubling the distance between two objects weakens the force of gravity by a factor of 2^2, or 4.

These three statements tell us everything we need to know about Newton's universal law of gravitation. Mathematically, all three statements can be combined into a single equation, usually written like this:

$$F_g = G\frac{M_1 M_2}{d^2}$$

where F_g is the force of gravitational attraction, M_1 and M_2 are the masses of the two objects, and d is the distance between their centers (Figure 4.14). The symbol G is a constant called the **gravitational constant**, and its numerical value has been measured to be $G = 6.67 \times 10^{-11} \text{m}^3/(\text{kg} \times \text{s}^2)$.

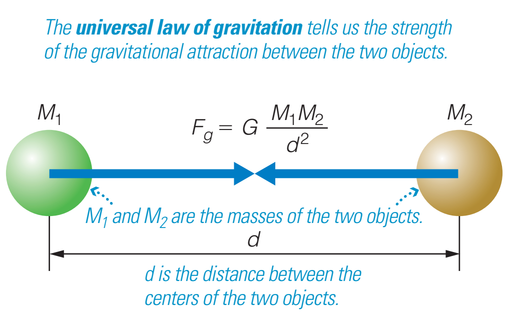


Figure 4.14

The universal law of gravitation is an *inverse square law*, which means that the force of gravity declines with the *square* of the distance d between two objects.

think about it How does the gravitational force between two objects change if the distance between them triples? If the distance between them drops by half?

MA Orbits and Kepler's Law Tutorial, Lessons 1–4

• How does Newton's law of gravity extend Kepler's laws?

By the time Newton published *Principia* in 1687, Kepler's laws of planetary motion **[Section 3.3]** had already been known and tested for some 70 years. Kepler's laws had proven so successful that there was little doubt about their validity. However, there was great debate among scientists about *why* Kepler's laws hold true, a debate resolved only when Newton showed mathematically that Kepler's laws are consequences of the laws of motion and the universal law of gravitation. In doing so, Newton discovered that he could generalize Kepler's laws in several ways, three of which are particularly important for our purposes.

First, Newton discovered that Kepler's first two laws apply to all orbiting objects, not just to planets going around the Sun. For example, the orbits of a satellite around Earth, of a moon around a planet, and of an asteroid around the Sun are all ellipses in which the orbiting object moves faster at the nearer points in its orbit and slower at the farther points.

Second, Newton found that ellipses are not the only possible orbital paths (Figure 4.15). Kepler was right when he found that ellipses (which include circles) are the only possible shapes for **bound orbits—**orbits in which an object goes around another object over and over again. (The term *bound orbit* comes from the idea that gravity creates a *bond* that holds the objects together.) However, Newton discovered that objects can also follow **unbound orbits—**paths that bring an object close to another object just once. For example, some comets that enter the inner solar system follow unbound orbits. They come in from afar just once, loop around the Sun, and never return.

Newton's version of Kepler's third law allows us to calculate the masses of distant objects.

Third, and perhaps most important, Newton generalized Kepler's third law in a way that allows us to calculate the masses of distant objects. Recall that the precise statement of Kepler's third law is $p^2 = a^3$, where p is a planet's orbital period in years and a is the planet's average distance from the Sun in AU. Newton found that this statement is actually a special case of a more general equation that we call **Newton's version of Kepler's third law** (see Cosmic Calculations 4.1). This equation allows us to calculate the mass of a distant object if we can observe another object orbiting it and measure the orbiting object's orbital period and distance. For example, it allows us to calculate the mass of the Sun from Earth's orbital period (1 year) and its average distance (1 AU) from the Sun; it allows us to calculate Jupiter's mass by measuring the orbital period and average distance of one of Jupiter's moons; and it allows us to determine the masses of distant stars if they are members of binary star systems, in which two stars orbit one another. In fact, Newton's version of Kepler's third law is the primary means by which we determine masses throughout the universe.

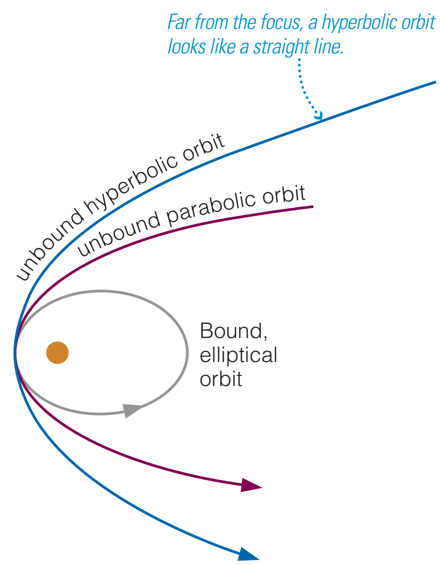


Figure 4.15

Newton showed that ellipses are not the only possible orbital paths. Orbits can also be unbound, taking the mathematical shapes of either parabolas or hyperbolas.

cosmic Calculations 4.1

Newton's Version of Kepler's Third Law

For an object of mass M_1 orbiting another object of mass M_2, Newton's version of Kepler's third law states

$$p^2 = \frac{4\pi^2}{G(M_1 + M_2)}a^3$$

$$\left(G = 6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg} \times \text{s}^2} \text{ is the gravitational constant.}\right)$$

This equation allows us to calculate the sum $M_1 + M_2$ if we know the orbital period p and average (semimajor axis) distance a. The equation is especially useful when one object is much more massive than the other.

Example: Use the fact that Earth orbits the Sun in 1 year at an average distance of 1 AU to calculate the Sun's mass.

Solution: Newton's version of Kepler's third law becomes

$$p^2_{\text{Earth}} = \frac{4\pi^2}{G(M_{\text{Sun}} + M_{\text{Earth}})}a^3_{\text{Earth}}$$

Because the Sun is much more massive than Earth, the sum of their masses is nearly the mass of the Sun alone: $M_{\text{Sun}} + M_{\text{Earth}} \approx M_{\text{Sun}}$. Using this approximation, we find

$$p^2_{\text{Earth}} \approx \frac{4\pi^2}{GM_{\text{Sun}}}a^3_{\text{Earth}}$$

We now solve for the mass of the Sun and plug in Earth's orbital period ($p_{\text{Earth}} = 1$ year $\approx 3.15 \times 10^7$ seconds) and average orbital distance ($a_{\text{Earth}} = 1$ AU $\approx 1.5 \times 10^{11}$ m):

$$M_{\text{Sun}} \approx \frac{4\pi^2 a^3_{\text{Earth}}}{Gp^2_{\text{Earth}}} \approx \frac{4\pi^2(1.5 \times 10^{11}\text{ m})^3}{\left(6.67 \times 10^{-11}\dfrac{\text{m}^3}{\text{kg} \times \text{s}^2}\right)(3.15 \times 10^7\text{ s})^2}$$

$$= 2.0 \times 10^{30}\text{ kg}$$

The Sun's mass is about 2×10^{30} kilograms.

• How do gravity and energy allow us to understand orbits?

We've seen that Newton's law of universal gravitation explains Kepler's laws of planetary motion, which describe the simple and stable orbits of the planets. By extending Kepler's laws, Newton also explained many other stable orbits, such as the orbit of a satellite around Earth or of a moon around a planet. But orbits do not always stay the same. For example, you've probably heard of satellites crashing to Earth from orbit, proving that orbits can sometimes change dramatically. To understand how and why orbits sometimes change, we need to consider the role of energy in orbits.

Orbital Energy Consider the orbit of a planet around the Sun. An orbiting planet has both kinetic energy (because it is moving around the Sun) and gravitational potential energy (because it would fall toward the Sun if it stopped orbiting). The planet's kinetic energy depends on its orbital speed, and its gravitational potential energy depends on its distance from the Sun. Because the planet's distance and speed both vary as it orbits the Sun, its gravitational potential energy and kinetic energy also vary (Figure 4.16). However, the planet's total **orbital energy**—the sum of its kinetic and gravitational potential energies—always stays the same. This fact is a consequence of the law of conservation of energy. As long as no other object causes the planet to gain or lose orbital energy, its orbital energy cannot change and its orbit must remain the same.

Orbits cannot change spontaneously—an object's orbit can change only if it gains or loses orbital energy.

Generalizing from planets to other objects leads us to a very important idea about motion throughout the cosmos: *Orbits cannot change spontaneously*. Left undisturbed, planets would forever keep the same orbits around the Sun, moons would keep the same orbits around planets, and stars would keep the same orbits in their galaxies.

Gravitational Encounters Although orbits cannot change spontaneously, they can change through exchanges of energy. One way that two objects can exchange orbital energy is through a **gravitational encounter**, in which they pass near enough so that each can feel the effects of the other's gravity. For example, in the rare cases in which a comet happens to pass near a planet, the comet's orbit can change dramatically. Figure 4.17 shows a comet headed toward the Sun on an unbound orbit. The comet's close passage by Jupiter allows the comet and Jupiter to exchange energy. In this case, the comet loses so much orbital energy that

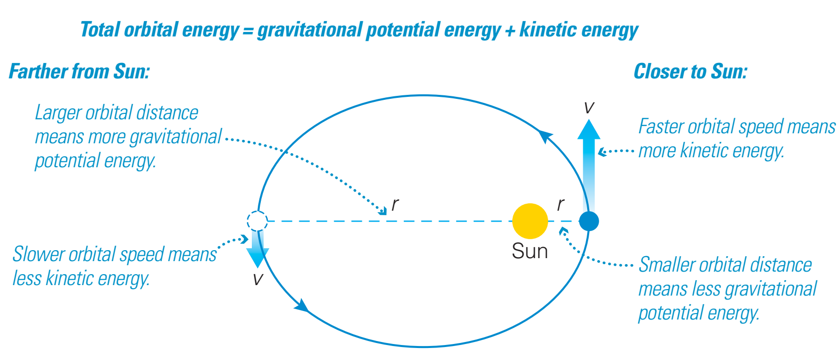


Figure 4.16

The total orbital energy of a planet stays the same throughout its orbit, because its gravitational potential energy increases when its kinetic energy decreases, and vice versa.

its orbit changes from unbound to bound and elliptical. Jupiter gains exactly as much energy as the comet loses, but the effect on Jupiter is unnoticeable because of its much greater mass.

Spacecraft engineers can use the same basic idea in reverse. For example, the *New Horizons* spacecraft now en route to Pluto was deliberately sent past Jupiter on a path that allowed it to gain orbital energy at Jupiter's expense. This extra orbital energy sped up the spacecraft so that the trip to Pluto will take four years less than it would have taken otherwise. Of course, the effect of the tiny spacecraft on Jupiter was unnoticeable.

A similar dynamic sometimes occurs naturally and may explain why most comets orbit so far from the Sun. Astronomers think that most comets once orbited in the same region of the solar system as the large outer planets **[Section 9.2]**. Gravitational encounters with Jupiter or the other large planets then caused some of these comets to be "kicked out" into much more distant orbits around the Sun, or ejected from the solar system completely.

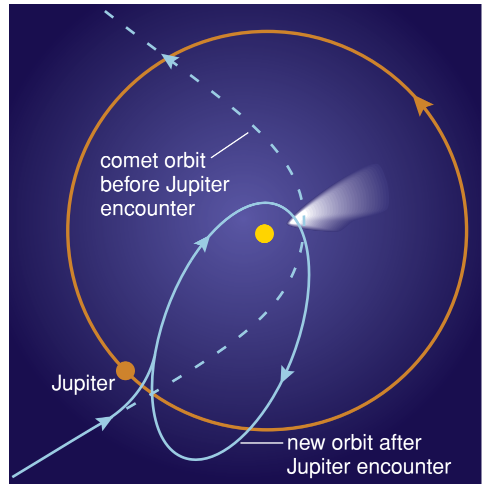


Figure 4.17

This diagram shows a comet in an unbound orbit of the Sun that happens to pass near Jupiter. The comet loses orbital energy to Jupiter, changing its unbound orbit to a bound orbit around the Sun.

Atmospheric Drag Friction can cause objects to lose orbital energy. For example, consider a satellite orbiting Earth. If the orbit is fairly low—say, just a few hundred kilometers above Earth's surface—the satellite experiences a bit of drag from Earth's thin upper atmosphere. This drag gradually causes the satellite to lose orbital energy until it finally plummets to Earth. The satellite's lost orbital energy is converted to thermal energy in the atmosphere, which is why a falling satellite usually burns up.

Friction may also have played a role in shaping the current orbits of some of the small moons of Jupiter and other planets. These moons may once have orbited the Sun independently, and their orbits could not have changed spontaneously. However, the outer planets probably once were surrounded by clouds of gas **[Section 6.4]**, and friction would have slowed objects passing through this gas. Some of these small objects may have lost just enough energy to friction to allow them to be "captured" as moons. Mars may have captured its two small moons in a similar way.

Escape Velocity An object that gains orbital energy moves into an orbit with a higher average altitude. For example, if we want to boost the orbital altitude of a spacecraft, we can give it more orbital energy by firing a rocket. The chemical potential energy released by the rocket fuel is converted to orbital energy for the spacecraft.

A spacecraft that achieves escape velocity can escape Earth completely.

If we give a spacecraft enough orbital energy, it may end up in an unbound orbit that allows it to *escape* Earth completely (Figure 4.18). For example, when we send a space probe to Mars, we must use a large rocket that gives the probe enough energy to leave Earth orbit. Although it would probably make more sense to say that the probe achieves "escape energy," we instead say that it achieves **escape velocity**. The escape velocity from Earth's surface is about 40,000 km/hr, or 11 km/s, meaning that this is the minimum velocity required to escape Earth's gravity for a spacecraft that starts near the surface.

Notice that the escape velocity does not depend on the mass of the escaping object—*any* object must travel at a velocity of 11 km/s to escape from Earth, whether it is an individual atom or molecule escaping from

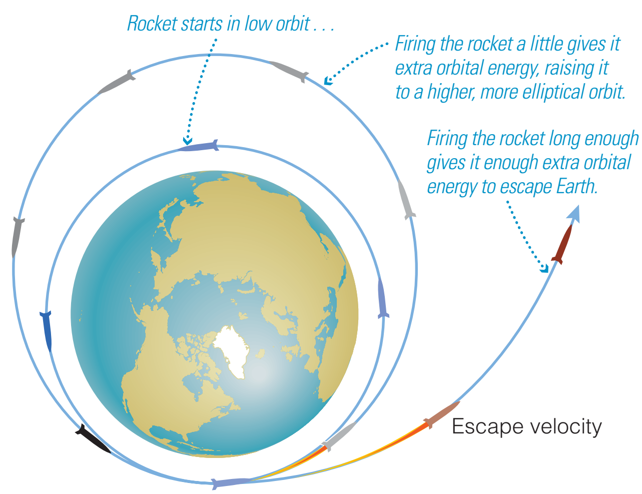


Figure 4.18 MA interactive figure

If an object orbiting Earth gains orbital energy, it moves to a higher or more elliptical orbit. With enough extra orbital energy, it may achieve escape velocity. Escape velocity depends on how high the object is when it starts. From Earth's surface, escape velocity is about 11 km/s.

common Misconceptions

The Origin of Tides

Many people believe that tides arise because the Moon pulls Earth's oceans toward it. But if that were the whole story, there would be a bulge only on the side of Earth facing the Moon, and hence only one high tide each day. The correct explanation for tides must account for why Earth has two tidal bulges.

Only one explanation works: Earth must be stretching from its center in both directions (toward and away from the Moon). This stretching force, or tidal force, arises from the difference between the force of gravity attracting different parts of Earth to the Moon. In fact, stretching due to tides affects many objects, not just Earth. Many moons are stretched into slightly oblong shapes by tidal forces caused by their parent planets, and mutual tidal forces stretch close binary stars into teardrop shapes. In regions where gravity is extremely strong, such as near a black hole, tides can have even more dramatic effects (see Chapter 13).

the atmosphere, a spacecraft being launched into deep space, or a rock blasted into the sky by a large impact. Escape velocity *does* depend on whether you start from the surface or from someplace high above the surface. Because gravity weakens with distance, it takes less energy—and hence a lower velocity—to escape from a point high above Earth than from Earth's surface.

• How does gravity cause tides?

Newton's universal law of gravitation has applications that go far beyond explaining Kepler's laws and orbits. For our purposes, however, there is just one more topic we need to cover: how gravity causes tides.

If you've spent time near an ocean, you've probably observed the rising and falling of the tides. In most places, tides rise and fall twice each day. Tides arise because gravity attracts Earth and the Moon toward each other (with the Moon staying in orbit as it "falls around" Earth), but it affects different parts of Earth slightly differently: Because the strength of gravity declines with distance, the gravitational attraction of each part of Earth to the Moon becomes weaker as we go from the side of Earth facing the Moon to the side facing away from the Moon. This difference in attraction creates a "stretching force," or **tidal force**, that stretches the entire Earth to create two tidal bulges—one facing the Moon and one opposite the Moon (Figure 4.19). If you are still unclear about why there are *two* tidal bulges, think about a rubber band: If you pull on a rubber band it will stretch in both directions relative to its center, even if you pull on only one side. In the same way, Earth stretches on both sides even though the Moon is tugging harder on only one side.

Tidal forces cause the entire Earth to stretch along the Earth–Moon line, creating two tidal bulges.

Tides affect both land and ocean, but we generally notice only the ocean tides because water flows much more readily than land. Earth's rotation carries any location through each of the two bulges each day, creating two high tides. Low tides occur when the location is at the points halfway between the two tidal bulges. The height and timing of ocean tides can vary considerably from place to place on Earth. For example, while the tide rises gradually in most locations, the incoming tide near the famous abbey on Mont-Saint-Michel, France,

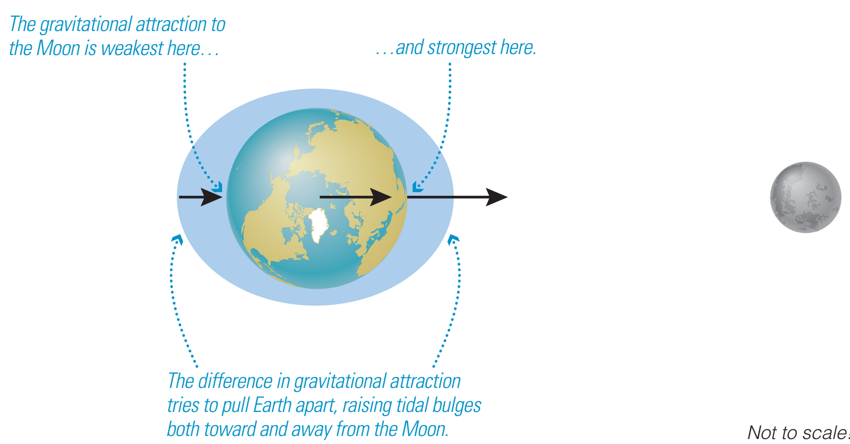


Figure 4.19

Tides are created by the difference in the force of attraction between different parts of Earth and the Moon. There are two daily high tides as any location on Earth rotates through the two tidal bulges. (The diagram highly exaggerates the tidal bulges, which raise the oceans only about 2 meters and the land only about a centimeter.)

specialTopic: Why Does the Moon Always Show the Same Face to Earth?

YOU ARE PROBABLY aware that we always see (nearly) the same face of the Moon. This happens because the Moon rotates on its axis in exactly the same time period that it takes to orbit Earth, a trait called **synchronous rotation**. A simple demonstration shows this idea (Figure 1). Place a ball or other model on a table to represent Earth while you represent the Moon. The only way you can face the ball at all times is by completing exactly one rotation while you complete one orbit. But *why* does the Moon have this synchronous rotation? We can trace the answer directly to tides.

It's easiest to start by considering the effects of tides on Earth. So far, we have talked as if Earth rotates smoothly through the tidal bulges. But because tidal forces stretch Earth itself, the process causes some friction, called *tidal friction*. Figure 2 shows the effects of this friction. In essence, the Moon's gravity tries to keep the tidal bulges on the Earth–Moon line, while Earth's rotation tries to pull the bulges around with it. The resulting "compromise" keeps the bulges just ahead of the Earth–Moon line at all times, which causes two important effects. First, the Moon's gravity always pulls back on the bulges, slowing Earth's rotation. Second, the gravity of the bulges pulls the Moon slightly ahead in its orbit, causing the Moon to move farther from Earth. These effects are barely noticeable on human time scales, but they add up over billions of years. Early in Earth's history, a day may have been only 5 or 6 hours long and the Moon may have been one-tenth or less of its current distance from Earth. These changes also provide a great example of conservation of angular momentum: The Moon's growing orbit gains the angular momentum that Earth loses as its rotation slows.

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

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

Figure 1

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

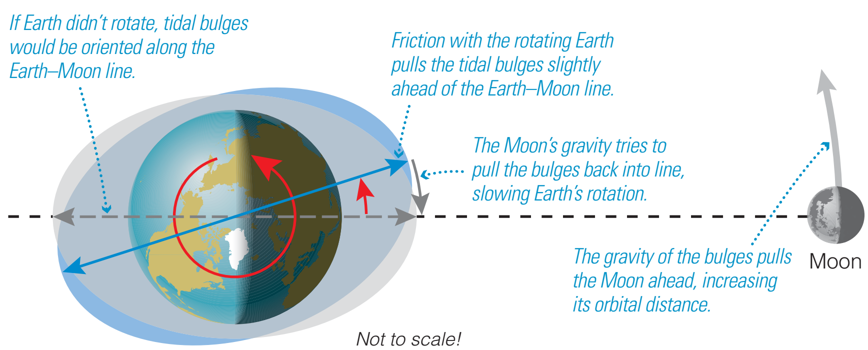


Figure 2

Earth's rotation pulls its tidal bulges slightly ahead of the Earth–Moon line, leading to gravitational effects that gradually slow Earth's rotation and increase the Moon's orbital distance.

Now, let's turn the situation around to see how tides affect the Moon. Because Earth is more massive than the Moon, Earth's tidal force has a greater effect on the Moon than the Moon's tidal force has on Earth. This tidal force gives the Moon two tidal bulges along the Earth–Moon line, much like the two tidal bulges that the Moon creates on Earth. (The Moon does not have visible tidal bulges, but it does indeed have excess mass along the Earth–Moon line.) As a result, if the Moon were rotating through its tidal bulges in the same way that Earth rotates through its tidal bulges, the resulting friction would cause the Moon's rotation to slow down. This is exactly what we think happened long ago.

The Moon probably once rotated much faster than it does today. As a result, it *did* rotate through its tidal bulges, and its rotation gradually slowed. Once the Moon's rotation slowed to the point at which the Moon and its bulges rotated at the same rate—that is, synchronously with the orbital period—there was no further source for tidal friction. The Moon's synchronous rotation therefore was a natural outcome of Earth's tidal effects on the Moon.

Similar tidal friction has led to synchronous rotation in many other cases. For example, Jupiter's four large moons (Io, Europa, Ganymede, and Callisto) keep nearly the same face toward Jupiter at all times, as do many other moons. Pluto and its moon Charon *both* rotate synchronously: Like two dancers, they always keep the same face toward each other. Many binary star systems also rotate in this way. Tidal forces may be most familiar because of their effects on our oceans, but they are important throughout the universe.

Figure 4.20

Photographs of high and low tide at the abbey of Mont-Saint-Michel, France. Here the tide rushes in much faster than a person can swim. Before a causeway was built (visible to the left), the Mont was accessible by land only at low tide. At high tide, it became an island.

moves much faster than a person can swim (Figure 4.20). In centuries past, the Mont was an island twice a day at high tide but was connected to the mainland at low tide. Many pilgrims drowned when they were caught unprepared by the tide rushing in. Another unusual tidal pattern occurs in coastal states along the northern shore of the Gulf of Mexico, where topography and other factors combine to make only one noticeable high tide and low tide each day.

The Sun also affects the tides. Although the Sun is much more massive than the Moon, its tidal effect on Earth is smaller because its much greater distance means that the *difference* in the Sun's pull on the near and far sides of Earth is relatively small. The overall tidal force caused by the Sun is a little less than half that caused by the Moon (Figure 4.21). When the tidal forces of the Sun and the Moon work together, as is the case at both new moon and full moon, we get the especially pronounced *spring tides* (so named because the water tends to "spring up" from Earth). When the tidal forces of the Sun and the Moon counteract each other, as is the case at first- and third-quarter moon, we get the relatively small tides known as *neap tides*.

Tidal forces affect not only Earth, but also many other objects. Earth exerts tidal forces on the Moon that explain why the Moon always shows the same face to Earth (see Special Topic on page 103), and in Chapter 8 we'll see how tidal forces have led to the astonishing volcanic activity of Jupiter's moon Io and the possibility of a subsurface ocean on its moon Europa.

think about it Explain why any tidal effects on Earth caused by the other planets would be unnoticeably small.

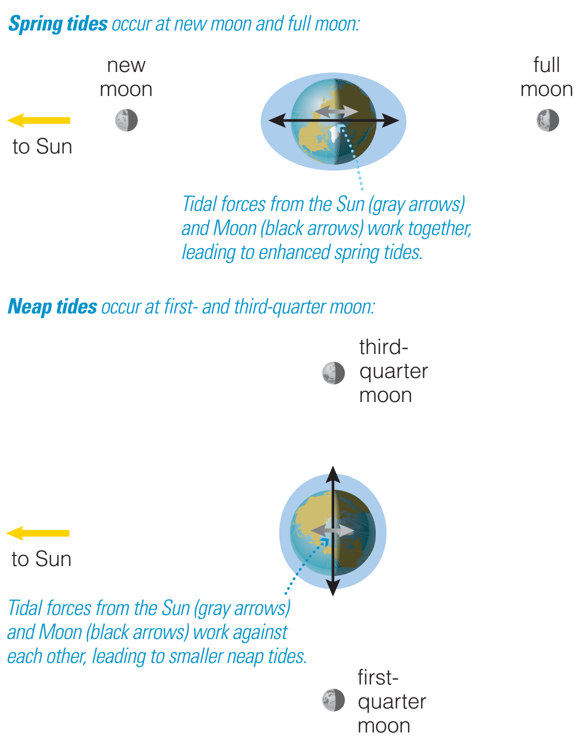


Figure 4.21 MA interactive figure

The Sun exerts a tidal force on Earth less than half as strong as that from the Moon. When the tidal forces from the Sun and Moon work together at new moon and full moon, we get enhanced *spring tides*. When they work against each other, at first- and third-quarter moons, we get smaller *neap tides*.

the big picture

Putting Chapter 4 into Perspective

We've covered a lot of ground in this chapter, from the scientific terminology of motion to the overarching principles that govern motion throughout the universe. Be sure you understand the following "big picture" ideas:

- Understanding the universe requires understanding motion. Motion may seem complex, but it can be described simply using Newton's three laws of motion.
- Today, we know that Newton's laws of motion stem from deeper physical principles, including the laws of conservation of angular momentum and of energy. These principles enable us to understand a wide range of astronomical phenomena.
- Newton also discovered the universal law of gravitation, which explains how gravity holds planets in their orbits and much more—including how satellites can reach and stay in orbit, the nature of tides, and why the Moon rotates synchronously around Earth.
- Newton's discoveries showed that the same physical laws we observe on Earth apply throughout the universe.

summary of key concepts

4.1 Describing Motion: Examples from Daily Life

• How do we describe motion?

Speed is the rate at which an object is moving. **Velocity** is speed in a certain direction. **Acceleration** is a change in velocity, meaning a change in either speed or direction. **Momentum** is mass × velocity. A **force** can change an object's momentum, causing it to accelerate.

• How is mass different from weight?

An object's **mass** is the same no matter where it is located, but its **weight** varies with the strength of gravity or other forces acting on the object. An object becomes **weightless** when it is in **free-fall**, even though its mass is unchanged.

4.2 Newton's Laws of Motion

• How did Newton change our view of the universe?

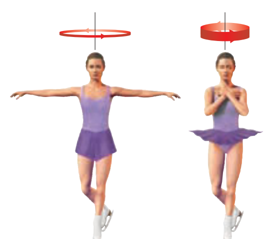
Newton showed that the same physical laws that operate on Earth also operate in the heavens, making it possible to learn about the universe by studying physical laws on Earth.

• What are Newton's three laws of motion?

(1) An object moves at constant velocity if there is no net force acting upon it. (2) Force = mass × acceleration ($F = ma$). (3) For any force, there is always an equal and opposite reaction force.

4.3 Conservation Laws in Astronomy

• What keeps a planet rotating and orbiting the Sun?



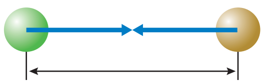
Conservation of angular momentum means that a planet's rotation and orbit cannot change unless it transfers angular momentum to another object. The planets in our solar system do not exchange substantial angular momentum with each other or anything else, so their orbits and rotation rates remain steady.

• Where do objects get their energy?

Energy is always conserved—it can be neither created nor destroyed. Objects received whatever energy they now have from exchanges of energy with other objects. Energy comes in three basic categories—**kinetic, radiative**, and **potential**.

4.4 The Force of Gravity

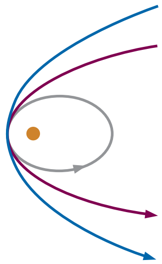
- **What determines the strength of gravity?**



According to the **universal law of gravitation**, every object attracts every other object with a gravitational force that is directly proportional to the product of the objects' masses and declines with the square of the distance between their centers:

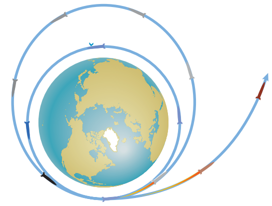
$$F_g = G\frac{M_1 M_2}{d^2}$$

- **How does Newton's law of gravity extend Kepler's laws?**



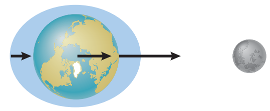
(1) Newton showed that Kepler's first two laws apply to all orbiting objects, not just planets. (2) He showed that elliptical **bound orbits** are not the only possible orbital shape—orbits can also be **unbound** (taking the shape of a parabola or a hyperbola). (3) **Newton's version of Kepler's third law** allows us to calculate the masses of orbiting objects from their orbital periods and distances.

- **How do gravity and energy allow us to understand orbits?**



Gravity determines orbits, and an object cannot change its orbit unless it gains or loses **orbital energy**—the sum of its kinetic and gravitational potential energy—through energy transfer with other objects. If an object gains enough orbital energy, it may achieve **escape velocity** and leave the gravitational influence of the object it was orbiting.

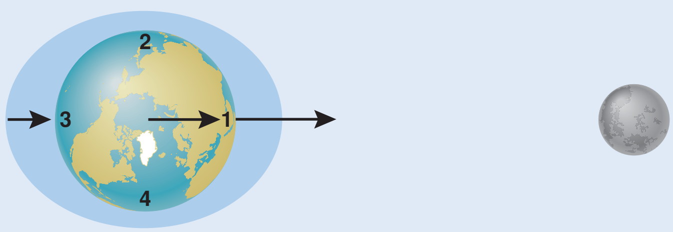
- **How does gravity cause tides?**



The Moon's gravity creates a **tidal force** that stretches Earth along the Earth–Moon line, causing Earth to bulge both toward and away from the Moon. Earth's rotation carries us through the two bulges each day, giving us two daily high tides and two daily low tides.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 4 Visual Quiz at www.masteringastronomy.com.



The figure above, based on Figure 4.19, shows how the Moon causes tides on Earth. Note that the North Pole is in the center of the diagram, so the numbers 1 through 4 label points along Earth's equator.

1. What do the three black arrows represent?
   a. the tidal force Earth exerts on the Moon
   b. the Moon's gravitational force at different points on Earth
   c. the direction in which Earth's water is flowing
   d. Earth's orbital motion
2. Where is it high tide?
   a. Point 1 only b. Point 2 only
   c. Points 1 and 3 d. Points 2 and 4
3. Where is it low tide?
   a. Point 1 only b. Point 2 only
   c. Points 1 and 3 d. Points 2 and 4
4. What time is it at Point 1?
   a. noon b. midnight c. 6 a.m.
   d. cannot be determined from the information in the figure
5. The light blue region represents tidal bulges. In what way are these bulges drawn inaccurately?
   a. There should be only one bulge rather than two.
   b. They should be aligned with the Sun rather than the Moon.
   c. They should be much smaller compared to Earth.
   d. They should be more pointy in shape.

exercises and problems

For instructor-assigned homework go to www.masteringastronomy.com.

Review Questions

1. How does *speed* differ from *velocity?* Give an example in which you can be traveling at constant speed but not at constant velocity.
2. What do we mean by *acceleration?* What is the *acceleration of gravity?* Explain what we mean when we state an acceleration in units of meters per second squared (m/s^2).
3. What is *momentum?* How can momentum be affected by a *force?* What do we mean when we say that momentum can be changed only by a *net force?*
4. What is *free-fall*, and why does it make you *weightless?* Briefly describe why astronauts are weightless in the Space Station.
5. State *Newton's three laws of motion*. For each law, give an example of its application.
6. What are the laws of *conservation of momentum, conservation of angular momentum,* and *conservation of energy?* For each, give an example of how it is important in astronomy.
7. Define *kinetic energy, radiative energy,* and *potential energy*. For each type of energy, give at least two examples of objects that either have it or use it.
8. Define *temperature* and *thermal energy*. How are they related? How are they different?
9. Which has more gravitational potential energy: a rock on the ground or a rock that you hold out the window of a 10-story building? Explain.
10. What do we mean by *mass-energy?* Is it a form of kinetic, radiative, or potential energy? How is the idea of mass-energy related to the formula $E = mc^2$?
11. Summarize the *universal law of gravitation* in words. Then state the law mathematically, explaining the meaning of each symbol in the equation.
12. What is the difference between *bound orbits* and *unbound orbits?*
13. What do we need to know if we want to measure an object's mass with *Newton's version of Kepler's third law?* Explain.
14. Explain why orbits cannot change spontaneously. How can atmospheric drag affect an orbit? How can a *gravitational encounter* cause an orbit to change? How can an object achieve *escape velocity?*
15. Explain how the Moon creates tides on Earth. Why do we have two high and low tides each day?
16. How do the tides vary with the phase of the Moon? Why?

Test Your Understanding

Does It Make Sense?

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

17. If you could buy a pound of chocolate on the Moon, you'd get a lot more chocolate than if you bought a pound on Earth. (*Hint:* Pounds are a unit of weight, not mass.)
18. Suppose you could enter a vacuum chamber (on Earth), that is, a chamber with no air in it. Inside this chamber, if you dropped a hammer and a feather from the same height at the same time, both would hit the bottom at the same time.
19. When an astronaut goes on a space walk outside the Space Station, she will quickly float away from the station unless she has a tether holding her to the station or constantly fires thrusters on her space suit.
20. I used Newton's version of Kepler's third law to calculate Saturn's mass from orbital characteristics of its moon Titan.
21. If the Sun were magically replaced with a giant rock that had precisely the same mass, Earth's orbit would not change.
22. The fact that the Moon rotates once in precisely the time it takes to orbit Earth once is such an astonishing coincidence that scientists probably never will be able to explain it.
23. Venus has no oceans, so it could not have tides even if it had a moon (which it doesn't).
24. If an asteroid passed by Earth at just the right distance, Earth's gravity would capture it and make it our second moon.
25. When I drive my car at 30 miles per hour, it has more kinetic energy than it does at 10 miles per hour.
26. Someday soon, scientists are likely to build an engine that produces more energy than it consumes.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

27. Which one of the following describes an object that is accelerating? (a) a car traveling on a straight, flat road at 50 miles per hour (b) a car traveling on a straight uphill road at 30 miles per hour (c) a car going around a circular track at a steady 100 miles per hour
28. Suppose you visited another planet: (a) Your mass and weight would be the same as they are on Earth. (b) Your mass would be the same as on Earth, but your weight would be different. (c) Your weight would be the same as on Earth, but your mass would be different.
29. Which person is weightless? (a) a child in the air as she plays on a trampoline (b) a scuba diver exploring a deep-sea wreck (c) an astronaut on the Moon
30. Consider the statement "There's no gravity in space." This statement is (a) completely false. (b) false if you are close to a planet or moon, but true in between the planets. (c) completely true.
31. To make a rocket turn left, you need to (a) fire an engine that shoots out gas to the left. (b) fire an engine that shoots out gas to the right. (c) spin the rocket clockwise.
32. Compared to its angular momentum when it is farthest from the Sun, Earth's angular momentum when it is nearest to the Sun is (a) greater. (b) less. (c) the same.
33. The gravitational potential energy of a contracting interstellar cloud (a) stays the same at all times. (b) gradually transforms into other forms of energy. (c) gradually grows larger.
34. If Earth were twice as far from the Sun, the force of gravity attracting Earth to the Sun would be (a) twice as strong. (b) half as strong. (c) one-quarter as strong.
35. According to the law of universal gravitation, what would happen to Earth if the Sun were somehow replaced by a black hole of the same mass? (a) Earth would be quickly sucked into the

black hole. (b) Earth would slowly spiral into the black hole. (c) Earth's orbit would not change.

36. If the Moon were closer to Earth, high tides would (a) be higher than they are now. (b) be lower than they are now. (c) occur three or more times a day rather than twice a day.

Process of Science

37. *Testing Gravity.* Scientists are constantly trying to learn whether our current understanding of gravity is complete or must be modified. Describe how the observed motion of spacecraft headed out of the solar system (such as the *Voyager* spacecraft) can be used to test the accuracy of our current theory of gravity.
38. *How Does the Table Know?* Thinking deeply about seemingly simple observations sometimes reveals underlying truths that we might otherwise miss. For example, think about holding a golf ball in one hand and a bowling ball in the other. To keep them motionless, you must actively adjust the tension in your arm muscles so that each arm exerts a different upward force that exactly balances the weight of each ball. Now, think about what happens when you set the balls on a table. Somehow, the table exerts exactly the right amount of upward force to keep the balls motionless, even though their weights are very different. How does a table "know" to make the same type of adjustment that you make consciously when you hold the balls motionless in your hands? (*Hint:* Think about the origin of the force pushing upward on the objects.)

Group Work Exercise

39. *Your Ultimate Energy Source.* According to the law of conservation of energy, the energy your body is using right now had to come from somewhere else. Your task in this exercise is to trace the flow of that energy as far back in time as you can. Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Proposer* (proposes explanations to the group), *Skeptic* (points out weaknesses in proposed explanations), and *Moderator* (leads group discussion and makes sure the group works as a team). After you have your roles, make a list going backwards in time describing how the energy you are using right now has proceeded through time. Then, for each item on the list, state whether that energy was in the form of kinetic energy, gravitational potential energy, chemical potential energy, electrical potential energy, mass-energy, or radiative energy.

Investigate Further

Short-Answer/Essay Questions

40. *Weightlessness.* Astronauts are weightless when in orbit in the Space Shuttle. Are they also weightless during the Shuttle's launch? How about during its return to Earth? Explain.
41. *Einstein's Famous Formula.*
    a. What is the meaning of the formula $E = mc^2$? Be sure to define each variable.
    b. How does this formula explain the generation of energy by the Sun?
    c. How does this formula explain the destructive power of nuclear bombs?
42. *The Gravitational Law.*
    a. How does quadrupling the distance between two objects affect the gravitational force between them?
    b. Suppose the Sun were somehow replaced by a star with twice as much mass. What would happen to the gravitational force between Earth and the Sun?
    c. Suppose Earth were moved to one-third of its current distance from the Sun. What would happen to the gravitational force between Earth and the Sun?
43. *Allowable Orbits?*
    a. Suppose the Sun were replaced by a star with twice as much mass. Could Earth's orbit stay the same? Why or why not?
    b. Suppose Earth doubled in mass (but the Sun stayed the same as it is now). Could Earth's orbit stay the same? Why or why not?
44. *Head-to-Foot Tides.* You and Earth attract each other gravitationally, so you should also be subject to a tidal force resulting from the difference between the gravitational attraction felt by your feet and that felt by your head (at least when you are standing). Explain why you can't feel this tidal force.

Quantitative Problems

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

45. *Energy Comparisons.* Use the data in Table 4.1 to answer each of the following questions.
    a. Compare the energy of a 1-megaton H-bomb to the energy released by a major earthquake.
    b. If the United States obtained all its energy from oil, how much oil would be needed each year?
    c. Compare the Sun's annual energy output to the energy released by a supernova.
46. *Fusion Power.* No one has yet succeeded in creating a commercially viable way to produce energy through nuclear fusion. However, suppose we could build fusion power plants using the hydrogen in water as a fuel. Based on the data in Table 4.1, how much water would we need each minute to meet U.S. energy needs? Could such a reactor power the entire United States with the water flowing from your kitchen sink? Explain. (*Hint:* Use the annual U.S. energy consumption to find the energy consumption per minute, and then divide by the energy yield from fusing 1 liter of water to figure out how many liters would be needed each minute.)
47. *Understanding Newton's Version of Kepler's Third Law I.* Imagine another solar system, with a star of the same mass as the Sun. Suppose there is a planet in that solar system with a mass twice that of Earth orbiting at a distance of 1 AU from the star. What is the orbital period of this planet? Explain. (*Hint:* The calculations for this problem are so simple that you will not need a calculator.)
48. *Understanding Newton's Version of Kepler's Third Law II.* Suppose a solar system has a star that is four times as massive as our Sun. If that solar system has a planet the same size as Earth orbiting at a distance of 1 AU, what is the orbital period of the planet? Explain. (*Hint:* The calculations for this problem are so simple that you will not need a calculator.)
49. *Using Newton's Version of Kepler's Third Law I.*
    a. The Moon orbits Earth in an average time of 27.3 days at an average distance of 384,000 km. Use these facts to determine the mass of Earth. (*Hint:* You may neglect the mass of the Moon, since its mass is only about $\frac{1}{80}$ of Earth's.)

b. Jupiter's moon Io orbits Jupiter every 42.5 hours at an average distance of 422,000 km from the center of Jupiter. Calculate the mass of Jupiter. (*Hint:* Io's mass is very small compared to Jupiter's.)

c. You discover a planet orbiting a distant star that has about the same mass as the Sun. Your observations show that the planet orbits the star every 63 days. What is its orbital distance?

50. *Using Newton's Version of Kepler's Third Law II.*

a. Pluto's moon Charon orbits Pluto every 6.4 days with a semi-major axis of 19,700 kilometers. Calculate the *combined* mass of Pluto and Charon. Compare this combined mass to the mass of Earth, which is about 6×10^{24} kg.

b. Calculate the orbital period of the Space Shuttle in an orbit 300 kilometers above Earth's surface.

c. The Sun orbits the center of the Milky Way Galaxy every 230 million years at a distance of 28,000 light-years. Use these facts to determine the mass of the galaxy. (As we'll discuss in Chapter 14, this calculation actually tells us only the mass of the galaxy *within* the Sun's orbit.)

Discussion Questions

51. *Knowledge of Mass-Energy.* Einstein's discovery that energy and mass are equivalent has led to technological developments that are both beneficial and dangerous. Discuss some of these developments. Overall, do you think the human race would be better or worse off if we had never discovered that mass is a form of energy? Defend your opinion.

52. *Perpetual Motion Machines.* Every so often, someone claims to have built a machine that can generate energy perpetually from nothing. Why isn't this possible according to the known laws of nature? Why do you think claims of perpetual motion machines sometimes receive substantial media attention?

Web Projects

53. *Space Station.* Visit a NASA site with pictures from the Space Station. Choose two photos that illustrate some facet of Newton's laws. Explain how Newton's laws apply to each photo.

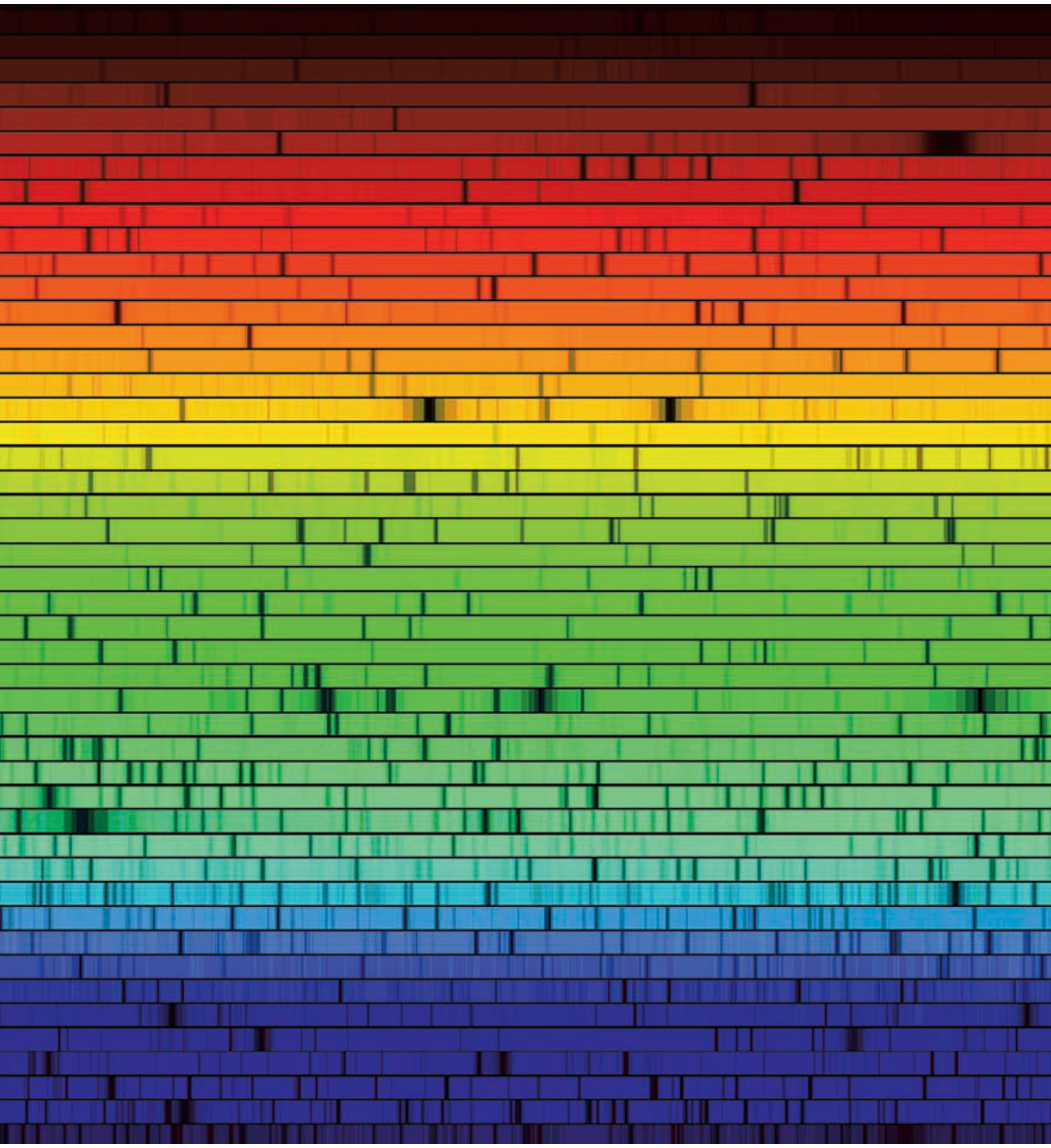
54. *Energy Comparisons.* Using information from the U.S. Energy Information Administration Web site, choose some aspect of national or international energy use that interests you. Write a short report on the topic.

55. *Nuclear Power.* There are two basic ways to generate energy from atomic nuclei: through nuclear fission (splitting nuclei) and through nuclear fusion (combining nuclei). All current nuclear reactors are based on fission, but using fusion would have many advantages if we could develop the technology. Research some of the advantages of fusion and some of the obstacles to developing fusion power. Do you think fusion power will be a reality in your lifetime? Explain.

5

Light

The Cosmic Messenger



learning goals

5.1 Basic Properties of Light and Matter
- What is light?
- What is matter?
- How do light and matter interact?

5.2 Learning from Light
- What are the three basic types of spectra?
- How does light tell us what things are made of?
- How does light tell us the temperatures of planets and stars?
- How does light tell us the speed of a distant object?

5.3 Collecting Light with Telescopes
- How do telescopes help us learn about the universe?
- Why do we put telescopes in space?
- How is technology revolutionizing astronomy?

Ancient observers could discern only the most basic features of the light that they saw, such as color and brightness. Over the past several hundred years, we have discovered that light carries far more information. Today, we can analyze the light of distant objects to learn what they are made of, how hot they are, how fast they are moving, and much more. Light is truly the cosmic messenger, bringing the stories of distant objects to Earth.

Understanding the messages carried by light requires familiarity with the way light and matter interact. In this chapter, we'll explore the basic properties of light and matter that allow us to learn so much about the universe by studying light from distant objects. We'll also discuss how telescopes are used to collect light, and the technologies that make telescopes so much more powerful than our eyes.

essential preparation

1. How did Galileo solidify the Copernican revolution? [Section 3.3]
2. What are Newton's three laws of motion? [Section 4.2]
3. Where do objects get their energy? [Section 4.3]

MA Light and Spectroscopy Tutorial, Lesson 1

5.1 Basic Properties of Light and Matter

The photograph that opens this chapter shows a detailed view of the Sun's **spectrum**—the light from the Sun as it appears when we pass it through a prism or similar device. The rainbow of color, which stretches in horizontal rows from the upper left to the lower right of the photograph, probably reminds you of what we see whenever we pass white light through a prism (Figure 5.1). However, notice that the Sun's spectrum is not a pure rainbow. Instead, its spectrum shows hundreds of dark lines, representing places where a small piece of the rainbow is missing from the sunlight. All the features of the spectrum, including the rainbow and the dark lines, are created by interactions between light and matter in the Sun. Careful study of these features can tell us the Sun's chemical composition, its temperature, the motions of its atmosphere, and more.

We see similar dark or bright lines when we look at almost any spectrum in detail, whether it is the spectrum of the flame from a backyard gas grill or the spectrum of a distant galaxy whose light we collect with a gigantic telescope. As long as we collect enough light to see details in the spectrum, we can learn many fundamental properties of the object we are viewing, no matter how far away it is located.

Our primary goal in this chapter is to understand how we can learn about distant objects from their spectra. First, however, we must explore the nature of light and matter.

• What is light?

Light is familiar to all of us, but its nature remained a mystery until quite recently in human history. Experiments performed by Isaac Newton in the 1660s provided the first real insights into the nature of light. It was already known that passing white light through a prism produced a rainbow of color, but many people thought the colors came from the prism rather than from the light itself. Newton proved that the colors came from the light by placing a second prism in front of the light of just one

Figure 5.1

When we pass white light through a prism, it disperses into a rainbow of color that we call a *spectrum*.

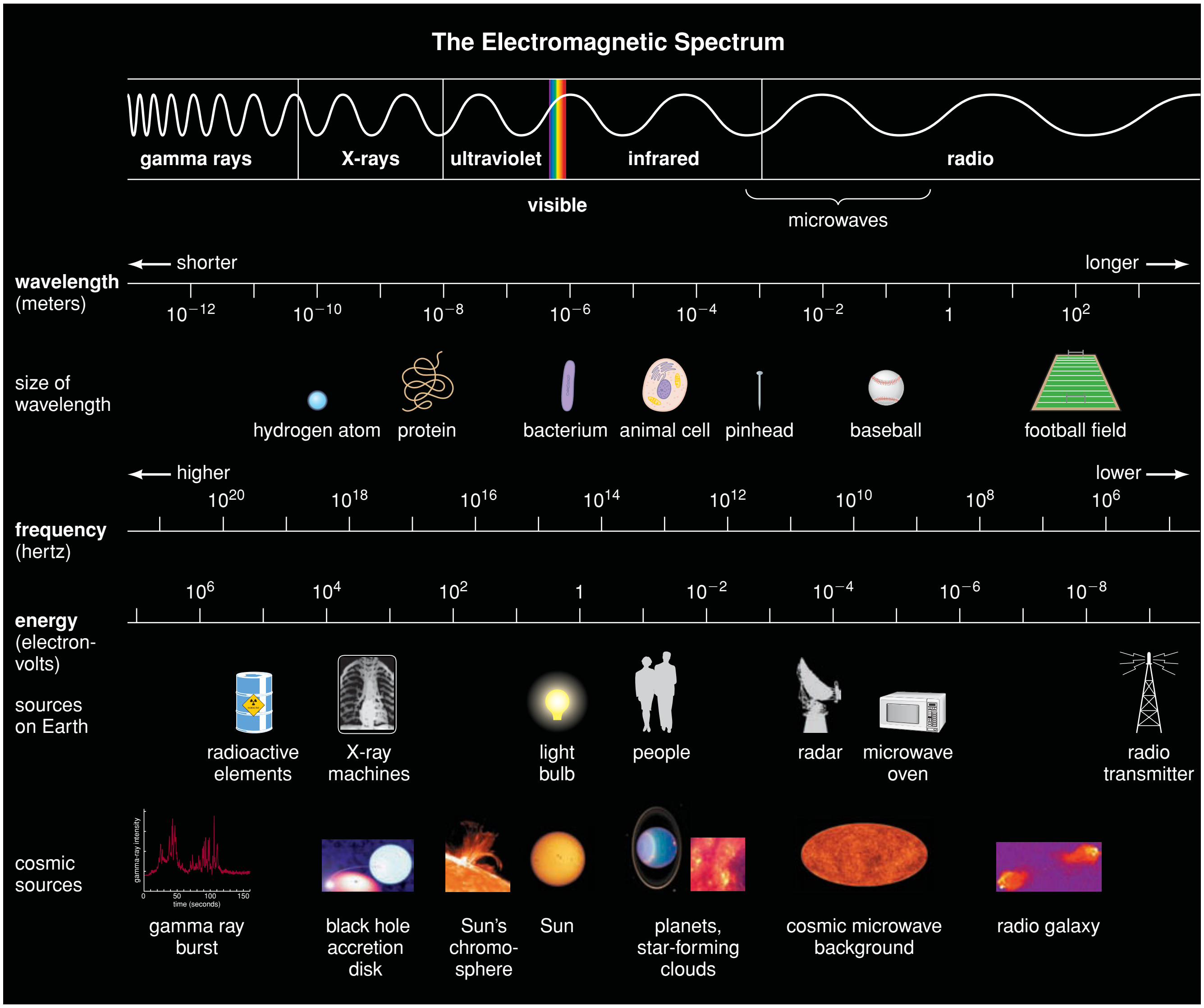


Figure 5.2 MA interactive figure

The electromagnetic spectrum. Notice that wavelength increases as we go from gamma rays to radio waves, while frequency and energy increase in the opposite direction.

color, such as red, from the first prism. If the rainbow of color came from the prism itself, the second prism would have produced a rainbow just like the first. But it did not: When only red light entered the second prism, only red light emerged, proving that the color was a property of the light and not of the prism.

Light is also known as electromagnetic radiation.

Newton's experiment proved that *white* light is actually a mix of all the colors in the rainbow. Later scientists found that there is light "beyond the rainbow" as well. Just as there are sounds that our ears cannot hear (such as the sound of a dog whistle), there is light that our eyes cannot see. In fact, the **visible light** that splits into the rainbow of color is only a tiny part of the complete spectrum of light. Figure 5.2 shows this complete spectrum, usually called the **electromagnetic spectrum**. Light itself is often called **electromagnetic radiation**. Let's investigate why.

Wave Properties of Light You've probably heard that light is a wave, but what exactly does that mean? In general, a wave is something that can transmit energy without carrying material along with it.

For example, you can make waves move along a rope by shaking one end of it up and down (Figure 5.3a). The shaking creates a series of peaks and troughs that move along the rope, making every piece of the rope bob up and down as the peaks and troughs go by. We define the **wavelength** as the distance between adjacent peaks and the **frequency** as the number of times that any piece of the rope moves up and down each second. For example, if a piece of the rope moves up and down three times each second, we say the wave has a frequency of three cycles per second, or three *hertz* for short. Notice that the rope itself stays intact as the wave moves along it, showing that it is energy and not material that is moving with the wave.

Light is different from waves on a rope because we cannot see anything moving up and down as it travels. However, we can tell that light is a wave from its effect on matter. If you could set up a row of electrically charged particles such as electrons, it would wriggle like a snake as a wave of light passed by (Figure 5.3b). The distance between adjacent peaks in this row of electrons would tell us the wavelength of the light wave, while the number of times each electron bobbed up and down would tell us the frequency (Figure 5.3c). Because light can affect both electrically charged particles and magnets, we say that light is an **electromagnetic wave**—which is why light is called *electromagnetic radiation* and the spectrum of light is called the *electromagnetic spectrum*.

The longer the wavelength of light, the lower its frequency and energy.

All light travels through empty space at the same speed—the **speed of light**—which is about 300,000 kilometers per second. Because the speed of any wave is its wavelength times its frequency, we find an important relationship between wavelength and frequency for light: *The longer the wavelength, the lower the frequency, and vice versa* (Figure 5.4). For example, gamma rays have the shortest wavelengths and the highest frequencies of any form of light (see Figure 5.2).

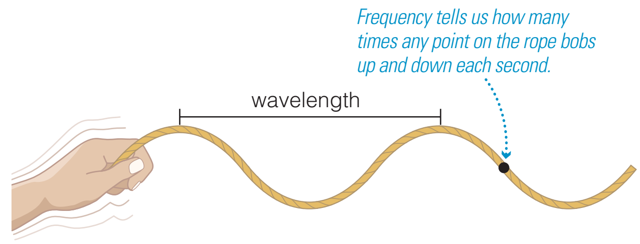
Particle Properties of Light In everyday life, waves seem to be quite different from particles. A wave exists only as a pattern of motion with a wavelength and a frequency, while a particle is a "thing" such as a marble, a baseball, or an individual atom. However, experiments show that light can behave both as a wave and as a particle.

Light comes in "pieces" called photons, each with a precise wavelength, frequency, and energy.

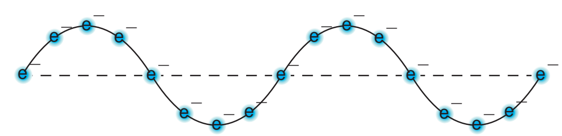
The idea that light can be both a wave and a particle may seem quite strange, but it is fundamental to our modern understanding of physics. We think of light as consisting of many individual "pieces," or **photons**. Like baseballs, photons of light can be counted individually and can hit a wall one at a time. Like waves, each photon travels at the speed of light and is characterized by a wavelength and frequency. Moreover, each photon carries a particular amount of energy that depends on its frequency: the higher the frequency of the photon, the more energy it carries. That is why energy increases in the same direction as frequency in Figure 5.2.

think about it How does the energy of a photon depend on its wavelength? Briefly explain why.

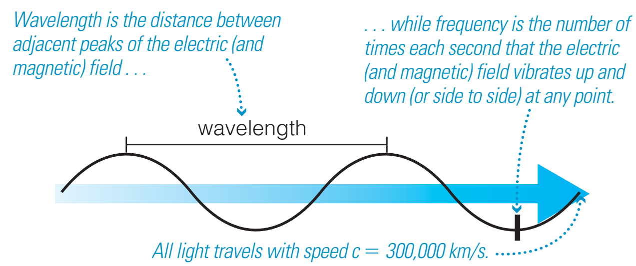
The Many Forms of Light Figure 5.2 also shows that we give special names to different portions of the electromagnetic spectrum. Visible light has wavelengths ranging from about 400 nm at the blue or violet end of



a Shaking one end of a rope up and down generates waves moving along it. All waves are characterized by a wavelength and a frequency.



b If you could line up electrons, they would wriggle up and down as light passes by, demonstrating that light is a wave.



c Light can affect both electrically charged particles and magnets, so we say that light is an *electromagnetic wave.*

Figure 5.3 MA interactive figure

These diagrams explain the wave properties of light.

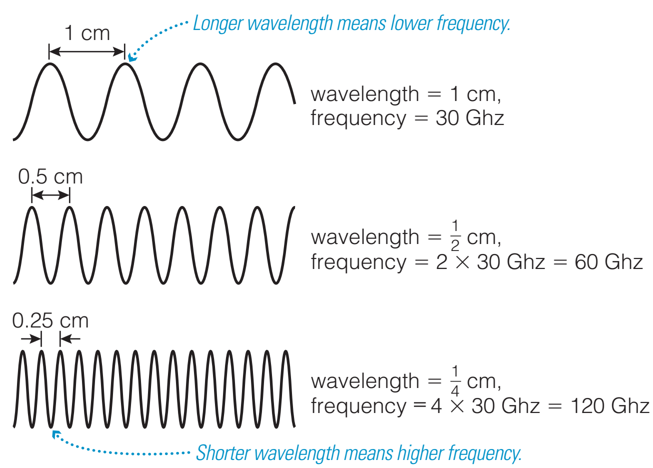


Figure 5.4

Because all light travels through space at the same speed, light of longer wavelength must have lower frequency, and vice versa. (GHz stands for gigahertz, or 10^9 hertz.)

common Misconceptions

Is Radiation Dangerous?

Many people associate the word *radiation* with danger. However, the word *radiate* simply means "to spread out from a center" (note the similarity between *radiation* and *radius* [of a circle]). Radiation is energy being carried through space. If energy is being carried by particles of matter, such as protons or neutrons, we call it *particle radiation*. If energy is being carried by light, we call it *electromagnetic radiation*.

High-energy forms of radiation, such as particles from radioactive materials or X rays, are dangerous because they can penetrate body tissues and cause cell damage. Low-energy forms of radiation, such as radio waves, are usually harmless. The visible-light radiation from the Sun sustains life on Earth. Thus, while some forms of radiation are dangerous, others are harmless or beneficial.

common Misconceptions

Can You Hear Radio or See an X Ray?

Most people associate the term *radio* with sound, but radio waves are a form of *light* with long wavelengths—too long for our eyes to see. Radio stations encode sounds (such as voices and music) as electrical signals, which they broadcast as radio waves. What we call "a radio" in daily life is an electronic device that receives these radio waves and decodes them to re-create the sounds played at the radio station. Televisions, cell phones, and other wireless devices also work by encoding and decoding information in the form of light called radio waves.

X rays are also a form of light, with wavelengths far too short for our eyes to see. In a doctor's or dentist's office, a special machine works somewhat like the flash on an ordinary camera but emits X rays instead of visible light. This machine flashes the X rays at you, and a piece of photographic film or an electronic detector records the X rays that are transmitted through your body. You never see the X rays themselves—you see only the image recorded by the film or detector.

the rainbow to about 700 nm at the red end. (A nanometer [nm] is a billionth of a meter.) Light with wavelengths somewhat longer than red light is called **infrared**, because it lies beyond the red end of the rainbow. **Radio waves** are the longest-wavelength light. That is, radio waves are a form of light, *not* a form of sound. The region near the border between infrared and radio waves, where wavelengths range from micrometers to millimeters, is sometimes given the name **microwaves**.

On the other side of the spectrum, light with wavelengths somewhat shorter than blue light is called **ultraviolet**, because it lies beyond the blue (or violet) end of the rainbow. Light with even shorter wavelengths is called **X rays**, and the shortest-wavelength light is called **gamma rays**. Notice that visible light is an extremely small part of the entire electromagnetic spectrum: The reddest red that our eyes can see has only about twice the wavelength of the bluest blue, but the radio waves from your favorite radio station are a billion times as long as the X rays used in a doctor's office.

Radio waves, microwaves, infrared, visible light, ultraviolet, X rays, and gamma rays are all forms of light.

The different energies of different forms of light explain many familiar effects in everyday life. Radio waves carry so little energy that they have no noticeable effect on our bodies. However, radio waves can make electrons move up and down in an antenna, which is how your car radio receives the radio waves coming from a radio station. Molecules moving around in a warm object emit infrared light, which is why we sometimes associate infrared light with heat. Receptors in our eyes respond to visible-light photons, making vision possible. Ultraviolet photons carry enough energy to harm cells in our skin, causing sunburn or skin cancer. X-ray photons have enough energy to penetrate through skin and muscle but can be blocked by bones or teeth. That is why doctors and dentists can see our bone and tooth structures in images taken with X-ray light.

• What is matter?

Light carries information about matter across the universe, but we are usually more interested in the matter the light is coming from than we are in the light itself. Planets, stars, and galaxies are made of matter, and we must understand the nature of matter if we are to decode the messages we receive in light.

Like the nature of light, the nature of matter remained mysterious for most of human history. The ancient Greeks imagined that all material was made of four elements: fire, water, earth, and air. Some Greeks, beginning with the philosopher Democritus (c. 470–380 B.C.), further imagined that these four elements came in the form of tiny particles they called *atoms*, a Greek term meaning "indivisible." Our modern ideas of atoms differ in many details from the ideas of the ancient Greeks. For example, we now know of more than 100 types of atoms, or chemical **elements**, and fire, water, earth, and air are *not* among them. Some of the most familiar elements are hydrogen, helium, carbon, oxygen, silicon, iron, gold, silver, lead, and uranium. (See Appendix D for a complete list.)

Atomic Structure Each chemical element represents a different type of atom, and atoms are in turn made of particles that we call **protons**, **neutrons**, and **electrons** (Figure 5.5). Protons and neutrons are found in the tiny **nucleus** at the center of the atom. The rest of the atom's volume contains the electrons that surround the nucleus. Although the nucleus is very small compared to the atom as a whole, it contains most of the atom's mass, because protons and neutrons are each about 2000 times as massive as an electron. Note that atoms are incredibly small: Millions could fit end to end across the period at the end of this sentence. The number of atoms in a single drop of water (typically, 10^{22} to 10^{23} atoms) may exceed the number of stars in the observable universe.

The chemical elements are made of atoms, which in turn are made of protons, neutrons, and electrons.

The properties of an atom depend mainly on the **electrical charge** in its nucleus. Electrical charge is a fundamental physical property that describes how strongly an object will interact with electromagnetic fields; total electrical charge is always conserved, just as energy is always conserved. We define the electrical charge of a proton as the basic unit of positive charge, which we write as $+1$. An electron has an electrical charge that is precisely opposite that of a proton, so we say it has negative charge (-1). Neutrons are electrically neutral, meaning that they have no charge.

Oppositely charged particles attract one another, and similarly charged particles repel one another. The attraction between the positively charged protons in the nucleus and the negatively charged electrons that surround it is what holds an atom together. Ordinary atoms have identical numbers of electrons and protons, making them electrically neutral overall. (You may wonder why electrical repulsion doesn't cause the positively charged protons in a nucleus to fly apart from one another. The answer is that an even stronger force, called the *strong force*, overcomes electrical repulsion and holds the nucleus together **[Section 10.2]**.)

Although we can think of electrons as tiny particles, they are not quite like tiny grains of sand and they don't orbit the nucleus the way planets orbit the Sun. Instead, the electrons in an atom form a kind of "smeared out" cloud that surrounds the nucleus and gives the atom its apparent size. The electrons aren't really cloudy, but it is impossible to pinpoint their positions in the atom. In Figure 5.5, you can see that the electrons give the atom a size far larger than its nucleus even though they represent only a tiny portion of the atom's mass. If we imagine an atom on a scale that makes its nucleus the size of your fist, its electron cloud would be many kilometers wide.

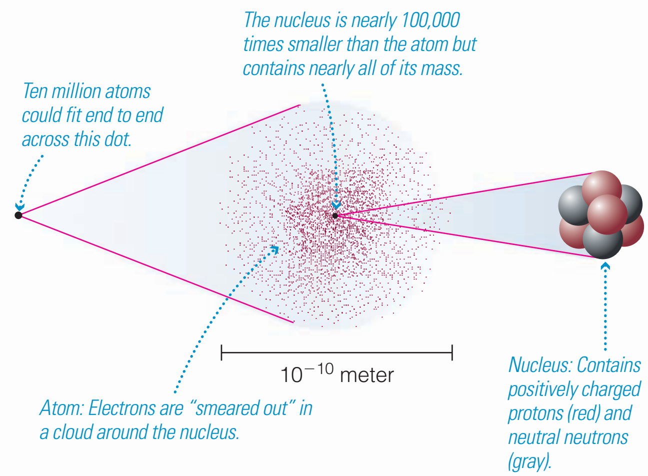


Figure 5.5

The structure of a typical atom. Notice that atoms are extremely tiny: The atom shown in the middle is magnified to about 1 billion times its actual size, and the nucleus on the right is magnified to about 100 trillion times its actual size.

Atomic Terminology

You've probably learned the basic terminology of atoms in past science classes, but let's review it just to be sure. Figure 5.6 summarizes the key terminology we will use in this book.

Atoms of different chemical elements have different numbers of protons.

Each different chemical element contains a different number of protons in its nucleus. This number is its **atomic number**. For example, a hydrogen nucleus contains just one proton, so its atomic number is 1. A helium nucleus contains two protons, so its atomic number is 2. The *combined* number of protons and neutrons in an atom is called its **atomic mass number**. The atomic mass number of ordinary hydrogen is 1 because its nucleus is just a single proton. Helium usually has two neutrons in addition to its two protons, giving it an atomic mass number of 4. Carbon usually has six protons and six neutrons, giving it an atomic mass number of 12.

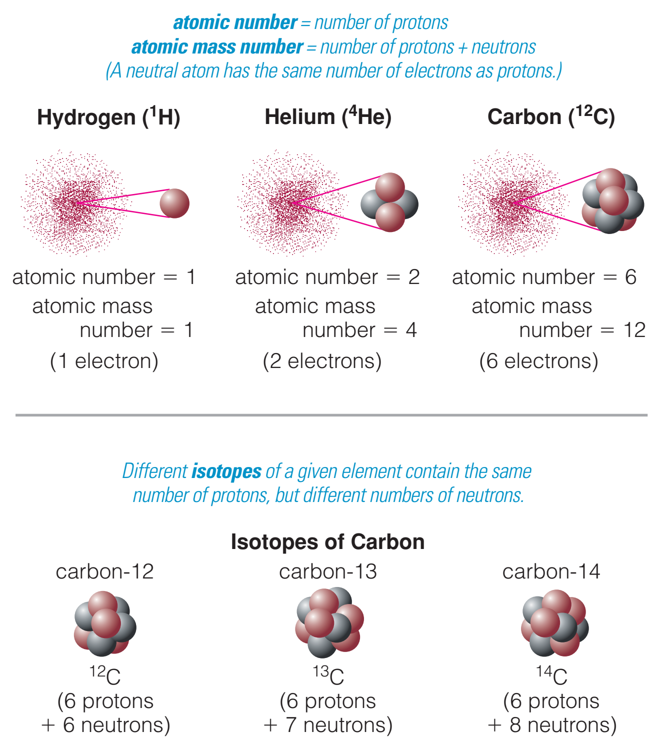


Figure 5.6

Terminology of atoms.

common Misconceptions

The Illusion of Solidity

Bang your hand on a table. Although the table feels solid, it is made almost entirely of empty space! Nearly all the mass of the table is contained in the nuclei of its atoms. But the volume of an atom is more than a trillion times the volume of its nucleus, so the nuclei of adjacent atoms are nowhere near to touching one another. The solidity of the table comes about from a combination of electrical interactions between the charged particles in its atoms and the strange quantum laws governing the behavior of electrons. If we could somehow pack all the table's nuclei together, the table's mass would fit into a microscopic speck. Although we cannot pack matter together in this way, nature can and does—in *neutron stars*, which we will study in Chapter 13.

Every atom of a given element contains exactly the same number of protons, but the number of neutrons can vary. For example, all carbon atoms have six protons, but they may have six, seven, or eight neutrons. Versions of an element with different numbers of neutrons are called **isotopes** of that element. Isotopes are named by listing their element name and atomic mass number. For example, the most common isotope of carbon has 6 protons and 6 neutrons, giving it atomic mass number 6 + 6 = 12, so we call it carbon-12. The other isotopes of carbon are carbon-13 (six protons and seven neutrons) and carbon-14 (six protons and eight neutrons). We can also write the atomic mass number of an isotope as a superscript to the left of the element symbol: ^{12}C, ^{13}C, ^{14}C. We read ^{12}C as "carbon-12."

Isotopes of a particular chemical element all have the same number of protons but different numbers of neutrons.

think about it The symbol ^{4}He represents helium with an atomic mass number of 4. ^{4}He is the most common form of helium, containing two protons and two neutrons. What does the symbol ^{3}He represent?

The number of different material substances is far greater than the number of chemical elements because atoms can combine to form **molecules**. Some molecules consist of two or more atoms of the same element. For example, we breathe O_2, oxygen molecules made of two oxygen atoms. Other molecules, such as water, are made up of atoms of two or more different elements. The symbol H_2O tells us that a water molecule contains two hydrogen atoms and one oxygen atom. The chemical properties of a molecule are different from those of its individual atoms. For example, water behaves very differently than pure hydrogen or pure oxygen.

• How do light and matter interact?

Now that we have discussed the nature of light and of matter individually, we are ready to explore how light and matter interact. Energy carried by light can interact with matter in four general ways:

- **Emission:** A light bulb *emits* visible light; the energy of the light comes from electrical potential energy supplied to the bulb.
- **Absorption:** When you place your hand near an incandescent light bulb, your hand *absorbs* some of the light, and this absorbed energy warms your hand.
- **Transmission:** Some forms of matter, such as glass or air, *transmit* light, which means allowing it to pass through.
- **Reflection/scattering:** Light can bounce off matter, leading to what we call *reflection* (when the bouncing is all in the same general direction) or *scattering* (when the bouncing is more random).

Matter can emit, absorb, transmit, or reflect light.

Materials that transmit light are said to be *transparent*, and materials that absorb light are called *opaque*. Many materials are neither perfectly transparent nor perfectly opaque. For example, dark sunglasses and clear eyeglasses are both partially transparent, but the dark glasses absorb more light and transmit less. Materials can also affect different colors of light differently. For example, red glass transmits red light but absorbs other colors, while a green lawn reflects (scatters) green light but absorbs all other colors.

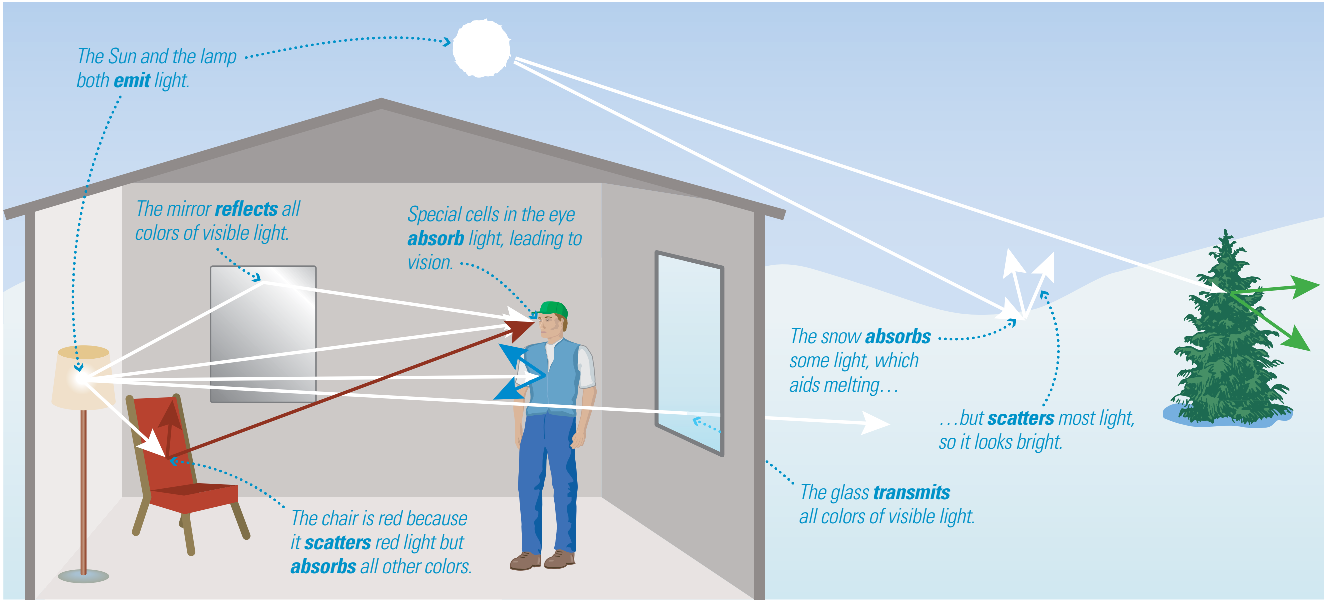


Figure 5.7 MA interactive figure

This diagram shows examples of the four basic interactions between light and matter: emission, absorption, transmission, and reflection (or scattering).

Let's put these ideas together to understand what happens when you walk into a room and turn on the light switch (Figure 5.7). The light bulb begins to emit white light, which is a mix of all the colors in the visible spectrum. Some of this light exits the room, transmitted through the windows. The rest of the light strikes the surfaces of objects inside the room, and the material properties of each object determine the colors it absorbs or reflects. The light coming from each object therefore carries an enormous amount of information about the object's location, shape and structure, and composition. You acquire this information when light enters your eyes, where special cells in your retina absorb it and send signals to your brain. Your brain interprets the messages that light carries, recognizing materials and objects in the process we call *vision*.

5.2 Learning from Light

Light carries much more information than our naked eyes can recognize. Modern instruments can reveal otherwise hidden details in the spectrum of light, and specially equipped telescopes can record forms of light that are invisible to our eyes. In this section, we'll learn how detailed studies of light help us unlock the secrets of the universe. Let's start with the basic types of spectra and how they are produced, and then we will be ready to see what we can learn from them.

MA Light and Spectroscopy Tutorial, Lessons 2–4

• What are the three basic types of spectra?

Laboratory studies show that spectra come in three basic types,* summarized in Figure 5.8:

1. The spectrum of an ordinary (incandescent) light bulb is a rainbow of color. Because the rainbow spans a broad range of wavelengths without interruption, we call it a **continuous spectrum**.

*The rules that specify the conditions producing each type are often called *Kirchhoff's laws*.

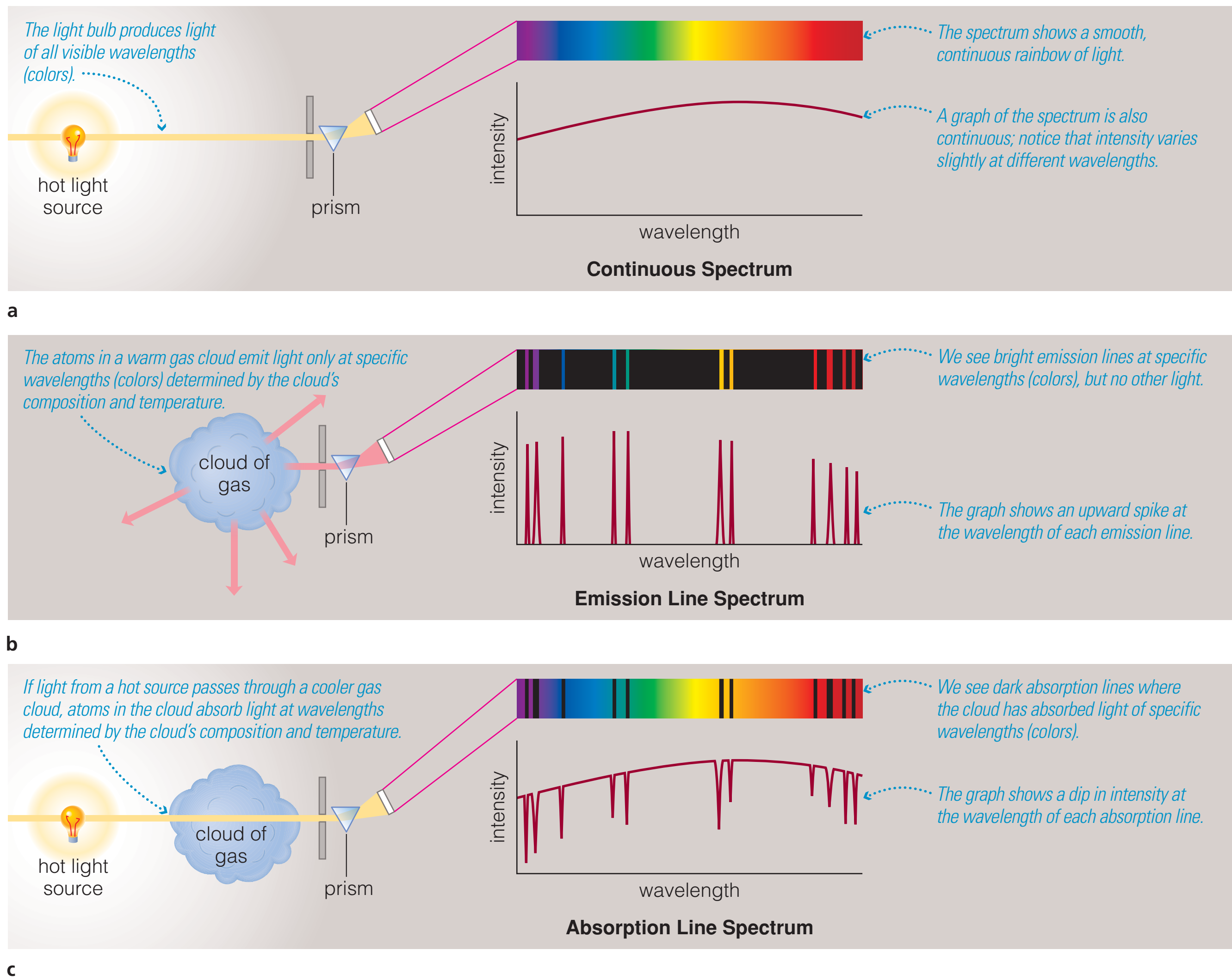


Figure 5.8 MA interactive figure

These diagrams show examples of the conditions under which we see the three basic types of spectra.

2. A thin or low-density cloud of gas does not produce a continuous spectrum. Instead, it emits light only at specific wavelengths that depend on its composition and temperature. The spectrum therefore consists of bright **emission lines** against a black background and is called an **emission line spectrum**.
3. If the cloud of gas lies between us and a light bulb, we still see most of the continuous light emitted by the light bulb. However, the cloud absorbs light of specific wavelengths, so that the spectrum shows dark **absorption lines** over the background rainbow from the light bulb.* We call this an **absorption line spectrum**.

There are three basic types of spectra: continuous, emission line, and absorption line.

As you study Figure 5.8, notice that each of the spectra is shown both as a band of light and as a graph. The band of light is essentially what you would see if you projected the light that passes through the prism onto a wall. The graph shows the amount, or **intensity**, of the light at each wavelength in the spectrum. The intensity is high at wavelengths where there is a lot of light and low where there is little light. For example, notice how the graph of the absorption line spectrum shows dips in

*More technically, we'll see an absorption line spectrum as long as the cloud is cooler in temperature than the source of background light (the light bulb filament in this case).

intensity at the wavelengths where the band of light shows dark lines. Astronomers usually display spectra as graphs because they make it easier to tell how the precise intensity of the light varies across the spectrum.

We can apply the ideas of Figure 5.8 to the solar spectrum that opens this chapter. Notice that it shows numerous absorption lines over a background rainbow of colors. This tells us that we are essentially looking at a hot light source through gas that is absorbing some of the colors, much as we see when looking through the cloud of gas to the light bulb in Figure 5.8c. For the solar spectrum, the hot light source is the hot interior of the Sun, while the "cloud" is the relatively cool and low-density layer of gas that makes up the Sun's visible surface, or *photosphere* **[Section 10.1]**.

• How does light tell us what things are made of?

We have just seen *how* different viewing conditions lead to different types of spectra, so we are now ready to discuss *why*. Let's start with absorption and emission line spectra. As we'll see, the positions of the lines in these spectra can tell us what distant objects are made of.

Energy Levels in Atoms To understand why we sometimes see emission and absorption lines, we must first discuss a strange fact about electrons in atoms: The electrons can have only particular amounts of energy, and not other energies in between. As an analogy, suppose you're washing windows on a building. If you use an adjustable platform to reach high windows, you can stop the platform at any height above the ground. But if you use a ladder, you can stand only at *particular* heights—the heights of the rungs of the ladder—and not at any height in between. The possible energies of electrons in atoms are like the possible heights on a ladder. Only a few particular energies are possible, and energies between these special few are not possible. The possible energies are known as the **energy levels** of an atom.

Electrons in atoms can have only particular amounts of energy, and not other energies in between.

Figure 5.9 shows the energy levels in hydrogen, the simplest of all elements. The energy levels are labeled on the left in numerical order and on the right with energies in units of *electron-volts*, or *eV* for short. ($1 \text{ eV} = 1.60 \times 10^{-19}$ joule.) The lowest possible energy level—called level 1 or the *ground state*—is defined as an energy of 0 eV. Each of the higher energy levels (sometimes called *excited states*) is labeled with the extra energy of an electron in that level compared to the ground state.

An electron can rise from a low energy level to a higher one or fall from a high level to a lower one. Such changes are called **energy level transitions**. Because energy must be conserved, energy level transitions can occur only when an electron gains or loses the specific amount of energy separating two levels. For example, an electron in level 1 can rise to level 2 only if it gains 10.2 eV of energy. If you try to give the electron 5 eV of energy, it won't accept it because that is not enough energy to reach level 2. Similarly, if you try to give it 11 eV, it won't accept it because it is too much for level 2 but not enough to reach level 3. Once in level 2, the electron can return to level 1 by giving up 10.2 eV of energy.

Notice that the amount of energy separating the various levels gets smaller at higher levels. For example, it takes more energy to raise the electron from level 1 to level 2 than from level 2 to level 3, which in turn takes more energy than the transition from level 3 to level 4. If the electron gains

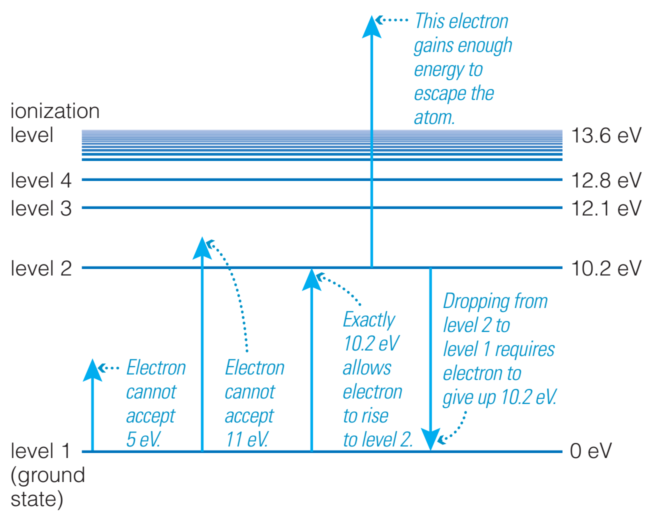
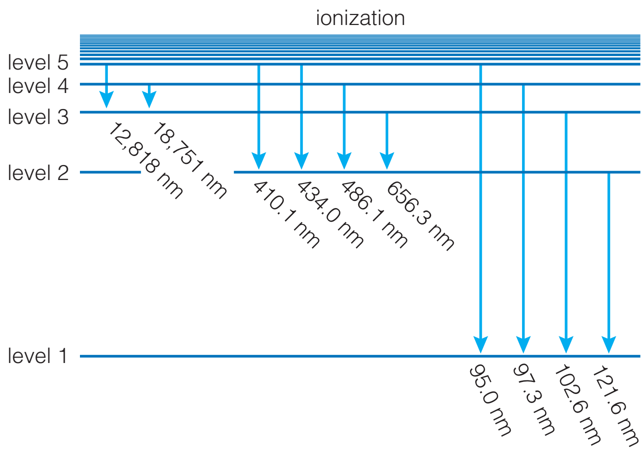


Figure 5.9

Energy levels for the electron in a hydrogen atom. The electron can change energy levels only if it gains or loses the amount of energy separating the levels. If the electron gains enough energy to reach the ionization level, it can escape from the atom, leaving behind a positively charged ion.



a Energy level transitions in hydrogen correspond to photons with specific wavelengths. Only a few of the many possible transitions are labeled.

b This spectrum shows emission lines produced by downward transitions between higher levels and level 2 in hydrogen.

c This spectrum shows absorption lines produced by upward transitions between level 2 and higher levels in hydrogen.

Figure 5.10 MA interactive figure

An atom emits or absorbs light only at specific wavelengths that correspond to changes in the atom's energy as an electron undergoes transitions between its allowed energy levels.

enough energy to reach the *ionization level*, it escapes the atom completely. Because the escaping electron carries away negative electrical charge, the atom is left with positive electrical charge. Electrically charged atoms are called **ions**, so we say that the escape of the electron *ionizes* the atom.

think about it Are there any circumstances under which an electron in a hydrogen atom can gain 2.6 eV of energy? Explain.

Other atoms also have distinct energy levels, but the levels correspond to different amounts of energy than those of hydrogen. Every type of ion and every type of molecule also has a distinct set of energy levels.

Emission and Absorption Lines The fact that each type of atom, ion, or molecule possesses a unique set of energy levels is what causes emission and absorption lines to appear at specific wavelengths in spectra. It is also what allows us to learn the compositions of distant objects in the universe. To see how, let's consider what happens in a cloud of gas consisting solely of hydrogen atoms.

The atoms in any cloud of gas are constantly colliding with one another, exchanging energy in each collision. Most of the collisions simply send the atoms careening off in new directions. However, a few of the collisions transfer the right amount of energy to bump an electron from a low energy level to a higher energy level. Electrons can't stay in higher energy levels for long. They always fall back down to level 1, usually in a tiny fraction of a second. The energy the electron loses when it falls to a lower energy level must go somewhere, and often it goes to *emitting* a photon of light. The emitted photon must have the same amount of energy that the electron loses, which means that it has a specific wavelength and frequency. Figure 5.10a again shows the energy levels in hydrogen that we saw in Figure 5.9, but it is also labeled with the wavelengths of the photons emitted by various downward transitions of an electron from a higher energy level to a lower one. For example, the transition from level 2 to level 1 emits an ultraviolet photon of wavelength 121.6 nm, and the transition from level 3 to level 2 emits a red visible-light photon of wavelength 656.3 nm.

The photons that produce emission lines are created when electrons fall to lower energy levels.

Although electrons that rise to higher energy levels in a gas quickly return to level 1, new collisions can raise other electrons into higher levels. As long as the gas remains moderately warm, collisions are always bumping some electrons into higher levels from which they fall back down and emit photons with some of the wavelengths shown in Figure 5.10a. The gas therefore emits light with these specific wavelengths. That is why a warm gas cloud produces an emission line spectrum, as shown in Figure 5.10b. The bright emission lines appear at the wavelengths that correspond to downward transitions of electrons, and the rest of the spectrum is dark (black). The specific set of lines that we see depends on the cloud's temperature as well as its composition: At higher temperatures, electrons are more likely to be bumped to higher energy levels.

think about it If nothing continues to heat the hydrogen gas, all the electrons eventually will end up in the lowest energy level (the ground state, or level 1). Use this fact to explain why we should not expect to see an emission line spectrum from a very cold cloud of hydrogen gas.

Now, suppose a light bulb illuminates the hydrogen gas from behind (as in Figure 5.8c). The light bulb emits light of all wavelengths, producing a spectrum that looks like a rainbow of color. However, the hydrogen atoms can absorb those photons that have the right amount of energy needed to raise an electron from a low energy level to a higher one. Figure 5.10c shows the result. It is an absorption line spectrum, because the light bulb produces a continuous rainbow of color while the hydrogen atoms absorb light at specific wavelengths.*

Absorption lines occur when photons cause electrons to rise to higher energy levels.

You can now see why the dark absorption lines in Figure 5.10c occur at the same wavelengths as the emission lines in Figure 5.10b: Both types of lines represent the same energy level transitions, except in opposite directions. For example, electrons moving downward from level 3 to level 2 in hydrogen can emit photons of wavelength 656.3 nm (producing an emission line at this wavelength), while electrons absorbing photons with this wavelength can jump up from level 2 to level 3 (producing an absorption line at this wavelength).

Chemical Fingerprints The fact that hydrogen emits and absorbs at specific wavelengths makes it possible to detect its presence in distant objects. For example, imagine that you look through a telescope at an interstellar gas cloud, and its spectrum looks like that shown in Figure 5.10b. Because this particular set of lines is produced only by hydrogen, you can conclude that the cloud is made of hydrogen. In essence, the spectrum contains a "fingerprint" left by hydrogen atoms.

Every kind of atom, ion, and molecule produces a unique spectral "fingerprint."

Real interstellar clouds are not made solely of hydrogen. However, the other chemical constituents in the cloud leave fingerprints on the spectrum in much the same way. Every type of atom, ion, and molecule has its own unique spectral fingerprint, because it has its own unique set of energy levels. Over the past century, scientists have done laboratory experiments to identify the spectral lines of every chemical element and many ions and molecules. When we see any of those lines in the spectrum of a distant object, we can determine what chemicals produced them. For example, if we see spectral lines of hydrogen, helium, and carbon in the spectrum of a distant star, we know that all three elements are present in the star. With more detailed analysis, we can determine the relative proportions of the various elements. That is how we have learned the chemical compositions of objects throughout the universe.

• How does light tell us the temperatures of planets and stars?

We have seen how emission and absorption line spectra form, and how we can use them to determine the composition of a cloud of gas. Now we are ready to turn our attention to continuous spectra. Although continuous spectra can be produced in more than one way, light bulbs, planets, and stars produce a particular kind of continuous spectrum that can help us determine their temperatures.

*You might wonder what happens to the electrons after they absorb photons and jump to a higher energy level: The electrons quickly fall back down, emitting photons of the same energy in random directions. We therefore see absorption lines because most of the emitted photons are not sent along our line of sight.

Thermal Radiation: Every Body Does It In a cloud of gas that produces a simple emission or absorption line spectrum, the individual atoms or molecules are essentially independent of one another. Most photons pass easily through such a gas, except those that cause energy level transitions in the atoms or molecules of the gas. However, the atoms and molecules within most of the objects we encounter in everyday life—such as rocks, light bulb filaments, and people—cannot be considered independent and therefore have much more complex sets of energy levels. These objects tend to absorb light across a broad range of wavelengths, which means light that strikes them cannot easily pass through and light emitted inside them cannot easily escape. The same is true of almost any large or dense object, including planets and stars.

In order to understand the spectra of such objects, let's consider an idealized case, in which an object absorbs all photons that strike it and does not allow photons inside it to escape easily. Photons tend to bounce randomly around inside such an object, constantly exchanging energy with its atoms or molecules. By the time the photons finally escape the object, their radiative energies have become randomized so that they are spread over a wide range of wavelengths. The wide wavelength range of the photons explains why the spectrum of light from such an object is smooth, or *continuous*, like a pure rainbow without any absorption or emission lines.

Most important, the spectrum from such an object depends on only one thing: the object's *temperature*. To understand why, remember that temperature represents the average kinetic energy of the atoms or molecules in an object **[Section 4.3]**. Because the randomly bouncing photons interact so many times with those atoms or molecules, they end up with energies that match the kinetic energies of the object's atoms or molecules—which means the photon energies depend only on the object's temperature, regardless of what the object is made of. The temperature dependence of this light explains why we call it **thermal radiation** (sometimes known as *blackbody* radiation) and why its spectrum is called a **thermal radiation spectrum**.

Planets, stars, rocks, and people emit thermal radiation that depends only on temperature.

No real object emits a perfect thermal radiation spectrum, but almost all familiar objects—including the Sun, the planets, rocks, and even you—emit light that approximates thermal radiation. Figure 5.11 shows a graph of the idealized thermal radiation spectra of three stars and a human, each with its temperature given on the Kelvin scale (see Figure 4.10). Be sure to notice that these spectra show the intensity of light *per unit surface area*, not the total amount of light emitted by the object. For example, a very large 3000 K star can emit more total light than a small 15,000 K star, even though the hotter star emits much more light per unit area of its surface.

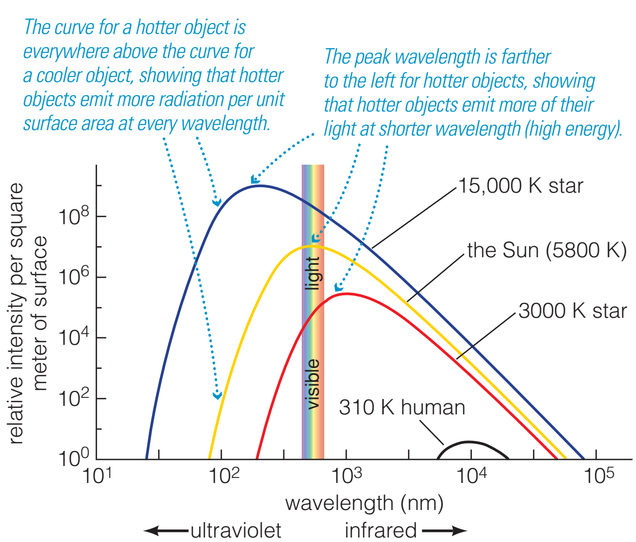


Figure 5.11 MA interactive figure

This graph of idealized thermal radiation spectra demonstrates the two laws of thermal radiation: (1) Each square meter of a hotter object's surface emits more light at all wavelengths; (2) hotter objects emit photons with a higher average energy. Notice that the graph uses power-of-10 scales on both axes, so that we can see all the curves even though the differences between them are quite large.

The Two Laws of Thermal Radiation

If you compare the spectra in Figure 5.11, you'll see that temperature affects them according to the two laws of thermal radiation:

- **Law 1 (Stefan-Boltzmann law):** *Each square meter of a hotter object's surface emits more light at all wavelengths*. For example, each square meter on the surface of the 15,000 K star emits a lot more light at every wavelength than each square meter of the 3000 K star, and the hotter star emits light at some ultraviolet wavelengths that the cooler star does not emit at all.

- **Law 2 (Wien's law** ["Wien" is pronounced *veen*]**):** *Hotter objects emit photons with a higher average energy*, which means a shorter average wavelength. That is why the peaks of the spectra are at shorter wavelengths for hotter objects. For example, the peak for the 15,000 K star is in ultraviolet light, the peak for the 5800 K Sun is in visible light, and the peak for the 3000 K star is in the infrared.

You can see these laws in action with a fireplace poker (Figure 5.12). While the poker is still relatively cool, it emits only infrared light, which we cannot see. As it gets hot (above about 1500 K), it begins to glow with visible light, and it glows more brightly as it gets hotter, demonstrating the first law. Its color demonstrates the second law. At first it glows "red hot," because red light has the longest wavelengths of visible light. As it gets even hotter, the average wavelength of the emitted photons moves toward the blue (short wavelength) end of the visible spectrum. The mix of colors emitted at this higher temperature makes the poker look white to your eyes, which is why "white hot" is hotter than "red hot."

see it for yourself Find an incandescent light that has a dimmer switch. What happens to the bulb temperature (which you can check by placing your hand near it) as you turn the switch up? How does the light change color? Explain how these observations demonstrate the two laws of thermal radiation.

Hotter objects emit more total light per unit surface area and emit photons with a higher average energy.

Because thermal radiation spectra depend only on temperature, we can use them to measure the temperatures of distant objects. In many cases we can estimate temperatures simply from the object's colors. Notice that while hotter objects emit more light at *all* wavelengths, the biggest difference appears at the shortest wavelengths. At human body temperature of about 310 K, people emit mostly in the infrared and emit no visible light at all—which explains why we don't glow in the dark! A relatively cool star, with a 3000 K surface temperature, emits mostly red light. That is why some bright stars in our sky, such as Betelgeuse (in Orion) and Antares (in Scorpius), appear reddish in color. The Sun's 5800 K surface emits most strongly in green light (around 500 nm), but the Sun looks yellow or white to our eyes because it also emits other colors throughout the visible spectrum. Hotter stars emit mostly in the ultraviolet but appear blue-white in color because our eyes cannot see their ultraviolet light. If an object were heated to a temperature of millions of degrees, it would radiate mostly X rays. Some astronomical objects are indeed hot enough to emit X rays, such as disks of gas encircling exotic objects like neutron stars and black holes (see Chapter 13.)

MA Doppler Shift Tutorial, Lessons 1–2

• How does light tell us the speed of a distant object?

There is still more that we can learn from light: We can use light to learn about the motion of distant objects (relative to us) from changes in their spectra caused by the **Doppler effect**.

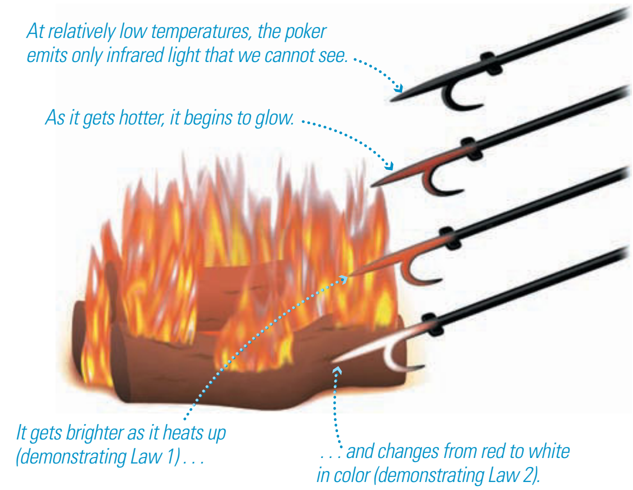


Figure 5.12

A fireplace poker shows the two laws of thermal radiation in action.

cosmic Calculations 5.1

Laws of Thermal Radiation

The two laws of thermal radiation have simple mathematical formulas. Law 1 (the *Stefan-Boltzmann law*) is expressed

$$\text{Law 1: emitted power (per square meter of surface)} = \sigma T^4$$

T is temperature (in Kelvin) and $\sigma = 5.7 \times 10^{-8} \frac{\text{watt}}{(\text{m}^2 \times \text{K}^4)}$ is a constant. (A *watt* is a unit of power, equivalent to 1 joule per second.) Law 2 (*Wien's law*) is expressed

$$\text{Law 2: } \lambda_{max} \text{ (in nanometers)} \approx \frac{2{,}900{,}000}{T(\text{in Kelvin})}$$

where λ_{max} (read as "lambda max") is the wavelength (in nanometers) of maximum intensity, which is located at the peak in a thermal radiation spectrum.

Example: Consider a 15,000 K object that emits thermal radiation. How much power does it emit per square meter? What is its wavelength of maximum intensity?

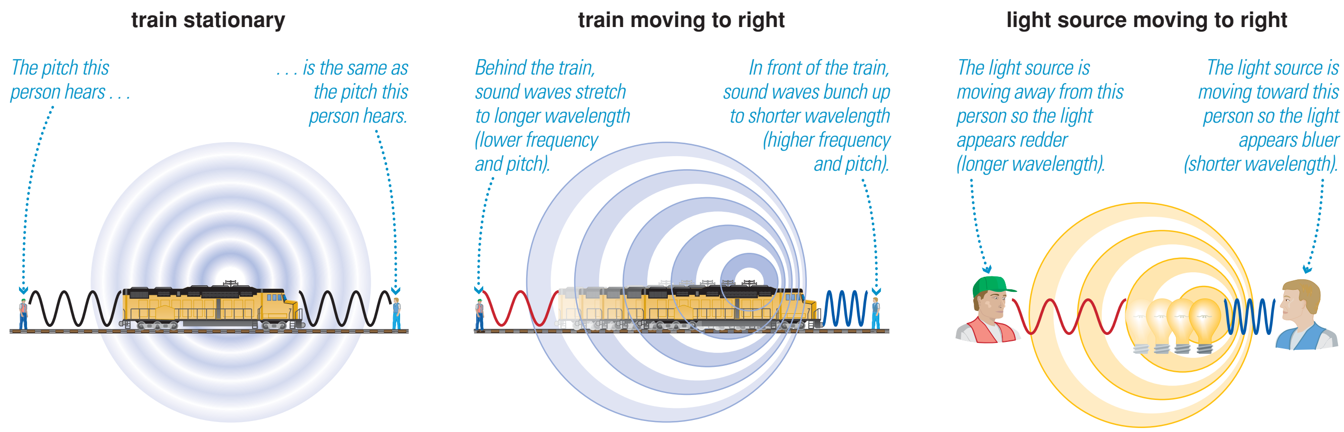
Solution: We use the first law to calculate the emitted power per square meter for an object with $T = 15{,}000$ K:

$$\sigma T^4 = 5.7 \times 10^{-8} \frac{\text{watt}}{\text{m}^2 \times \text{K}^4} \times (15{,}000\ \text{K})^4$$
$$= 2.9 \times 10^9\ \text{watt/m}^2$$

The second law gives the wavelength of maximum intensity:

$$\lambda_{\text{max}} \approx \frac{2{,}900{,}000}{15{,}000\ \text{K}}\ \text{nm} \approx 190\ \text{nm}$$

A 15,000 K object emits a total power of 2.9 billion watts per square meter of surface. Its wavelength of maximum intensity is about 190 nm, which is in the ultraviolet portion of the electromagnetic spectrum.



a The whistle sounds the same no matter where you stand near a stationary train.

b For a moving train, the sound you hear depends on whether the train is moving toward you or away from you.

c We get the same basic effect from a moving light source (although the shifts are usually too small to notice by eye).

Figure 5.13

The Doppler effect. Each circle represents the crests of sound (or light) waves going in all directions from the source. For example, the circles from the train might represent waves emitted 0.001 second apart.

cosmic Calculations 5.2

The Doppler Shift

We can calculate an object's radial velocity from its Doppler shift. For velocities that are small compared to the speed of light (less than a few percent of c), the formula is

$$\frac{v_{\text{rad}}}{c} = \frac{\lambda_{\text{shift}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}}$$

where v_{rad} is the object's radial velocity, λ_{rest} is the rest wavelength of a particular spectral line, and λ_{shift} is the shifted wavelength of the same line. (As always, c is the speed of light.) A positive answer means the object is redshifted and moving away from us; a negative answer means it is blueshifted and moving toward us.

Example: One of the visible lines of hydrogen has a rest wavelength of 656.285 nm, but it appears in the spectrum of the star Vega at 656.255 nm. How is Vega moving relative to us?

Solution: We use the rest wavelength $\lambda_{\text{rest}} = 656.285$ nm and the shifted wavelength $\lambda_{\text{shift}} = 656.255$ nm:

$$\begin{aligned}\frac{v_{\text{rad}}}{c} &= \frac{\lambda_{\text{shift}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}} \\ &= \frac{656.255 \text{ nm} - 656.285 \text{ nm}}{656.285 \text{ nm}} \\ &= -4.5712 \times 10^{-5}\end{aligned}$$

The negative answer tells us that Vega is moving *toward* us. Its speed is 4.5712×10^{-5} of the speed of light c. Because $c = 300{,}000$ km/s, this is equivalent to $4.5712 \times 10^{-5} \times \left(3 \times 10^5 \frac{\text{km}}{\text{s}}\right) \approx 13.7$ km/s.

The Doppler Effect You've probably noticed the Doppler effect on the *sound* of a train whistle near train tracks. If the train is stationary, the pitch of its whistle sounds the same no matter where you stand (Figure 5.13a). But if the train is moving, the pitch sounds higher when the train is coming toward you and lower when it's moving away from you. Just as the train passes by, you can hear the dramatic change from high to low pitch—a sort of "weeeeeeee–ooooooooooh" sound. To understand why, we have to think about what happens to the sound waves coming from the train (Figure 5.13b). When the train is moving toward you, each pulse of a sound wave is emitted a little closer to you. The result is that waves are bunched up between you and the train, giving them a shorter wavelength and higher frequency (pitch). After the train passes you by, each pulse comes from farther away, stretching out the wavelengths and giving the sound a lower frequency.

Spectral lines shift to shorter wavelengths when an object is moving toward us, and to longer wavelengths when an object is moving away from us.

The Doppler effect causes similar shifts in the wavelengths of light (Figure 5.13c). If an object is moving toward us, the light waves bunch up between us and the object, so that its entire spectrum is shifted to shorter wavelengths. Because shorter wavelengths of visible light are bluer, the Doppler shift of an object coming toward us is called a **blueshift**. If an object is moving away from us, its light is shifted to longer wavelengths. We call this a **redshift** because longer wavelengths of visible light are redder. For convenience, astronomers use the terms *blueshift* and *redshift* even when they aren't talking about visible light.

Spectral lines provide the reference points we use to identify and measure Doppler shifts (Figure 5.14). For example, suppose we recognize the pattern of hydrogen lines in the spectrum of a distant object. We know the **rest wavelengths** of the hydrogen lines—that is, their wavelengths in stationary clouds of hydrogen gas—from laboratory experiments in which a tube of hydrogen gas is heated so that the wavelengths of the spectral lines can be measured. If the hydrogen lines from the object appear at longer wavelengths, then we know they are redshifted and the object is moving away from us. The larger the shift, the faster the object is moving. If the lines appear at shorter wavelengths, then we know they are blueshifted and the object is moving toward us.

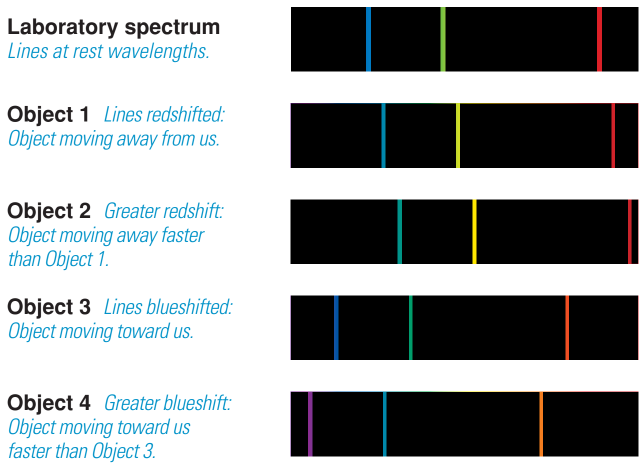


Figure 5.14 MA **interactive figure**

Spectral lines provide the crucial reference points for measuring Doppler shifts.

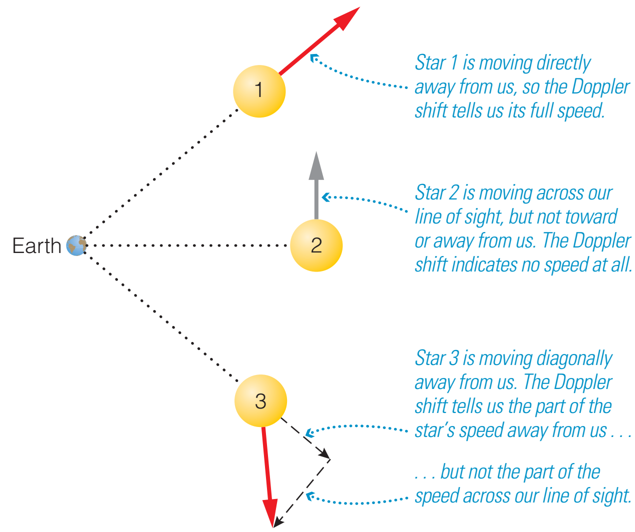


Figure 5.15 MA **interactive figure**

The Doppler shift tells us only the portion of an object's speed that is directed toward or away from us. It does not give us any information about how fast an object is moving across our line of sight.

think about it Suppose the hydrogen emission line with a rest wavelength of 121.6 nm (the transition from level 2 to level 1) appears at a wavelength of 120.5 nm in the spectrum of a particular star. Given that these wavelengths are in the ultraviolet, is the shifted wavelength closer to or farther from blue visible light? Why, then, do we say that this spectral line is *blueshifted?*

Notice that the Doppler shift tells us only the part of an object's full motion that is directed toward or away from us (the object's *radial* component of motion). Doppler shifts do not give us any information about how fast an object is moving across our line of sight (the object's *tangential* component of motion). For example, consider three stars all moving at the same speed, with one moving directly away from us, one moving across our line of sight, and one moving diagonally away from us (Figure 5.15). The Doppler shift will tell us the full speed only of the first star. It will not indicate any speed for the second star, because none of this star's motion is directed toward or away from us. For the third star, the Doppler shift will tell us only the part of the star's speed that is directed away from us. To measure how fast an object is moving across our line of sight, we must observe it long enough to notice how its position gradually shifts across our sky.

Spectral Summary We've covered the major ways in which we can learn from an object's spectrum, discussing how we learn about an object's composition, temperature, and motion. Figure 5.16 (on pages 126–127) summarizes the ways in which we learn from spectra.

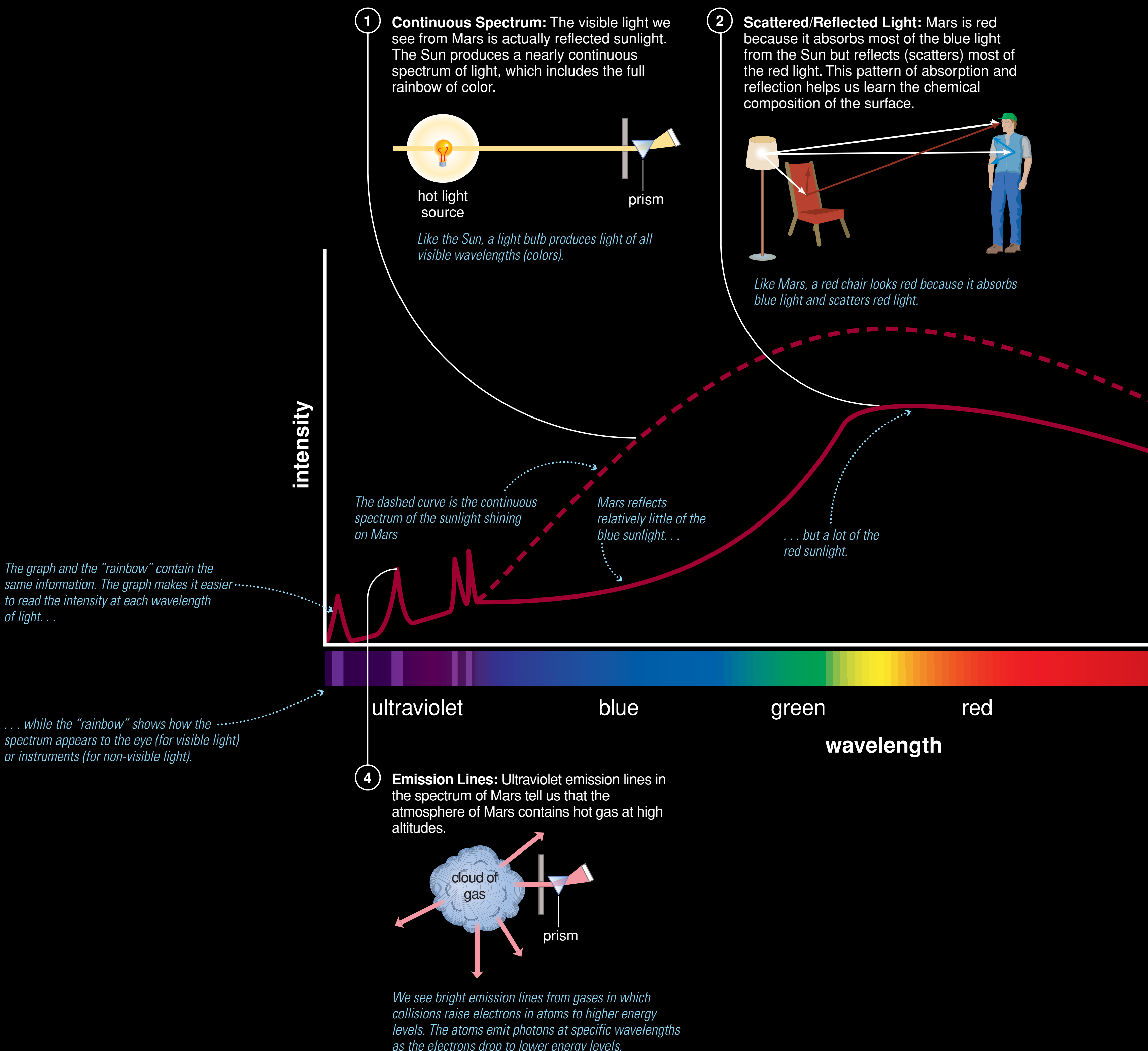
MA Telescopes Tutorial, Lessons 1–2

5.3 Collecting Light with Telescopes

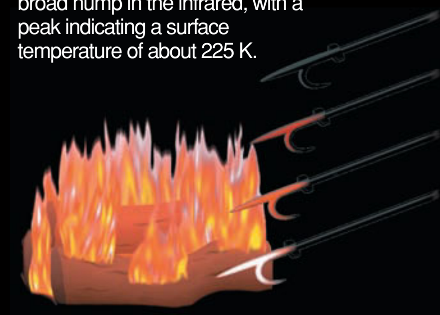
We've seen that light carries a great deal of information, but only a little of that information can be obtained when we look at the sky with our naked eyes. Most of the great advances that have taken place in astron-

Figure 5.16. Interpreting a Spectrum

An astronomical spectrum carries an enormous amount of information. This figure illustrates some of what we can learn from a spectrum, using a schematic spectrum of Mars as an example.

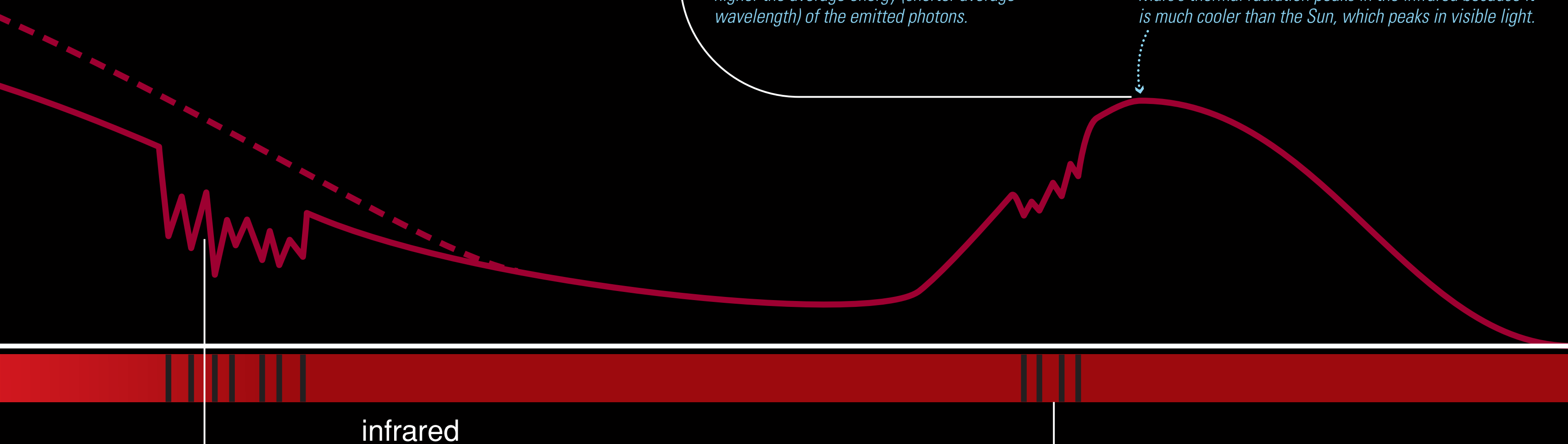


3 **Thermal Radiation:** Objects emit a continuous spectrum of thermal radiation that peaks at a wavelength determined by temperature. Thermal radiation from Mars produces a broad hump in the infrared, with a peak indicating a surface temperature of about 225 K.

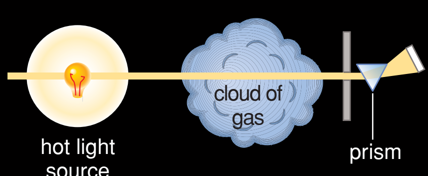


All objects—whether a fireplace poker, planet, or star—emit thermal radiation. The hotter the object, (1) the more total light (per unit area); and (2) the higher the average energy (shorter average wavelength) of the emitted photons.

Mars's thermal radiation peaks in the infrared because it is much cooler than the Sun, which peaks in visible light.

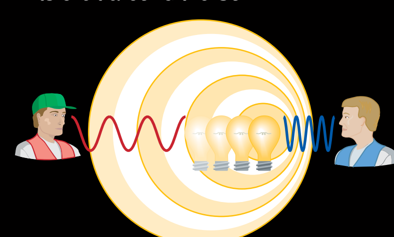


5 **Absorption Lines:** These absorption lines reveal the presence of carbon dioxide in Mars's atmosphere.



When light from a hot source passes through a cooler gas, the gas absorbs light at specific wavelengths that raise electrons to higher energy levels. Every different element, ion, and molecule has unique energy levels and hence its own spectral "fingerprint."

6 **Doppler Effect:** The wavelengths of the spectral lines from Mars are slightly shifted by an amount that depends on the velocity of Mars toward or away from us as it moves in its orbit around the Sun.



A Doppler shift toward the red side of the spectrum tells us the object is moving away from us. A shift toward the blue side of the spectrum tells us the object is moving toward us.

common Misconceptions

Magnification and Telescopes

Many people guess that magnification is the most important function of a telescope. However, even though telescopes can magnify images—much like telephoto camera lenses and binoculars—the amount of magnification a telescope can provide is *not* one of its crucial properties. No matter how much a telescope image is magnified, you cannot see details if the telescope does not collect enough light to show them, or if they are smaller than the angular resolution of the telescope. Magnifying an image too much just makes it look blurry, which is why a telescope's light-collecting area and angular resolution are much more important than its magnification.

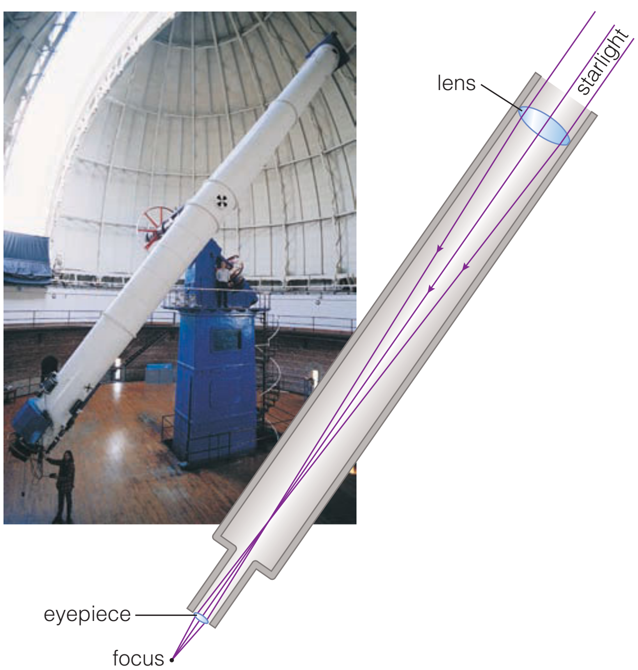


Figure 5.17

A refracting telescope collects light with a large transparent lens (see diagram). The photo shows the 1-meter refractor at the University of Chicago's Yerkes Observatory, the world's largest refracting telescope.

omy in the past three centuries have been made possible through the use of telescopes. In this section, we'll briefly explore how telescopes work and how they help us learn about the universe.

• How do telescopes help us learn about the universe?

Telescopes are essentially giant eyes that can collect far more light than our own eyes, allowing us to see much fainter objects in much greater detail. In addition, we can connect scientific instruments to telescopes, allowing us to analyze the light they collect. For example, sophisticated cameras can make high-quality images of light collected by a telescope, and spectrographs can disperse the light into spectra that can reveal an object's chemical composition, temperature, speed, and more.

The Two Key Properties of a Telescope The two most fundamental properties of any telescope are its *light-collecting area* and its *angular resolution*.

The **light-collecting area** tells us how much total light the telescope can collect at one time. Telescopes are generally round, so we usually characterize a telescope's "size" as the *diameter* of its light-collecting area. For example, a "10-meter telescope" has a light-collecting area that is 10 meters in diameter. Such a telescope has a light-collecting area more than a million times that of the human eye. Because area is proportional to the *square* of a telescope's diameter, a relatively small increase in diameter can mean a big increase in light-collecting area. A 10-meter telescope has five times the diameter of a 2-meter telescope, so its light-collecting area is $5^2 = 25$ times as great.

Telescopes collect far more light and allow us to see far more detail than does the naked eye.

Angular resolution is the smallest angle over which we can tell that two dots—or two stars—are distinct. For example, the human eye has an angular resolution of about 1 arcminute $\left(\frac{1}{60}{}^\circ\right)$, meaning that two stars can appear distinct only if they have at least this much angular separation in the sky. If the stars are separated by less than 1 arcminute, our eyes will not be able to distinguish them individually and they will appear as a single star.

Large telescopes can have amazing angular resolution. For example, the 2.4-meter Hubble Space Telescope has an angular resolution of about 0.05 arcsecond (for visible light), which would allow you to read this book from a distance of almost 1 kilometer. Larger telescopes can have even better (smaller) angular resolution, though Earth's atmosphere usually prevents ground-based telescopes from achieving their theoretical limits.

Basic Telescope Design Telescopes come in two basic designs: *refracting* and *reflecting*. A **refracting telescope** operates much like an eye, using transparent glass lenses to collect and focus light (Figure 5.17). The earliest telescopes, including those that Galileo built, were refracting telescopes. The world's largest refracting telescope, completed in 1897, has a lens that is 1 meter (40 inches) in diameter and a telescope tube that is 19.5 meters (64 feet) long.

A **reflecting telescope** uses a precisely curved *primary mirror* to gather light (Figure 5.18). This mirror reflects the gathered light to a *secondary mirror* that lies in front of it. The secondary mirror then reflects the light to a focus at a place where the eye or instruments can observe it—sometimes through a hole in the primary mirror and sometimes through the side of the telescope (often with the aid of additional small mirrors). The fact that the secondary mirror prevents some light from reaching the primary mirror might seem like a drawback to reflecting telescopes, but in practice it is not a problem because only a small fraction of the incoming light is blocked.

The world's largest reflecting telescopes have primary mirrors 10 meters or more in diameter.

Nearly all telescopes used in current astronomical research are reflectors. The sizes of the largest reflectors increased rapidly in the early 20th century, but then became limited by the sheer weight of the glass in their primary mirrors. The 5-meter Hale telescope on Mount Palomar (outside San Diego) therefore remained the most powerful telescope in the world for more than 40 years after its opening in 1948. By the 1990s, technological innovations made it possible to build lighter-weight mirrors, such as the 8-meter mirror in the Gemini telescope (see Figure 5.18). We are also now able to make many small mirrors work together as one large one, like the 10-meter Keck telescopes in Hawaii (Figure 5.19). Today, several of the largest telescopes have primary mirrors 10 meters or more in diameter, and much larger ones are being planned, including the Thirty Meter Telescope (TMT), which could open as early as 2018.

Telescopes Across the Spectrum

If we studied only visible light, we'd be missing much of the picture. Planets are relatively cool and emit primarily infrared light. The hot upper layers of stars such as the Sun emit ultraviolet and X-ray light. Some violent events even produce gamma rays. Indeed, most objects emit light over a broad range of wavelengths. Today, astronomers study light across the entire spectrum.

Telescopes specialized to observe different wavelengths of light allow us to learn far more than we could learn from visible light alone.

The basic idea behind all telescopes is the same: to collect as much light as possible with as much resolution as possible. However, telescopes for most nonvisible wavelengths require different designs than visible-light telescopes. For

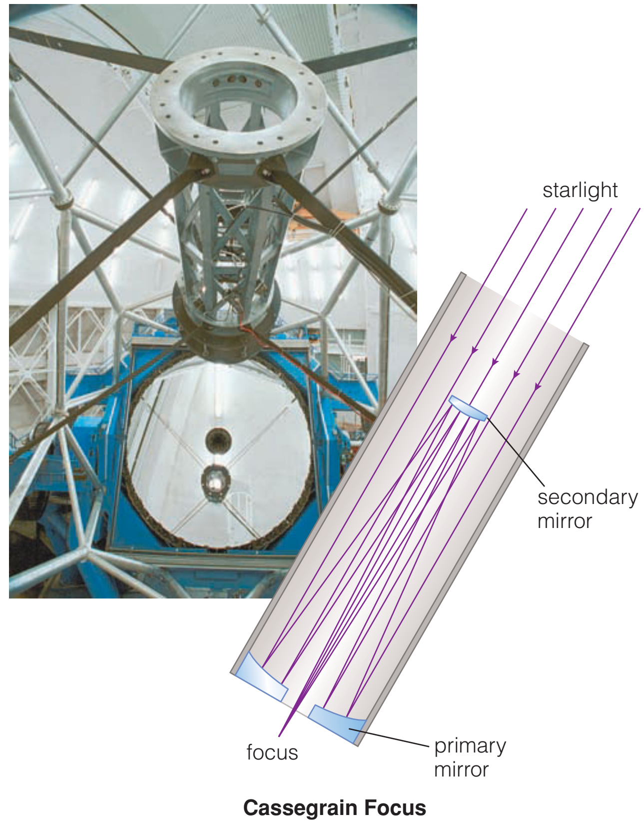


Figure 5.18

A reflecting telescope collects light with a precisely curved primary mirror (see diagram). The photo shows the Gemini North telescope, which has an 8-meter diameter primary mirror and is located on the summit of Mauna Kea, Hawaii. The secondary mirror, located in the smaller central lattice, reflects light back down through the hole visible in the center of the primary mirror. (This design, in which the secondary mirror reflects the light through a hole in the primary mirror, is only one of several alternative designs for reflecting telescopes.)

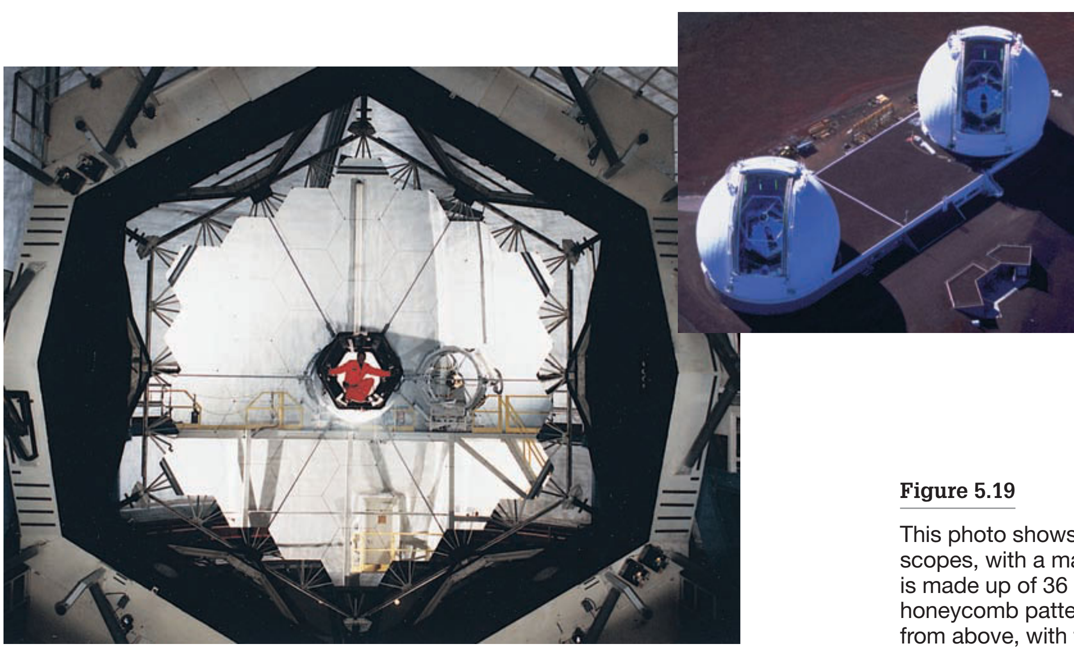


Figure 5.19

This photo shows the primary mirror of one of the Keck telescopes, with a man in the center for scale. The primary mirror is made up of 36 smaller, hexagonal mirrors, arranged in a honeycomb pattern. The inset shows the two Keck telescopes from above, with the primary mirrors visible inside the domes.

Figure 5.20

The Arecibo radio telescope stretches across a natural valley in Puerto Rico. At 305 meters across, it is the world's largest single telescope.

example, the long wavelengths of radio waves mean that very large telescopes are necessary to achieve reasonable angular resolution. The largest single telescope in the world, the Arecibo radio dish, stretches 305 meters (1000 feet) across a natural valley in Puerto Rico (Figure 5.20). (An even larger, 500-meter dish is under construction in China, slated to open in 2015.) Despite its large size, Arecibo's angular resolution is only about 1 arcminute at commonly observed radio wavelengths—a few hundred times worse than the visible-light resolution of the Hubble Space Telescope.

Near the other end of the spectrum, X rays present a different challenge. Trying to focus X rays is somewhat like trying to focus a stream of bullets. If the bullets are fired directly at a metal sheet, they will puncture or damage the sheet. However, if the metal sheet is angled so that the bullets barely graze its surface, then it will slightly deflect the bullets. The mirrors of X-ray telescopes, such as NASA's Chandra X-Ray Observatory, are designed to deflect X rays in much the same way (Figure 5.21).

Every wavelength range poses its own unique challenges in building telescopes, and many new technologies have been invented to meet these challenges. Today we have the technology to observe nearly every wavelength of light coming from the cosmos.

• Why do we put telescopes in space?

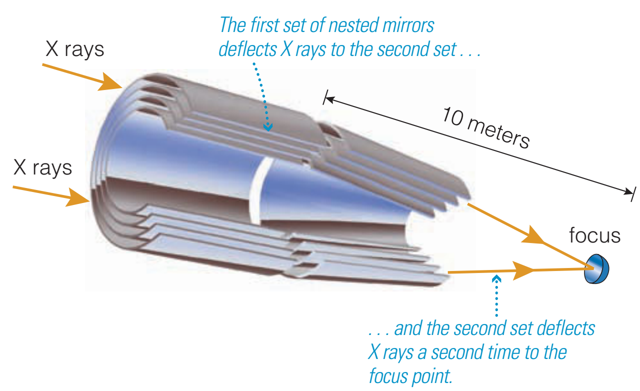
Many telescopes have been launched into space during the past few decades, including the Hubble Space Telescope and the Chandra X-Ray Observatory. To understand why we have put some telescopes in space—especially since it is much more expensive to do so than to build one on the ground—we must understand the ways in which Earth's atmosphere hinders observations from the ground.

Atmospheric Effects on Visible Light Some of the problems created by Earth's atmosphere are obvious. The brightness of the daytime sky limits visible-light observations to the night (ground-based radio telescopes can observe both day and night), and we cannot see the stars

Figure 5.21

The Chandra X-Ray Observatory focuses X rays that enter the front of the telescope by deflecting them twice so that they end up focused at the back of the telescope.

a Artist illustration of the Chandra X-Ray Observatory, which orbits Earth.



b This diagram shows the arrangement of Chandra's X-ray mirrors. There are two sets of cylindrical mirrors, one near the front of the telescope and one farther back. Each mirror is 0.8 meter long and between 0.6 and 1.2 meters in diameter.

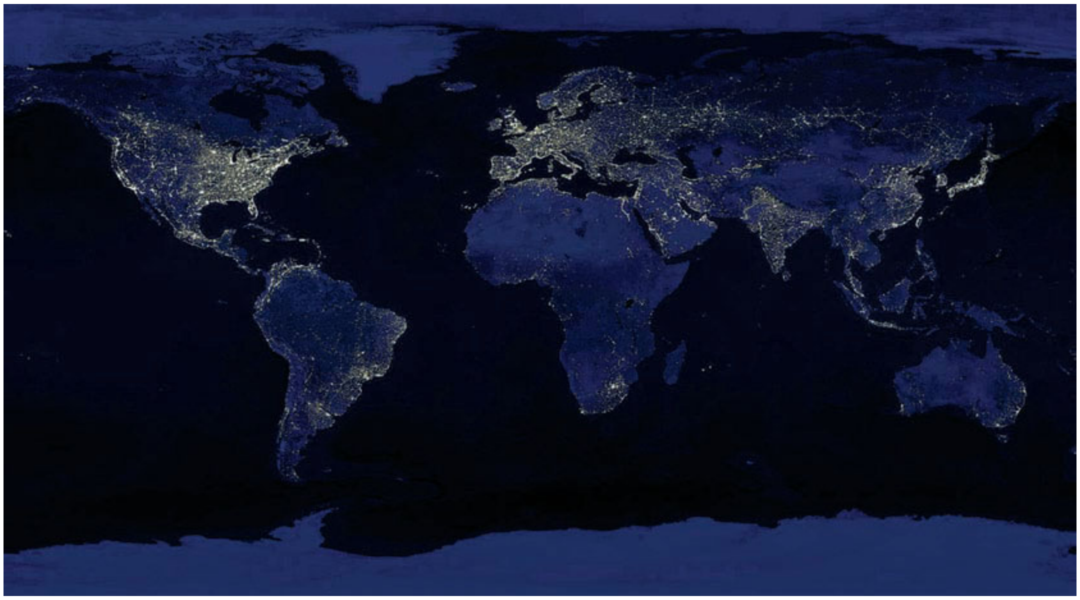


Figure 5.22

Earth at night: It's pretty, but to astronomers it's light pollution. This image, a composite made from hundreds of satellite photos, shows the bright lights of cities around the world as they appear from Earth orbit at night.

on cloudy nights. Another problem is that our atmosphere scatters the bright lights of cities, creating **light pollution** that can obscure the view even for the best telescopes (Figure 5.22). For example, the 2.5-meter telescope at Mount Wilson, the world's largest when it was built in 1917, would be much more useful today if it weren't located so close to the lights of what was once the small town of Los Angeles.

special**Topic:** | Would You Like Your Own Telescope?

JUST A FEW YEARS AGO, a decent telescope would have set you back a few thousand dollars and taken weeks of practice to learn to use. Today, you can get a good-quality telescope for just a few hundred dollars, and built-in computer drives can make it very easy to use.

Before you start thinking about what telescope to buy, it's important to understand what a personal telescope can and cannot do. A telescope will allow you to look for yourself at light that has traveled vast distances through space to reach your eyes. It can be a rewarding experience, but the images in your telescope will *not* look like the beautiful photographs in this book—those are obtained with much larger telescopes and sophisticated cameras. In addition, while your telescope can in principle let you see many distant objects, including star clusters, nebulae, and galaxies, it won't allow you to find anything unless you first set it up properly. Even computer-driven telescopes, usually called "go to" telescopes, typically take 15 minutes to a half-hour to set up for each use (and longer when you are first learning).

If your goal is just to see the Moon and a few other objects with relatively little effort, you may want to buy a good pair of binoculars rather than a telescope. Binoculars will help you learn about viewing the sky and are a lot less expensive. Binoculars are generally described by two numbers, such as 7× 35 or 12× 50. The first number is the magnification; for example, "7×" means that objects will look 7 times closer through the binoculars than to your eye. The second number is the diameter of each lens in millimeters. As with telescopes, larger lenses mean more light and better views. However, larger lenses also tend to be heavier and more difficult to hold steady. If you buy a large pair of binoculars, you should also get a tripod to help hold it steady.

If you decide to get a telescope, the first rule to remember is that magnification is *not* the key factor to consider. Avoid telescopes that are advertised by their magnification, such as "650 power," and instead focus on three factors when choosing your telescope:

1. *The light-collecting area* (also called *aperture*). Most personal telescopes are reflectors, so a "6-inch" telescope means it has a primary mirror that is 6 inches in diameter.
2. *Optical quality.* A poorly made telescope won't do you much good. If you cannot do side-by-side comparisons, stick with a major telescope manufacturer (such as Meade, Celestron, or Orion).
3. *Portability.* A large, bulky telescope can be great if you plan to keep it on your roof, but it won't be fun to carry on camping trips. Depending on how you plan to use your telescope, you'll need to make trade-offs between size and portability.

Most important, remember that a telescope is an investment that you will keep for many years. As with any investment, learn all you can before you settle on a particular model. Read reviews of telescopes in magazines such as *Astronomy, Mercury*, and *Sky and Telescope*. Talk to knowledgeable salespeople at stores that specialize in telescopes. And find a nearby astronomy club that holds observing sessions so that you can try out some telescopes and learn from experienced telescope users.

Figure 5.23

Observatories on the summit of Mauna Kea in Hawaii. Mauna Kea meets the all the key criteria for an observing site: It is far from big city lights, high in altitude, and located in an area where the air tends to be calm and dry.

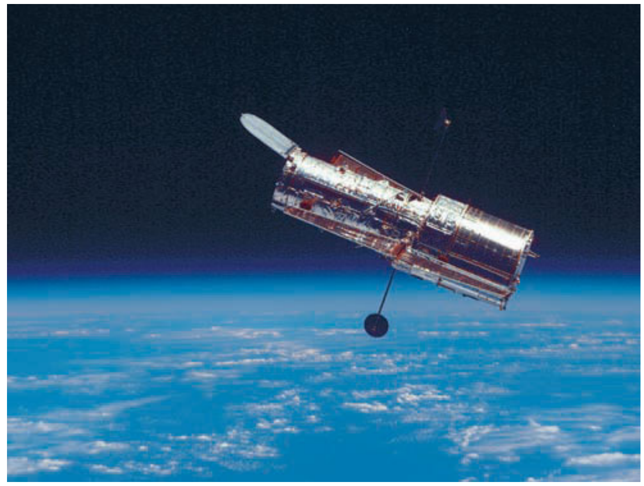


Figure 5.24

The Hubble Space Telescope orbits Earth. Its position above the atmosphere allows it an undistorted view of space. Hubble can observe infrared and ultraviolet light as well as visible light.

A somewhat less obvious problem is the distortion of light by the atmosphere. The ever-changing motion, or **turbulence**, of air in the atmosphere bends light in constantly shifting patterns. This turbulence causes the familiar twinkling of stars. Twinkling may be beautiful to the naked eye, but it causes problems for astronomers because it blurs astronomical images.

Telescopes in space are above the distorting effects of Earth's atmosphere.

see it for yourself Put a coin at the bottom of a cup of water. If you stir the water, the coin will appear to move around, even if it remains stationary on the bottom. What makes the coin appear to move? How is this similar to the way that our atmosphere makes stars appear to twinkle?

Astronomers can partially mitigate effects of weather, light pollution, and atmospheric distortion by choosing appropriate sites for observatories. The key criteria are that the sites be dark (limiting light pollution), dry (limiting rain and clouds), calm (limiting turbulence), and high (placing them above at least part of the atmosphere). Islands are often ideal, and the 4300-meter (14,000-foot) summit of Mauna Kea on the Big Island of Hawaii is home to many of the world's best observatories (Figure 5.23).

Of course, the ultimate solution to atmospheric distortion is to put telescopes in space, above the atmosphere. That is one reason why the Hubble Space Telescope (Figure 5.24) was built and why it has been so successful despite the relatively small size of its primary mirror.

Atmospheric Absorption of Light In some cases, new technologies make it possible for ground-based observatories to equal or better the visible-light observations of the Hubble Space Telescope. However, Earth's atmosphere poses one major problem that no Earth-bound technology can overcome: *Our atmosphere prevents most forms of light from reaching the ground at all*. Figure 5.25 shows the depth to which different forms of light penetrate Earth's atmosphere. Notice that only radio waves, visible light, and small parts of the infrared spectrum can be observed from the ground.

common **Misconceptions**

Twinkle, Twinkle, Little Star

Twinkling, or apparent variation in the brightness and color of stars, is not intrinsic to the stars. Instead, just as light is bent by water in a swimming pool, starlight is bent by Earth's atmosphere. Air turbulence causes twinkling because it constantly changes how the starlight is bent. Hence, stars tend to twinkle more on windy nights and at times when they are near the horizon (and therefore are viewed through a thicker layer of atmosphere). Above the atmosphere, in space, stars do not twinkle at all.

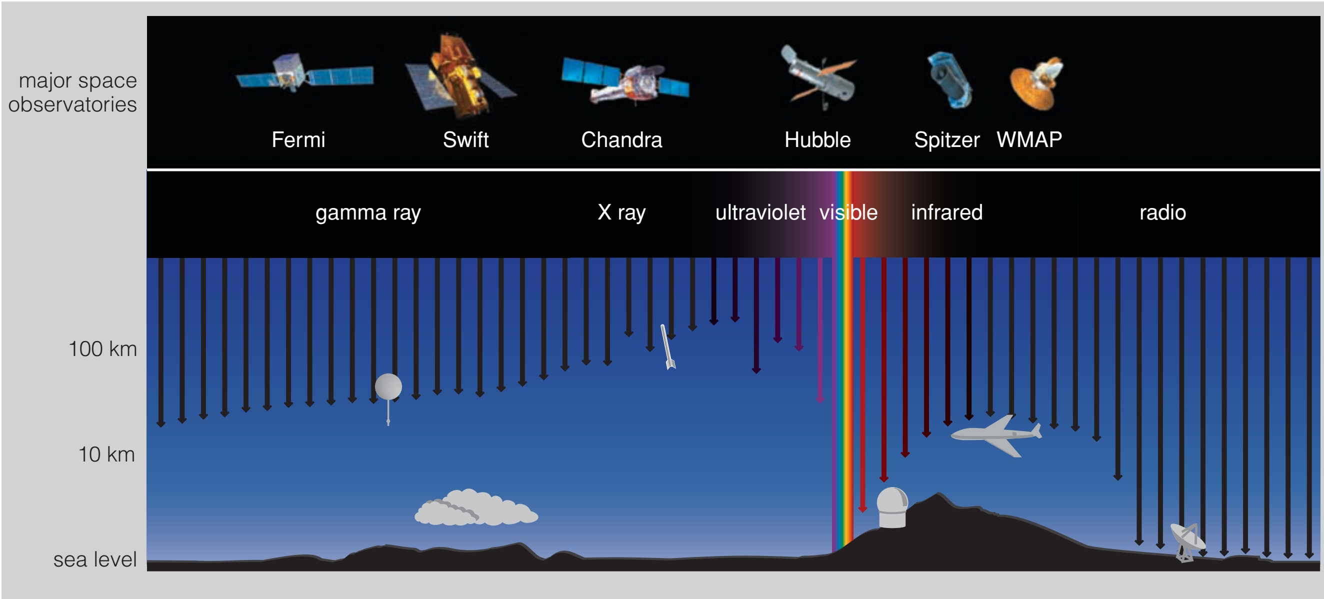


Figure 5.25 MA interactive figure

This diagram shows the approximate depths to which different wavelengths of light penetrate Earth's atmosphere. Note that most of the electromagnetic spectrum—except for visible light, a small portion of the infrared, and radio waves—can be observed only from very high altitudes or from space.

The most important reason for putting telescopes in space is to allow us to observe light that does not penetrate Earth's atmosphere. That is why the Chandra X-Ray Observatory is in space—an X-ray telescope would be completely useless on the ground. The same is true for other observatories in space. Indeed, the Hubble Space Telescope often observes in ultraviolet or infrared wavelengths that do not reach the ground, which is why it would remain a valuable observatory even if ground-based telescopes matched its visible-light capabilities.

Much of the electromagnetic spectrum can be observed only from space and not from the ground.

• How is technology revolutionizing astronomy?

Astronomers today are making new discoveries at an astonishing rate, driven largely by the availability of more and larger telescopes, including space telescopes that can observe previously inaccessible portions of the electromagnetic spectrum. However, larger telescopes are not the only fuel for the current astronomical revolution.

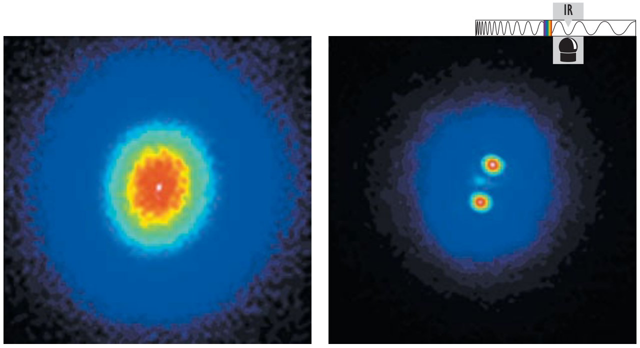
Some new technologies make it possible to obtain better images or spectra with existing telescopes. For example, electronic detectors are constantly improving. As a result, a relatively small telescope equipped with the latest camera technology can record images as good as those that could be captured only by much larger telescopes in the past. Other technologies make it possible to record and analyze data more efficiently. For example, obtaining spectra of distant galaxies used to be a very time-consuming and labor-intensive task. Today, astronomers can sometimes obtain hundreds of spectra simultaneously in a single telescopic observation, and then analyze this vast amount of data with the help of computers.

One of the most amazing technologies is **adaptive optics**, which can eliminate much of the blurring caused by our atmosphere. Remember

common Misconceptions

Closer to the Stars?

Many people mistakenly believe that space telescopes are advantageous because their locations above Earth make them closer to the stars. You can see why this is wrong if you think about scale. On the scale of the Voyage model solar system (discussed in Section 1.2) the Hubble Space Telescope is so close to the surface of the millimeter-diameter Earth that you would need a microscope to resolve its altitude, while the nearest stars are thousands of kilometers away. The distances to the stars are effectively the same whether a telescope is on the ground or in space. The real advantages of space telescopes arise from their being above Earth's atmosphere and not subject to the many observational problems it presents.



a Atmospheric distortion makes this ground-based image of a double star look like a single star.

b When the same telescope is used with adaptive optics, the two stars are clearly distinguished. The angular separation between the two stars is 0.28 arcsecond.

Figure 5.26

The technology of adaptive optics can enable a ground-based telescope to overcome most of the blurring caused by Earth's atmosphere. (Both these images were taken in near-infrared light with the Canada-France-Hawaii Telescope; colors represent infrared intensity.)

that this blurring occurs because air motions cause the light of a star to dance around as it enters a telescope. Adaptive optics essentially make the telescope's mirrors do an opposite dance, canceling out the atmospheric distortions (Figure 5.26). The shape of the mirror (often the secondary or even a third or fourth mirror) is changed slightly many times each second to compensate for the rapidly changing atmospheric distortions. A computer calculates the necessary changes by monitoring distortions in the image of a bright star near the object under study. In some cases, if there is no bright star near the object of interest, the observatory shines a laser into the sky to create an *artificial star* (a point of light in Earth's atmosphere) that it can monitor for distortions.

Adaptive optics allows ground-based telescopes to overcome atmospheric distortion.

Another technique for improving angular resolution is not new, but it is becoming increasingly powerful. Since the 1950s, radio astronomers have used a technique called **interferometry** to allow two or more individual telescopes to achieve the angular resolution of a much larger telescope. For example, the Very Large Array (VLA) in New Mexico links 27 individual radio dishes laid out in the shape of a Y (Figure 5.27). When the 27 dishes are spaced as widely as possible, the VLA can achieve an angular resolution that otherwise would require a single radio telescope with a diameter of almost 40 kilometers. Today, astronomers can achieve even higher angular resolution by linking radio telescopes around the world.

Interferometry allows small telescopes to work together to obtain the angular resolution of a much larger telescope.

Interferometry is more difficult for shorter-wavelength (higher-frequency) light, but astronomers are rapidly learning to use the technique beyond the radio portion of the spectrum. One spectacular example is the Atacama Large Millimeter/submillimeter Array (ALMA), currently under construction in Chile, which will combine light from 80 individual telescopes working at far infrared and short radio wavelengths.

Figure 5.27

The Very Large Array (VLA) in New Mexico consists of 27 telescopes that can be moved along train tracks. The telescopes work together through interferometry and can achieve an angular resolution equivalent to that of a single radio telescope almost 40 kilometers across.

Interferometry is also now possible at shorter infrared and visible wavelengths. New telescopes are often built in pairs (such as the Keck and Magellan telescope pairs) or with more than one telescope on a common mount (such as the Large Binocular Telescope) so that they can be used for infrared and visible-light interferometry. In addition, astronomers are testing technologies that may allow interferometry to be extended all the way to X rays. Someday, astronomers may use telescopes in space or on the Moon as giant interferometers, offering views of distant objects that may be as detailed in comparison to Hubble Space Telescope images as Hubble's images are in comparison to the naked eye's.

the big picture

Putting Chapter 5 into Perspective

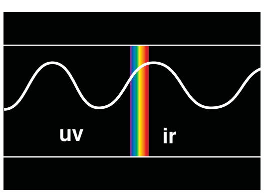
This chapter's main purpose was to show how we learn about the universe by observing the light of distant objects. "Big picture" ideas that will help you keep your understanding in perspective include the following:

- Light and matter interact in ways that allow matter to leave "fingerprints" on light. We can learn a great deal about the objects we observe by carefully analyzing their light. Most of what we know about the universe comes from information that we receive from light.
- The visible light that our eyes can see is only a small portion of the complete electromagnetic spectrum. Different portions of the spectrum may contain different pieces of the story of a distant object, so it is important to study all forms of light.
- There is far more to light than meets the eye. By dispersing the light of a distant object into a spectrum, we can determine the object's composition, surface temperature, motion toward or away from us, and more.
- Technology drives astronomical discovery. Every time we build a bigger telescope, develop a more sensitive detector, or open up a new wavelength region to study, we learn more about the universe.

summary of key concepts

5.1 Basic Properties of Light and Matter

- **What is light?**



Light is an **electromagnetic wave**, but also comes in individual "pieces" called **photons**. Each photon has a precise wavelength, frequency, and energy: The shorter the wavelength, the higher the frequency and energy. In order of decreasing wavelength, the forms of light are **radio waves, microwaves, infrared, visible light, ultraviolet, X rays**, and **gamma rays**.

- **What is matter?**

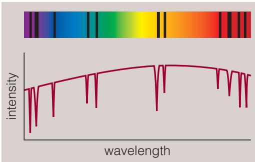
Ordinary matter is made of **atoms**, which are made of **protons, neutrons**, and **electrons**. Atoms of different **chemical elements** have different numbers of protons. **Isotopes** of a particular chemical element all have the same number of protons but different numbers of neutrons. **Molecules** are made from two or more atoms.

- **How do light and matter interact?**

Matter can emit, absorb, transmit, or reflect (or scatter) light.

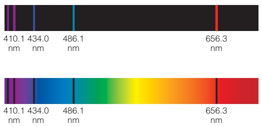
5.2 Learning from Light

- **What are the three basic types of spectra?**



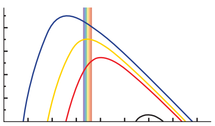
There are three basic types of spectra: a **continuous spectrum**, which looks like a rainbow; an **absorption line spectrum**, in which specific colors are missing from the rainbow; and an **emission line spectrum**, in which we see lines of specific colors against a black background.

- **How does light tell us what things are made of?**



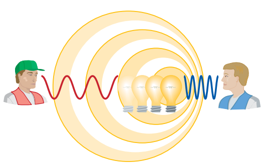
Emission or absorption lines occur only at specific wavelengths that correspond to particular energy level transitions in atoms or molecules. Every kind of atom, ion, and molecule produces a unique set of spectral lines, so we can determine an object's composition by identifying these lines.

- **How does light tell us the temperatures of planets and stars?**



Objects such as planets and stars produce **thermal radiation** spectra, the most common type of continuous spectra. We can determine temperature from these spectra because hotter objects emit more total radiation per unit area and emit photons with a higher average energy.

- **How does light tell us the speed of a distant object?**



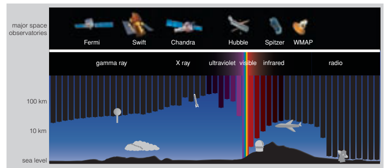
The **Doppler effect** tells us how fast an object is moving toward or away from us. Spectral lines are shifted to shorter wavelengths (a **blueshift**) for objects moving toward us and to longer wavelengths (a **redshift**) for objects moving away from us.

5.3 Collecting Light with Telescopes

- **How do telescopes help us learn about the universe?**

Telescopes allow us to see fainter objects and to see more detail than we can see with our eyes. Telescopes specialized to observe different wavelengths of light allow us to learn far more than we could from visible light alone. **Light-collecting area** describes how much light a telescope can collect, and **angular resolution** determines the amount of detail in telescopic images.

- **Why do we put telescopes in space?**



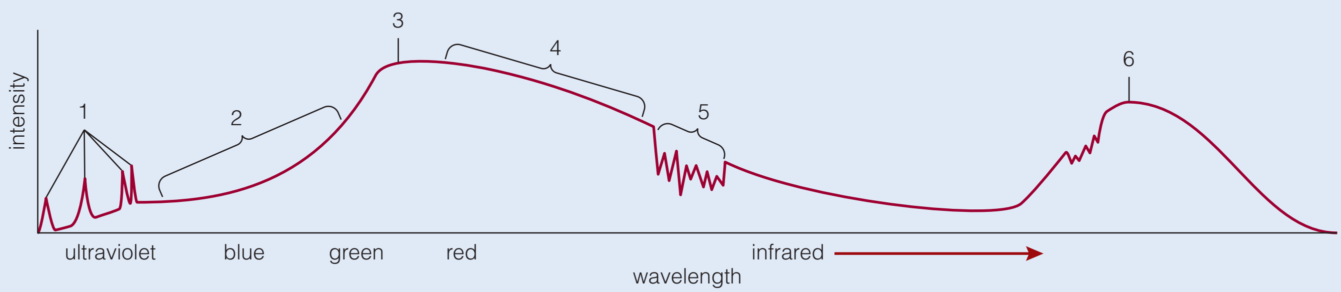
Telescopes in space are above Earth's atmosphere and not subject to problems caused by **light pollution**, atmospheric distortion of light, or the fact that most forms of light do not penetrate through the atmosphere to the ground.

- **How is technology revolutionizing astronomy?**

Technology makes it possible to build more powerful telescopes and to enhance the capabilities of existing telescopes. Two key technologies are **adaptive optics**, which can overcome the distorting effects of Earth's atmosphere, and **interferometry**, in which individual telescopes are linked in a way that allows them to obtain the angular resolution of a much larger telescope.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 5 Visual Quiz at www.masteringastronomy.com.



The graph above is a schematic spectrum of the planet Mars; it is the same spectrum shown in Figure 5.16. Keeping in mind that Mars reflects visible sunlight and emits infrared light, refer to the numbered features of the graph and answer the following questions.

1. Which of the six numbered features represents emission lines?
2. Which of the six numbered features represents absorption lines?
3. Which portion(s) of the spectrum represent(s) reflected sunlight?
   a. 1 only b. 2, 3, and 4
   c. 3 and 6 d. the entire spectrum
4. What does the wavelength of the peak labeled 6 tell us about Mars?
   a. its color b. its surface temperature
   c. its chemical composition d. its orbital speed
5. What feature(s) of this spectrum indicate(s) that Mars appears red in color?
   a. the wavelength of the peak labeled 3
   b. the wavelength of the peak labeled 6
   c. the fact that the intensity of region 4 is higher than that of region 2
   d. the fact that the peak labeled 3 is higher than the peak labeled 6

exercises and problems

Mastering ASTRONOMY

For instructor-assigned homework go to www.masteringastronomy.com.

Review Questions

1. Define *wavelength, frequency*, and *speed* for light waves. If light has a long wavelength, what can you say about its frequency? Explain.
2. What is a *photon?* In what way is a photon like a particle? In what way is it like a wave?
3. List the different forms of light in order from lowest to highest energy. Would the list be different if you went in order from lowest to highest frequency? From shortest to longest wavelength? Explain.
4. Briefly describe the structure of an atom. How big is an atom? How big is the *nucleus* compared to the entire atom?
5. What determines the atom's *atomic number?* What determines its *atomic mass number?* Under what conditions are two atoms different isotopes of the same element?
6. What is *electrical charge?* Will an electron and a proton attract or repel one another? Will two electrons attract or repel one another? Explain.
7. What are the four major ways in which light and matter can interact? Give an example from everyday life of each type of interaction.
8. Describe the conditions that would cause us to see each of the three basic types of spectra. What do we see in the Sun's spectrum shown on the opening page of this chapter?
9. Why do atoms emit or absorb light of specific wavelengths? Briefly explain how we can use emission or absorption lines to determine the chemical composition of a distant object.
10. Describe two ways in which the thermal radiation spectrum of an 8000 K star would differ from that of a 4000 K star.
11. Describe the *Doppler effect* for light and what we can learn from it. What does it mean to say that radio waves are *blueshifted?*
12. What are the two key properties of a telescope, and why is each important?
13. Suppose that two stars are separated in the sky by 0.1 arcsecond. What will you see if you look at them with a telescope that has an angular resolution of 0.01 arcsecond? What will you see if you look at them with a telescope that has an angular resolution of 0.5 arcsecond?
14. Briefly describe the differences between a refracting telescope and a reflecting telescope. Which type is more commonly used by professional astronomers?
15. List at least three ways Earth's atmosphere can hinder astronomical observations, and explain why putting a telescope in space helps in each case.
16. Briefly describe how adaptive optics and interferometry can improve astronomical observations.

Test Your Understanding

Does It Make Sense?

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

17. If you could view a spectrum of the light reflecting off a blue sweatshirt, you'd find the entire rainbow of color (looking the same as a spectrum of white light).
18. Because of their higher frequency, X rays must travel through space faster than radio waves.
19. Two isotopes of the element rubidium differ in their number of protons.
20. If the Sun's surface became much hotter (while the Sun's size remained the same), the Sun would emit more ultraviolet light but less visible light than it currently emits.
21. If you could see infrared light, you would see a glow from the backs of your eyelids when you closed your eyes.
22. If you had X-ray vision, then you could read this entire book without turning any pages.
23. If a distant galaxy has a substantial redshift (as viewed from our galaxy), then anyone living in that galaxy would see a substantial redshift in a spectrum of the Milky Way Galaxy.
24. Thanks to adaptive optics, telescopes on the ground can now make ultraviolet images of the cosmos.
25. Thanks to interferometry, a properly spaced set of 10-meter radio telescopes can achieve the angular resolution of a single 100-kilometer radio telescope.
26. If you lived on the Moon, you'd never see stars twinkle.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

27. Why is a sunflower yellow? (a) It emits yellow light. (b) It absorbs yellow light. (c) It reflects yellow light.
28. Blue light has higher frequency than red light. Blue light therefore has (a) higher energy and shorter wavelength than red light.

(b) higher energy and longer wavelength than red light. (c) lower energy and shorter wavelength than red light.

29. Radio waves are (a) a form of sound. (b) a form of light. (c) a type of spectrum.
30. Compared to an atom as a whole, an atomic nucleus (a) is very tiny but has most of the mass. (b) is quite large and has most of the mass. (c) is very tiny and has very little mass.
31. Some nitrogen atoms have 7 neutrons and some have 8 neutrons; these two forms of nitrogen are (a) ions of each other. (b) phases of each other. (c) isotopes of each other.
32. The set of spectral lines that we see in a star's spectrum depends on the star's (a) atomic structure. (b) chemical composition. (c) rotation rate.
33. A star whose spectrum peaks in the infrared is (a) cooler than our Sun. (b) hotter than our Sun. (c) larger than our Sun.
34. A spectral line that appears at a wavelength of 321 nm in the laboratory appears at a wavelength of 328 nm in the spectrum of a distant object. We say that the object's spectrum is (a) redshifted. (b) blueshifted. (c) whiteshifted.
35. How much greater is the light-collecting area of a 6-meter telescope than that of a 3-meter telescope? (a) two times (b) four times (c) six times
36. The Hubble Space Telescope obtains higher-resolution images than most ground-based telescopes because it is (a) larger. (b) closer to the stars. (c) above Earth's atmosphere.

Process of Science

37. *Elements in Space.* Astronomers claim that objects throughout the universe are made of the same chemical elements that exist here on Earth. Given that most of these objects are so far away that we can never hope to visit them, why are astronomers so confident that the objects are made from the same set of chemical elements, rather than completely different substances?
38. *Newton's Prisms.* Look back at the brief discussion in this chapter of how Newton proved that the colors seen when sunlight passes through a prism come from the light itself rather than from the prism. Suppose you wanted to test Newton's findings. Assuming you have two prisms and a white screen, describe how you would arrange the prisms to duplicate Newton's discovery.

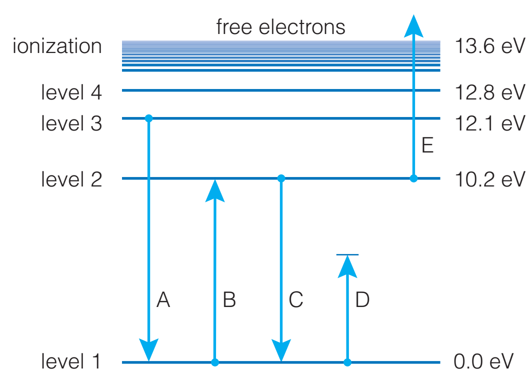
Group Work Exercise

39. *Which Telescope Would You Use?* Your job in this exercise is to choose the best telescope for observing matter around a black hole. You can assume that the matter is emitting photons at all wavelengths. Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Proposer* (proposes explanations to the group), *Skeptic* (points out weaknesses in proposed explanations), and *Moderator* (leads group discussion and makes sure everyone contributes). Then discuss the following four telescopes and rank them from best to worst for this particular observing task, explaining why you ranked each telescope where you did:
    a. an X-ray telescope, 2 meters in diameter, located at the South Pole
    b. an infrared telescope, 2 meters in diameter, on a spacecraft in orbit around Earth and observing at a wavelength of micrometers (2×10^{-6} m)
    c. an infrared telescope, 10 meters in diameter, equipped with adaptive optics, located on Mauna Kea in Hawaii and observing at a wavelength of micrometers (10^{-5} m)
    d. a radio telescope, 300 meters in diameter, located in Puerto Rico

Investigate Further

Short-Answer/Essay Questions

40. *Atomic Terminology Practice I.*
    a. The most common form of iron has 26 protons and 30 neutrons. State its atomic number, atomic mass number, and number of electrons if it is neutral.
    b. Consider the following three atoms: Atom 1 has seven protons and eight neutrons; atom 2 has eight protons and seven neutrons; atom 3 has eight protons and eight neutrons. Which two are *isotopes* of the same element?
    c. Oxygen has atomic number 8. How many times must an oxygen atom be ionized to create an O^{+5} ion? How many electrons are in an O^{+5} ion?
41. *Atomic Terminology Practice II.*
    a. What are the atomic number and atomic mass number of fluorine atoms with 9 protons and 10 neutrons? If we could add a proton to a fluorine nucleus, would the result still be fluorine? What if we added a neutron to a fluorine nucleus? Explain.
    b. The most common isotope of gold has atomic number 79 and atomic mass number 197. How many protons and neutrons does the gold nucleus contain? If it is electrically neutral, how many electrons does it have? If it is triply ionized, how many electrons does it have?
    c. Uranium has atomic number 92. Its most common isotope is ^{238}U, but the form used in nuclear bombs and nuclear power plants is ^{235}U. How many neutrons are in each of these two isotopes of uranium?
42. *Energy Level Transitions.* The following labeled transitions represent an electron moving between energy levels in hydrogen. Answer each of the following questions and explain your answers.



    a. Which transition could represent an atom that *absorbs* a photon with 10.2 eV of energy?
    b. Which transition could represent an atom that *emits* a photon with 10.2 eV of energy?
    c. Which transition represents an electron that is breaking free of the atom?
    d. Which transition, as shown, is *not* possible?
    e. Would transition A represent emission or absorption of light? How would the wavelength of the emitted or absorbed photon compare to that of the photon involved in transition C? Explain.
43. *Orion Nebula.* Viewed through a telescope, much of the Orion Nebula looks like a glowing cloud of gas. What type of spectrum would you expect to see from the glowing parts of the nebula? Why?

44. *The Doppler Effect.* In hydrogen, the transition from level 2 to level 1 has a rest wavelength of 121.6 nm. Suppose you see this line at a wavelength of 120.5 nm in Star A, at 121.2 nm in Star B, at 121.9 nm in Star C, and at 122.9 nm in Star D. Which stars are coming toward us? Which are moving away? Which star is moving fastest relative to us? Explain your answers without doing any calculations.
45. *Spectral Summary.* Clearly explain how studying an object's spectrum can allow us to determine each of the following properties of the object.
    a. The object's surface chemical composition
    b. The object's surface temperature
    c. Whether the object is a low-density cloud of gas or something more substantial
    d. The speed at which the object is moving toward or away from us
46. *Image Resolution.* What happens if you take a photograph from a newspaper, magazine, or book and blow it up to a larger size? Can you see more detail than you could before? Explain clearly, and relate your answer to the concepts of magnification and angular resolution in astronomical observations.
47. *Telescope Technology.* Suppose you were building a space-based observatory consisting of five individual telescopes. Which would be the best way to use these telescopes: as five individual telescopes with adaptive optics, or as five telescopes linked together for interferometry but without adaptive optics? Explain your reasoning clearly.
48. *Project: Twinkling Stars.* Using a star chart, identify 5–10 bright stars that should be visible in the early evening. On a clear night, observe each of these stars for a few minutes. Note the date and time, and for each star record the following information: approximate altitude and direction in your sky, brightness compared to other stars, color, and how much the star twinkles compared to other stars. Study your record. Can you draw any conclusions about how brightness and position in your sky affect twinkling?

Quantitative Problems

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

49. *Thermal Radiation Laws I.* Consider a 3000 K object that emits thermal radiation. How much power does it emit per square meter? What is its wavelength of peak intensity?
50. *Thermal Radiation Laws II.* Consider a 50,000 K object that emits thermal radiation. How much power does it emit per square meter? What is its wavelength of peak intensity?
51. *Hotter Sun.* Suppose the surface temperature of the Sun were about 12,000 K, rather than 6000 K.
    a. How much more thermal radiation would the Sun emit?
    b. What would happen to the Sun's wavelength of peak emission?
    c. Do you think it would still be possible to have life on Earth? Explain.
52. *Doppler Calculations I.* In hydrogen, the transition from level 2 to level 1 has a rest wavelength of 121.6 nm. Suppose you see this line at a wavelength of 120.5 nm in Star A and at 121.2 nm in Star B. Calculate each star's speed, and be sure to state whether it is moving toward or away from us.
53. *Doppler Calculations II.* In hydrogen, the transition from level 2 to level 1 has a rest wavelength of 121.6 nm. Suppose you see this line at a wavelength of 121.9 nm in Star C and at 122.9 nm in Star D. Calculate each star's speed, and be sure to state whether it is moving toward or away from us.
54. *Hubble's Field of View.* Large telescopes often have small fields of view. For example, the Hubble Space Telescope's (HST's) advanced camera has a field of view that is roughly square and about 0.06° on a side.
    a. Calculate the angular area of the HST's field of view in square degrees.
    b. The angular area of the entire sky is about 41,250 square degrees. How many pictures would the HST have to take with its camera to obtain a complete picture of the entire sky?

Discussion Questions

55. *The Changing Limitations of Science.* In 1835, French philosopher Auguste Comte stated that science would never allow us to learn the composition of stars. Although spectral lines had been seen in the Sun's spectrum at that time, it wasn't until the mid–19th century that scientists recognized that spectral lines give clear information about chemical composition (primarily through the work of Foucault and Kirchhoff). Why might our present knowledge have seemed unattainable in 1835? Discuss how new discoveries can change the apparent limitations of science. Today, other questions seem beyond the reach of science, such as the question of how life began on Earth. Do you think such questions will ever be answerable through science? Defend your opinion.
56. *Science and Technology Funding.* Technological innovation clearly drives scientific discovery in astronomy, but the reverse is also true. For example, Newton made his discoveries in part because he wanted to explain the motions of the planets, but his discoveries have had far-reaching effects on our civilization. Congress often must decide between funding programs with purely scientific purposes ("basic research") and funding programs designed to develop new technologies. If you were a member of Congress, how would you try to allocate spending for basic research and technology? Why?
57. *Your Microwave Oven.* A *microwave oven* emits microwaves that have just the right wavelength needed to cause energy level changes in water molecules. Use this fact to explain how a microwave oven cooks your food. Why doesn't a microwave oven make a plastic dish get hot? Why do some clay dishes get hot in the microwave? Why do dishes that aren't themselves heated by the microwave oven sometimes still get hot when you heat food on them? (*Note:* It's not a good idea to put empty dishes in a microwave.)

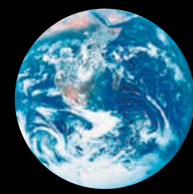
Web Projects

58. *Kids and Light.* Visit one of the many Web sites designed to teach middle and high school students about light. Read the content, and try the activities. If you were a teacher, would you find the site useful for your students? Why or why not? Write a one-page summary of your conclusions.
59. *Major Ground-Based Observatories.* Take a virtual tour of one of the world's major astronomical observatories. Write a short report on why the observatory is useful to astronomy.
60. *Space Observatory.* Visit the Web site of a major space observatory, either existing or under development. Write a short report about the observatory, including its purpose, its orbit, and how it operates.
61. *Really Big Telescopes.* Several studies are currently investigating the construction of telescopes far larger than any in operation. Learn about one or more of these projects (such as the 50-meter Overwhelming Large Telescope [OWL] or the Thirty Meter Telescope [TMT]), and write a short report about the telescope's potential capabilities and prospects.

cosmic **Context**

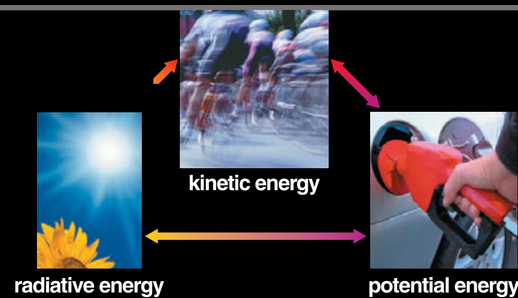
Part II at a Glance. The Universality of Physics

One of Isaac Newton's great insights was that physics is universal—the same physical laws govern both the motions of heavenly objects and the things we experience in everyday life. This illustration shows some of the key physical principles used in the study of astronomy, with examples of how they apply both on Earth and in space.



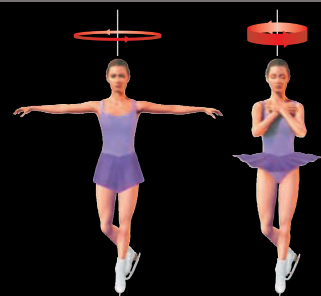
EXAMPLES ON EARTH

① **Conservation of Energy:** Energy can be transferred from one object to another or transformed from one type to another, but the total amount of energy is always conserved [Section 4.3].



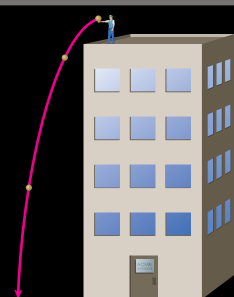
Plants transform the energy of sunlight into food containing chemical potential energy, which our bodies can convert into energy of motion.

② **Conservation of Angular Momentum:** An object's angular momentum cannot change unless it transfers angular momentum to another object. Because angular momentum depends on the product of mass, velocity, and radius, a spinning object must spin faster as it shrinks in size and an orbiting object must move faster when its orbital distance is smaller [Section 4.3].



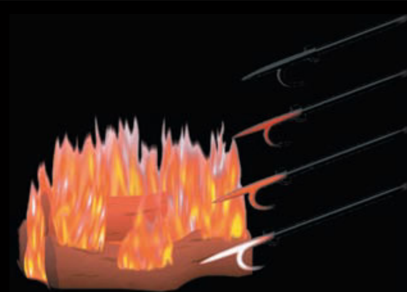
Conservation of angular momentum explains why a skater spins faster as she pulls in her arms.

③ **Gravity:** Every mass in the universe attracts every other mass through the force called gravity. The strength of gravity between two objects depends on the product of the masses divided by the square of the distance between them [Section 4.4].



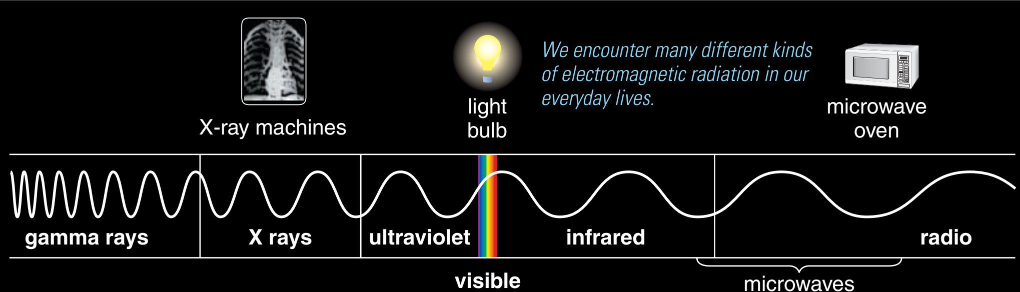
The force of gravity between a ball and Earth attracts both together, explaining why the ball accelerates as it falls.

④ **Thermal Radiation:** Large objects emit a thermal radiation spectrum that depends on the object's temperature. Hotter objects emit photons with a higher average energy and emit radiation of greater intensity at all wavelengths [Section 5.2].



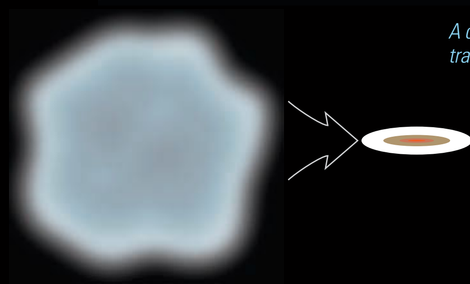
The glow you see from a hot fireplace poker is thermal radiation in the form of visible light.

⑤ **Electromagnetic Spectrum:** Light is a wave that affects electrically charged particles and magnets. The wavelength and frequency of light waves range over a wide spectrum, consisting of gamma rays, X rays, ultraviolet light, visible light, infrared light, and radio waves. Visible light is only a small fraction of the entire spectrum [Section 5.1].

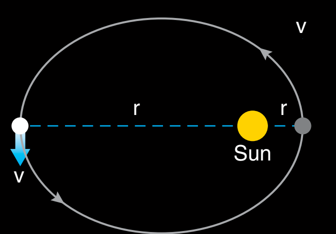


We encounter many different kinds of electromagnetic radiation in our everyday lives.

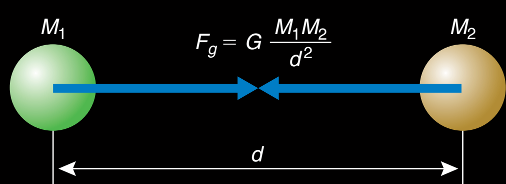
EXAMPLES IN SPACE



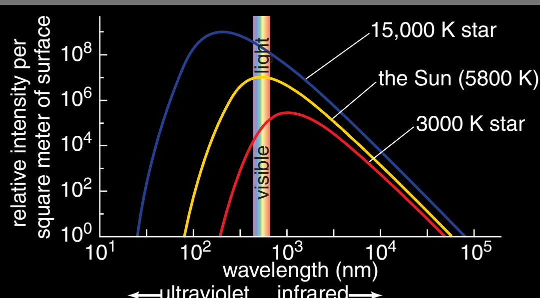
A contracting gas cloud in space heats up because it transforms gravitational potential energy into thermal energy.



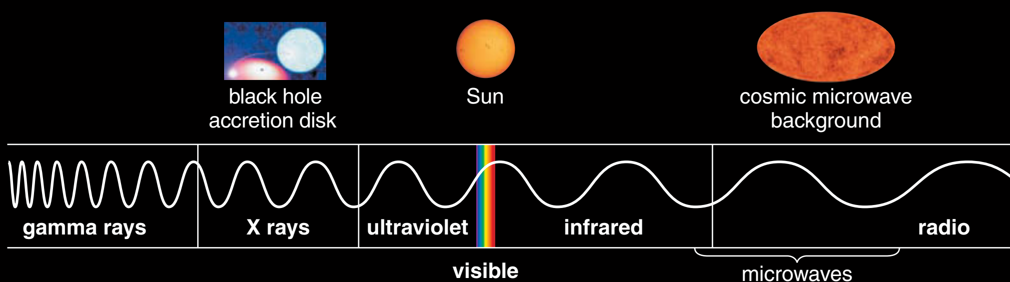
Conservation of angular momentum also explains why a planet's orbital speed increases when it is closer to the Sun.



Gravity also operates in space—its attractive force can act across great distances to pull objects closer together or to hold them in orbit.



Sunlight is also a visible form of thermal radiation. The Sun is much brighter and whiter than a fireplace poker because its surface is much hotter.



Many different forms of electromagnetic radiation are present in space. We therefore need to observe light of many different wavelengths to get a complete picture of the universe.

6

Formation of Planetary Systems

Our Solar System and Beyond

learning goals

6.1 A Brief Tour of the Solar System

- What does the solar system look like?

6.2 Clues to the Formation of Our Solar System

- What features of our solar system provide clues to how it formed?
- What theory best explains the features of our solar system?

6.3 The Birth of the Solar System

- Where did the solar system come from?
- What caused the orderly patterns of motion in our solar system?

6.4 The Formation of Planets

- Why are there two major types of planets?
- Where did asteroids and comets come from?
- How do we explain the existence of our Moon and other exceptions to the rules?
- When did the planets form?

6.5 Other Planetary Systems

- How do we detect planets around other stars?
- How do extrasolar planets compare with planets in our solar system?
- Do we need to modify our theory of solar system formation?

Now that we have discussed some of the key laws that govern nature, we can apply these laws to the study of objects throughout our universe. We will begin with our solar system in this and the next three chapters, and later study stars, galaxies, and the universe.

In this chapter, we'll explore the nature of our solar system and current scientific ideas about its birth. After a brief overview of the solar system and its individual worlds, we'll focus on characteristics of the solar system that offer key clues about how it formed. Finally, we'll learn how astronomers have discovered planets around other stars, and how these other planetary systems are helping us understand our own.

essential preparation

1. What is our place in the universe? **[Section 1.1]**
2. How did we come to be? **[Section 1.1]**
3. How big is Earth compared to our solar system? **[Section 1.2]**
4. What keeps a planet rotating and orbiting the Sun? **[Section 4.3]**
5. How does light tell us the speed of a distant object? **[Section 5.2]**

MA Scale of the Universe Tutorial, Lesson 1

6.1 A Brief Tour of the Solar System

Our ancestors long ago recognized the motions of the planets through the sky, but it has been only a few hundred years since we learned that Earth is also a planet that orbits the Sun. Even then, we knew little about the other planets until the development of large telescopes. More recently, space exploration has brought us far greater understanding of other worlds. We've lived in this solar system all along, but only now are we getting to know it. Let's begin with a quick tour of our planetary system, which will provide context for the more detailed study that will follow.

• What does the solar system look like?

The first step in getting to know our solar system is to visualize what it looks like as a whole. Imagine viewing the solar system from beyond the orbits of the planets. What would we see?

Without a telescope, the answer would be "not much." Remember that the Sun and planets are all quite small compared to the distances between them **[Section 1.2]**—so small that if we viewed them from the outskirts of our solar system, the planets would be only pinpoints of light, and even the Sun would be just a small bright dot in the sky. But if we magnify the sizes of the planets by about a million times compared to their distances from the Sun and show their orbital paths, we get the central picture in Figure 6.1 (pages 144–145).

The ten pages that follow Figure 6.1 offer a brief tour through our solar system, beginning at the Sun and continuing to each of the planets. The tour highlights a few of the most important features of each world we visit—just enough information so that you'll be ready for the comparative study we'll undertake in later chapters. The side of each page shows the planets to scale, using the 1-to-10-billion scale introduced in Chapter 1. The map along the bottom of each page shows the locations of the Sun and each of the planets in the Voyage scale model solar system (see Figures 1.5 and 1.6) so that you can see relative distances from the Sun. Table 6.1, which follows the tour, summarizes key planetary data.

As you study Figure 6.1, the tour pages, and Table 6.1, you'll quickly see that our solar system is *not* a random collection of worlds. Figure 6.1 shows that all the planets orbit the Sun in the same direction and in nearly the same plane, while the figure and tour show that the four inner planets are quite different in character from the next four planets.

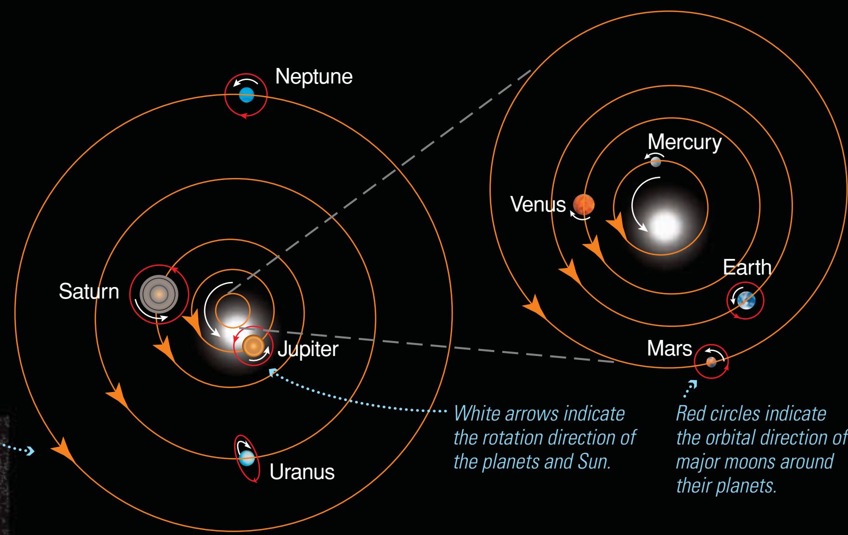
(main text continued on page 157)

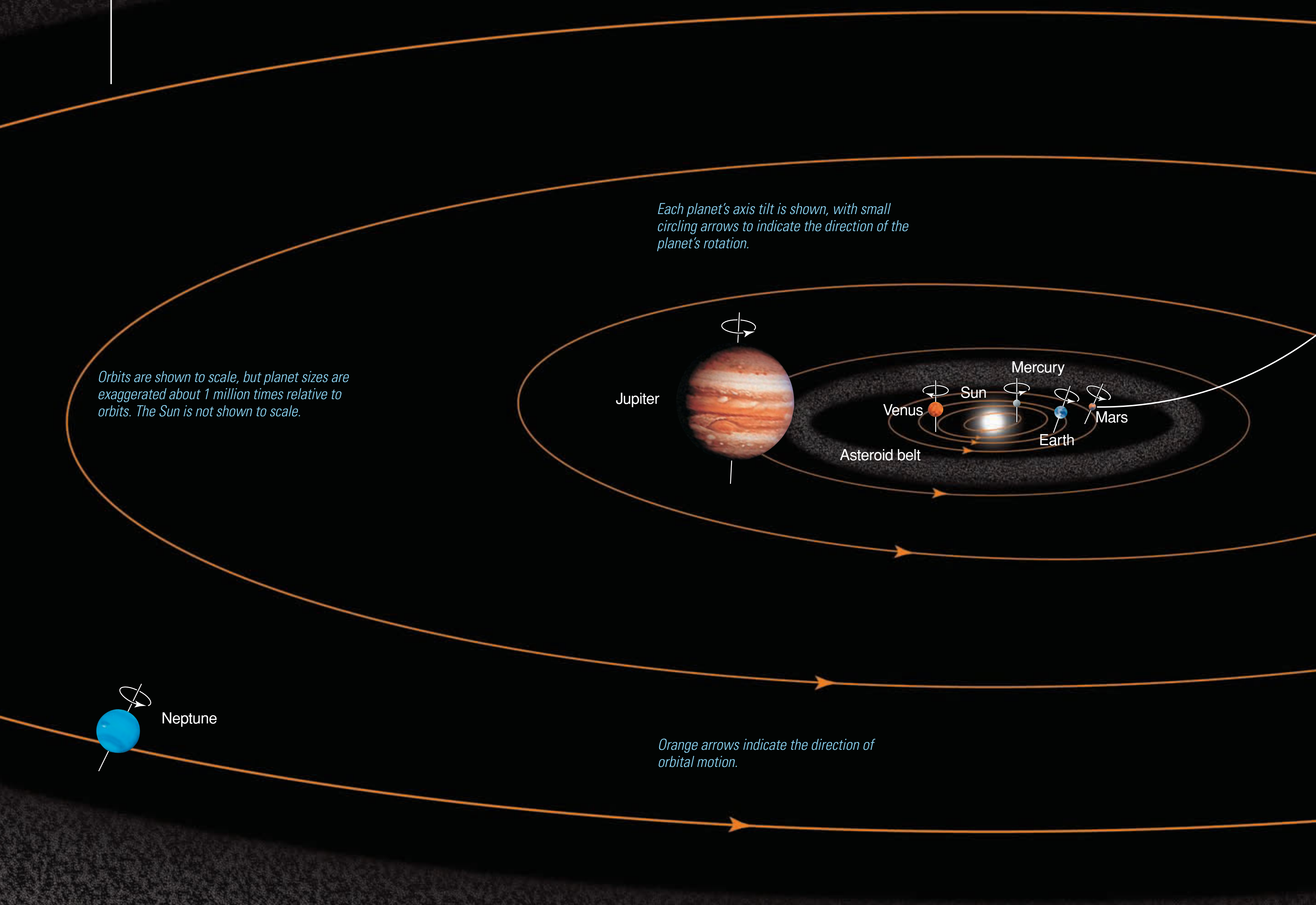
cosmic**Context** Figure 6.1. The Solar System

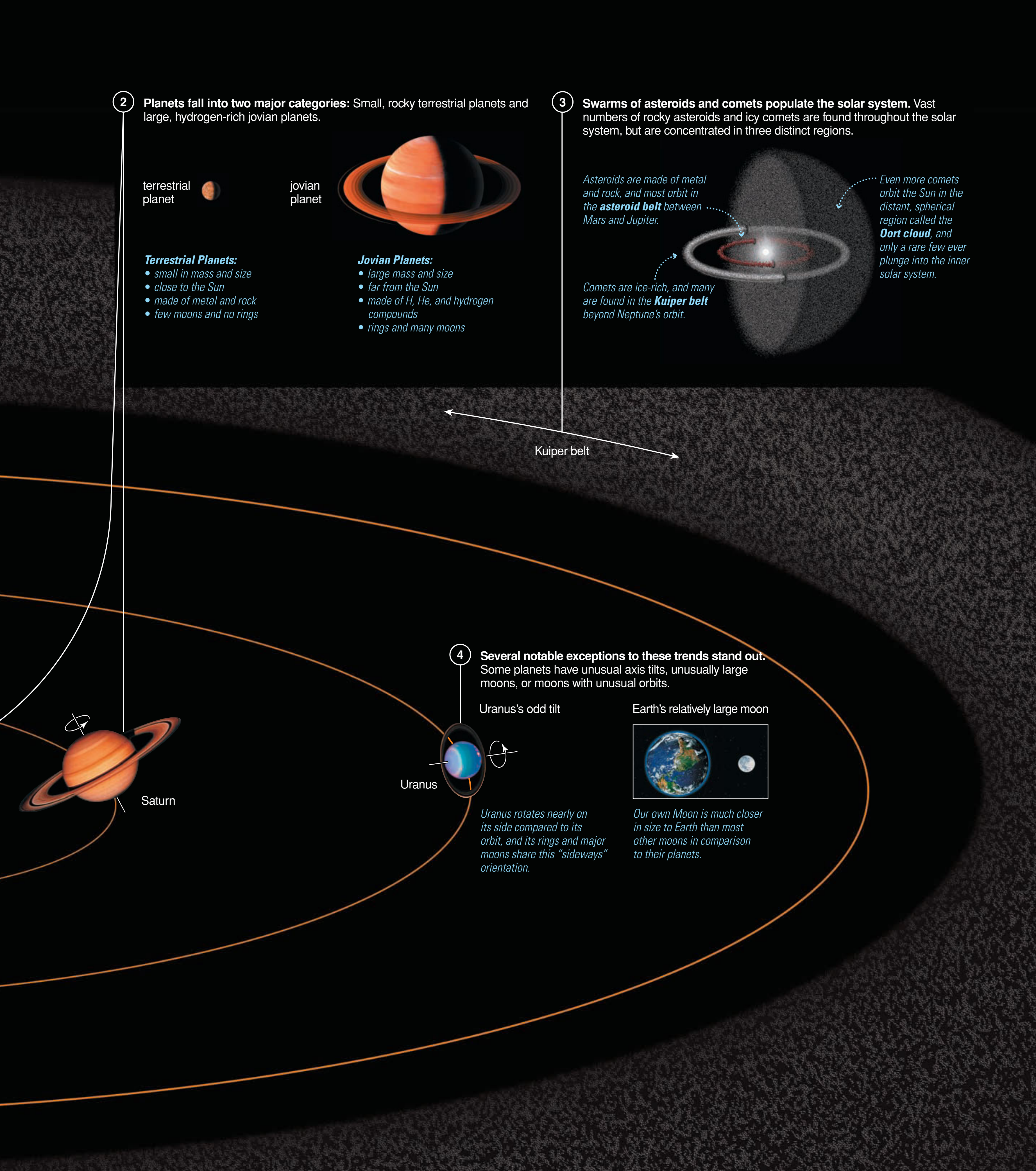
MA interactive figure

The solar system's layout and composition offer four major clues to how it formed. The main illustration below shows the orbits of planets in the solar system from a perspective beyond Neptune, with the planets themselves magnified by about a million times relative to their orbits.

1. **Large bodies in the solar system have orderly motions.** All planets have nearly circular orbits going in the same direction in nearly the same plane. Most large moons orbit their planets in this same direction, which is also the direction of the Sun's rotation.







2 Planets fall into two major categories: Small, rocky terrestrial planets and large, hydrogen-rich jovian planets.
terrestrial planet
jovian planet
Terrestrial Planets:
• small in mass and size
• close to the Sun
• made of metal and rock
• few moons and no rings
Jovian Planets:
• large mass and size
• far from the Sun
• made of H, He, and hydrogen compounds
• rings and many moons
3 Swarms of asteroids and comets populate the solar system. Vast numbers of rocky asteroids and icy comets are found throughout the solar system, but are concentrated in three distinct regions.
Asteroids are made of metal and rock, and most orbit in the asteroid belt between Mars and Jupiter.
Comets are ice-rich, and many are found in the Kuiper belt beyond Neptune's orbit.
Even more comets orbit the Sun in the distant, spherical region called the Oort cloud, and only a rare few ever plunge into the inner solar system.
Kuiper belt
4 Several notable exceptions to these trends stand out. Some planets have unusual axis tilts, unusually large moons, or moons with unusual orbits.
Uranus's odd tilt
Earth's relatively large moon
Uranus
Saturn
Uranus rotates nearly on its side compared to its orbit, and its rings and major moons share this "sideways" orientation.
Our own Moon is much closer in size to Earth than most other moons in comparison to their planets.

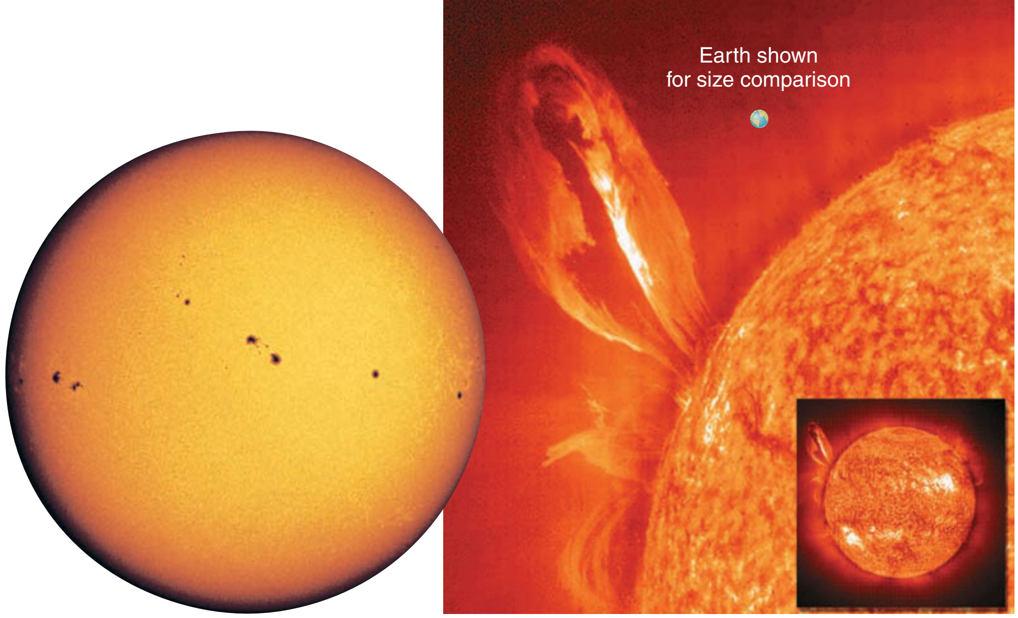


Figure 6.2

The Sun contains more than 99.8% of the total mass in our solar system.

a A visible-light photograph of the Sun's surface. The dark splotches are sunspots—each large enough to swallow several Earths.

b This ultraviolet photograph, from the *SOHO* spacecraft, shows a huge streamer of hot gas on the Sun.

• The Sun

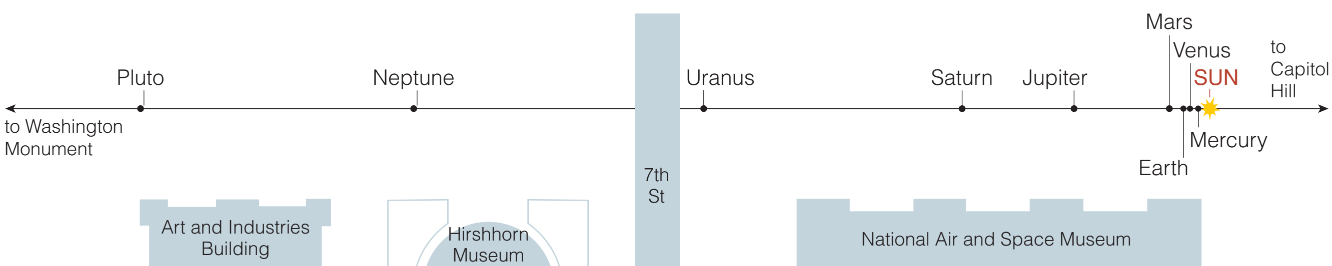
- Radius: 696,000 km = $108R_{\text{Earth}}$
- Mass: $333{,}000M_{\text{Earth}}$
- Composition (by mass): 98% hydrogen and helium, 2% other elements

The Sun is by far the largest and brightest object in our solar system. It contains more than 99.8% of the solar system's total mass, making it more than a thousand times as massive as everything else in the solar system combined.

The Sun's surface looks solid in photographs (Figure 6.2), but it is actually a roiling sea of hot (about 5800 K, or 5500°C or 10,000°F) hydrogen and helium gas. The surface is speckled with sunspots that appear dark in photographs only because they are slightly cooler than their surroundings. Solar storms sometimes send streamers of hot gas soaring far above the surface.

The Sun is gaseous throughout, and the temperature and pressure both increase with depth. The source of the Sun's energy lies deep in its core, where the temperatures and pressures are so high that the Sun is a nuclear fusion power plant. Each second, fusion transforms about 600 million tons of the Sun's hydrogen into 596 million tons of helium. The "missing" 4 million tons becomes energy in accord with Einstein's famous formula, $E = mc^2$ **[Section 4.3]**. Despite losing 4 million tons of mass each second, the Sun contains so much hydrogen that it has already shone steadily for almost 5 billion years and will continue to shine for another 5 billion years.

The Sun is the most influential object in our solar system. Its gravity governs the orbits of the planets. Its heat is the primary influence on the temperatures of planetary surfaces and atmospheres. It is the source of virtually all the visible light in our solar system—the Moon and planets shine only by virtue of the sunlight they reflect. In addition, charged particles flowing outward from the Sun (the *solar wind*) help shape planetary magnetic fields and can influence planetary atmospheres. Nevertheless, we can understand almost all the present characteristics of the planets without knowing much more about the Sun than what we have just discussed. We'll save more detailed study of the Sun for Chapter 10, where we will study it as our prototype for understanding other stars.



The Voyage scale model solar system represents sizes and distances in our solar system at one ten-billionth of their actual values (see Figure 1.6). The strip along the side of the page shows the sizes of the Sun and planets on this scale, and the map above shows their locations in the Voyage model on the National Mall in Washington, D.C. The Sun is about the size of a large grapefruit on this scale.

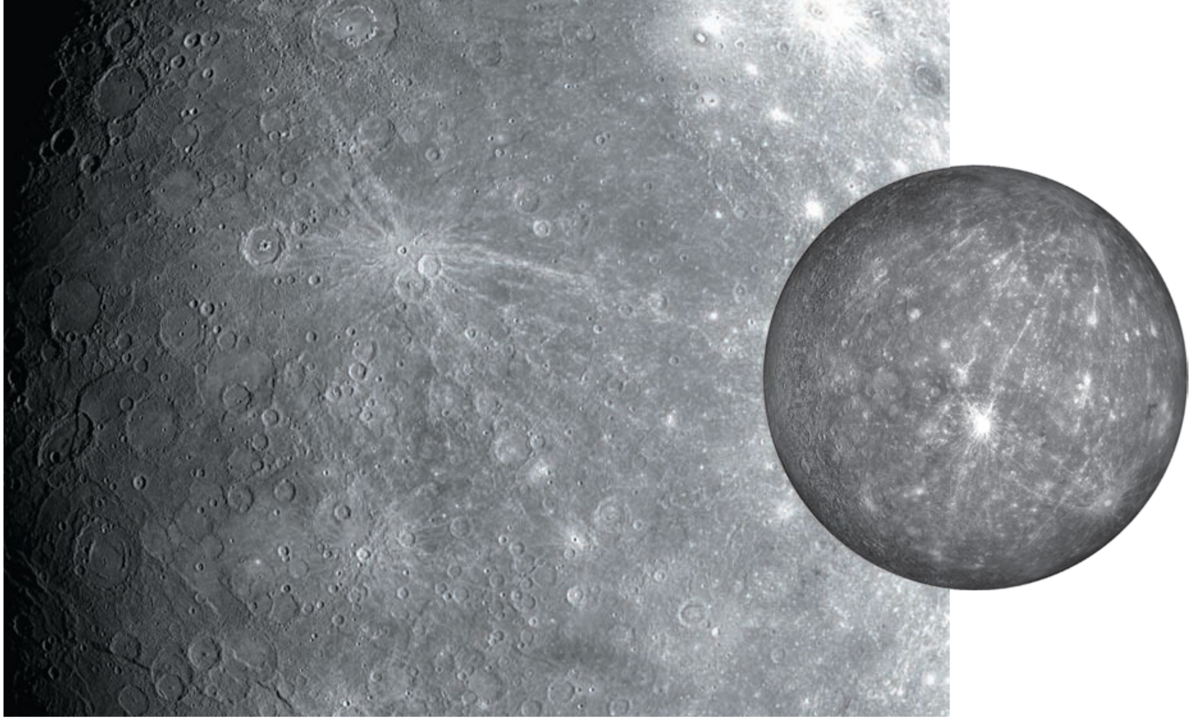


Figure 6.3

The main image, taken by the *MESSENGER* spacecraft, shows that Mercury's surface is heavily cratered but also has smooth volcanic plains and long, steep cliffs. The inset shows a nearly global composite image from *MESSENGER*.

Mercury

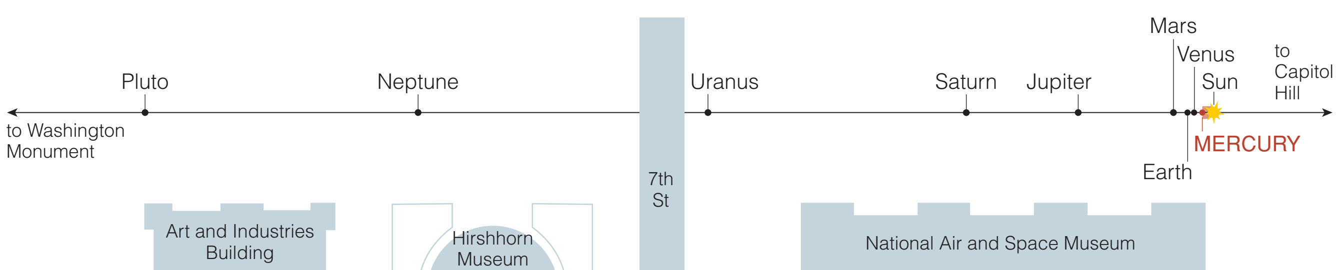
- Average distance from the Sun: 0.39 AU
- Radius: 2440 km = $0.38R_{\text{Earth}}$
- Mass: $0.055M_{\text{Earth}}$
- Average density: 5.43 g/cm^3
- Composition: rocks, metals
- Average surface temperature: 700 K (day), 100 K (night)
- Moons: 0

Mercury is the innermost planet of our solar system, and the smallest of the eight official planets. It is a desolate, cratered world with no active volcanoes, no wind, no rain, and no life. Because there is virtually no air to scatter sunlight or color the sky, you could see stars even in the daytime if you stood on Mercury with your back toward the Sun.

You might expect Mercury to be very hot because of its closeness to the Sun, but in fact it is a world of both hot and cold extremes. Tidal forces from the Sun have forced Mercury into an unusual rotation pattern: Its 58.6-day rotation period means it rotates exactly three times for every two of its 87.9-day orbits of the Sun. This combination of rotation and orbit gives Mercury days and nights that last about 3 Earth months each. Daytime temperatures reach 425°C—nearly as hot as hot coals. At night or in shadow, the temperature falls below −150°C—far colder than Antarctica in winter.

Mercury's surface is heavily cratered, much like the surface of our Moon (Figure 6.3). But it also shows evidence of past geological activity, such as plains created by ancient lava flows and tall, steep cliffs that run hundreds of kilometers in length. These cliffs may be wrinkles from an episode of "planetary shrinking" early in Mercury's history. Mercury's high density (calculated from its mass and volume) indicates that it has a very large iron core, perhaps because it once suffered a huge impact that blasted its outer layers away.

Mercury is the least studied of the inner planets, in part because its proximity to the Sun makes it difficult to observe through telescopes. We are on the brink of a new wave of exploration, with NASA's *MESSENGER* mission reaching Mercury orbit in 2011 (after three earlier flybys) and ESA's *Bepi Colombo* mission launching in 2013.



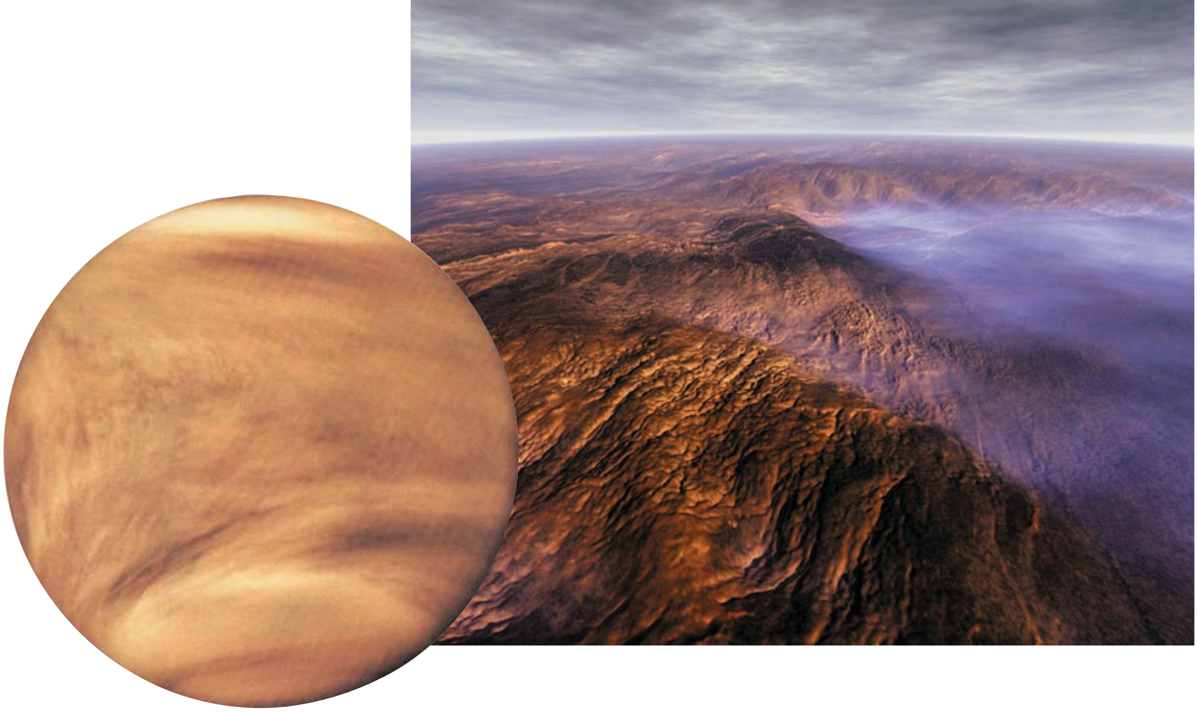


Figure 6.4

The image above shows an artistic rendition of the surface of Venus as scientists think it would appear to our eyes. The surface topography is based on data from NASA's *Magellan* spacecraft. The inset (left) shows the full disk of Venus photographed by NASA's *Pioneer Venus Orbiter* with cameras sensitive to ultraviolet light. With visible light, cloud features cannot be distinguished from the general haze. (Image above from the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image by David P. Anderson, Southern Methodist University © 2001.)

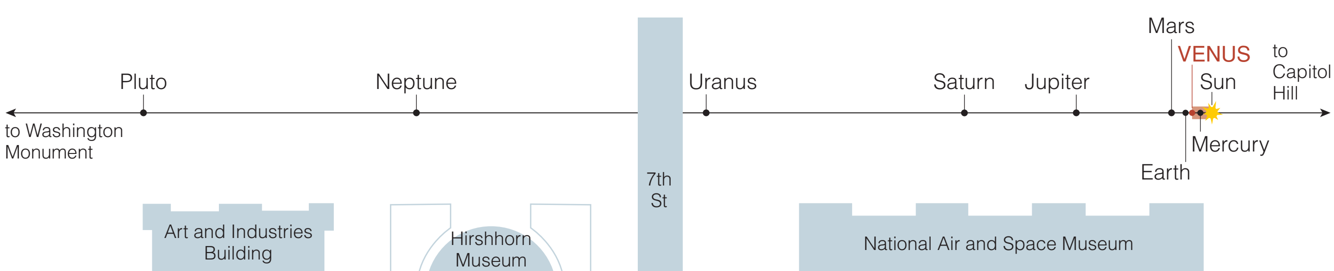
Venus

- Average distance from the Sun: 0.72 AU
- Radius: 6051 km = $0.95R_{\mathrm{Earth}}$
- Mass: $0.82M_{\mathrm{Earth}}$
- Average density: 5.24 g/cm^3
- Composition: rocks, metals
- Average surface temperature: 740 K
- Moons: 0

Venus, the second planet from the Sun, is nearly identical in size to Earth. Before the era of spacecraft visits, Venus stood out largely for its strange rotation: It rotates on its axis very slowly and in the opposite direction of Earth, so days and nights are very long and the Sun rises in the west and sets in the east instead of rising in the east and setting in the west. Its surface is completely hidden from view by dense clouds, so we knew little about it until a few decades ago, when spacecraft began to map Venus with cloud-penetrating radar (Figure 6.4). Because we knew so little about it, some science fiction writers used its Earth-like size, thick atmosphere, and closer distance to the Sun to speculate that it might be a lush, tropical paradise—a "sister planet" to Earth.

The reality is far different. We now know that an extreme *greenhouse effect* bakes Venus's surface to an incredible 470°C (about 880°F), trapping heat so effectively that nighttime offers no relief. Day and night, Venus is hotter than a pizza oven, and the thick atmosphere bears down on the surface with a pressure equivalent to that nearly a kilometer (0.6 mile) beneath the ocean's surface on Earth. Far from being a beautiful sister planet to Earth, Venus resembles a traditional view of hell.

Venus has mountains, valleys, and craters, and shows many signs of past or present volcanic activity. But Venus also has geological features unlike any on Earth, and we see no evidence of Earth-like plate tectonics. We are learning more about Venus through studies by the European Space Agency's *Venus Express* spacecraft, orbiting Venus since 2006, and Japan's Venus Climate Orbiter *Akatsuki*, orbiting since late 2010.



a This image (left), computer generated from satellite data, shows the striking contrast between the daylight and nighttime hemispheres of Earth. The day side reveals little evidence of human presence, but at night our presence is revealed by the lights of human activity. (From the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image created by ARC Science Simulations © 2001.)

b Earth and the Moon, shown to scale. The Moon's diameter is about one-fourth of Earth's diameter, and its mass is about 1/80 of Earth's mass. If you wanted to show the distance between Earth and Moon on the same scale, you'd need to hold these two photographs about 1 meter (3 feet) apart.

Figure 6.5

Earth, our home planet.

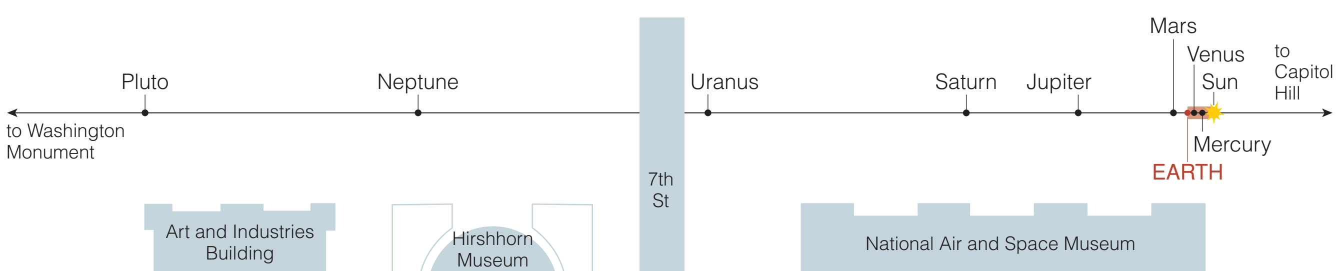
Earth

- Average distance from the Sun: 1.00 AU
- Radius: 6378 km = $1R_{\mathrm{Earth}}$
- Mass: $1.00M_{\mathrm{Earth}}$
- Average density: 5.52 g/cm^3
- Composition: rocks, metals
- Average surface temperature: 290 K
- Moons: 1

Beyond Venus, we next encounter our home planet, Earth, the only known oasis of life in our solar system. Earth is also the only planet in our solar system with oxygen to breathe, ozone to shield the surface from deadly solar radiation, and abundant surface water to nurture life. Temperatures are pleasant because Earth's atmosphere contains just enough carbon dioxide and water vapor to maintain a moderate greenhouse effect.

Despite Earth's small size, its beauty is striking (Figure 6.5a). Blue oceans cover nearly three-fourths of the surface, broken by the continental land masses and scattered islands. The polar caps are white with snow and ice, and white clouds are scattered above the surface. At night, the glow of artificial lights reveals the presence of an intelligent civilization.

Earth is the first planet on our tour with a moon. The Moon is surprisingly large compared with Earth (Figure 6.5b), although it is not the largest moon in the solar system; almost all other moons are much smaller relative to the planets they orbit. As we'll discuss later in this chapter, the leading hypothesis holds that the Moon formed as a result of a giant impact early in Earth's history.



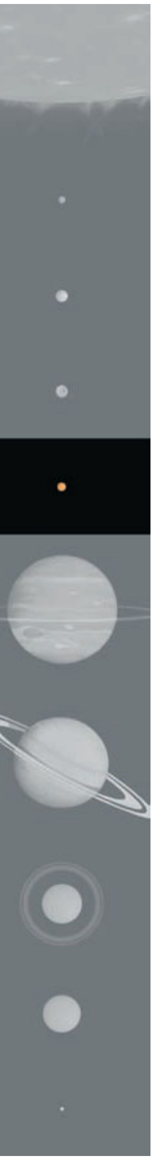
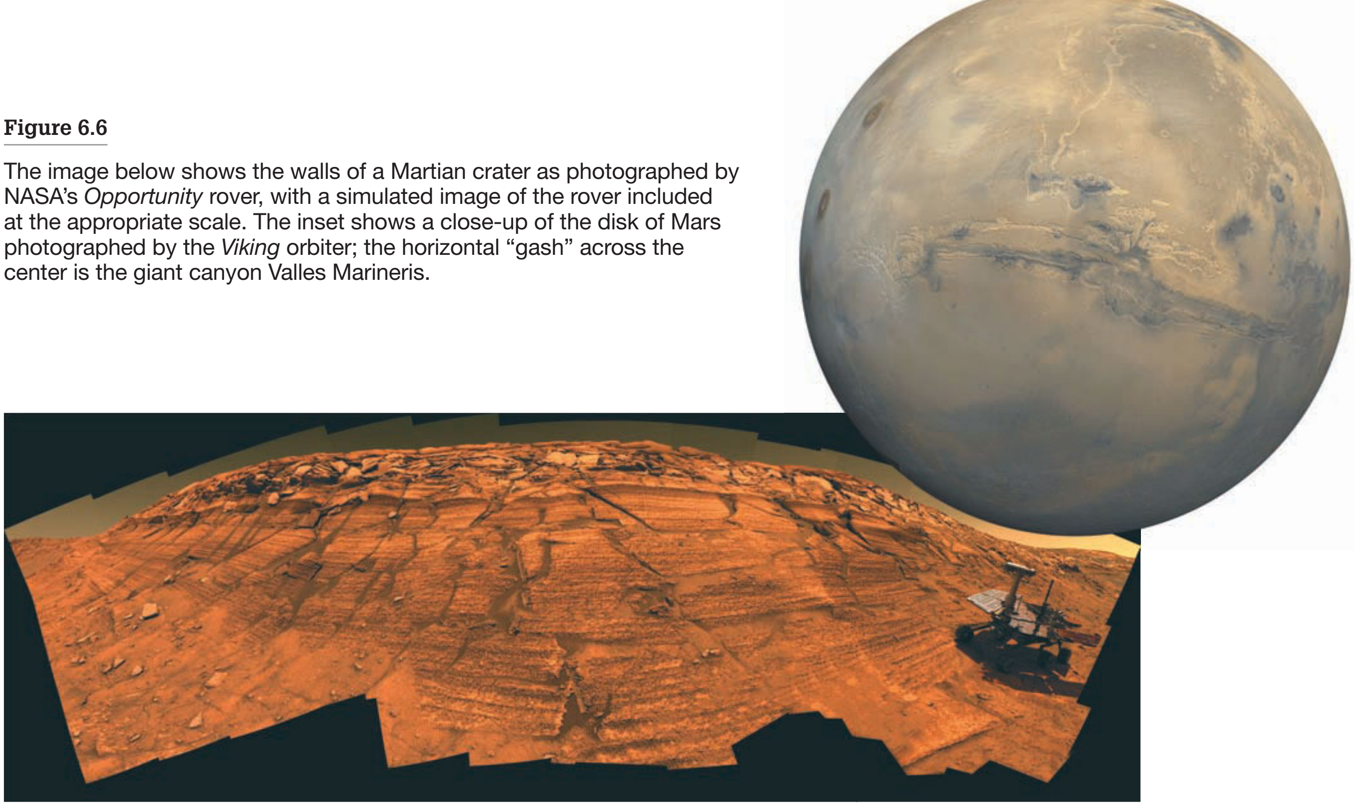


Figure 6.6

The image below shows the walls of a Martian crater as photographed by NASA's *Opportunity* rover, with a simulated image of the rover included at the appropriate scale. The inset shows a close-up of the disk of Mars photographed by the *Viking* orbiter; the horizontal "gash" across the center is the giant canyon Valles Marineris.



Mars

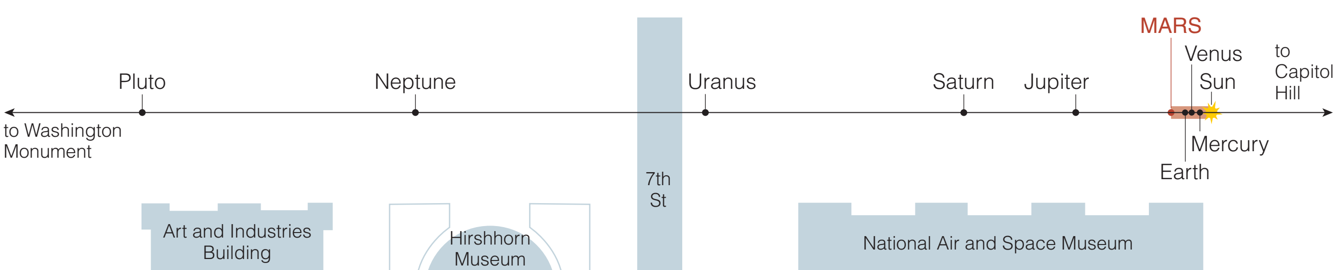
- Average distance from the Sun: 1.52 AU
- Radius: 3397 km = $0.53R_{Earth}$
- Mass: $0.11M_{Earth}$
- Average density: 3.93 g/cm^3
- Composition: rocks, metals
- Average surface temperature: 220 K
- Moons: 2 (very small)

The next planet on our tour is Mars, the last of the four inner planets of our solar system (Figure 6.6). Mars is larger than Mercury and the Moon but only about half Earth's size in diameter; its mass is about 10% that of Earth. Mars has two tiny moons, Phobos and Deimos, that probably once were asteroids that were captured into Martian orbit early in the solar system's history.

Mars is a world of wonders, with ancient volcanoes that dwarf the largest mountains on Earth, a great canyon that runs nearly one-fifth of the way around the planet, and polar caps made of frozen carbon dioxide ("dry ice") and water. Although Mars is frozen today, the presence of dried-up riverbeds, rock-strewn floodplains, and minerals that form in water offers clear evidence that Mars had at least some warm and wet periods in the past. Major flows of liquid water probably ceased at least 3 billion years ago, but some liquid water could persist underground, perhaps flowing to the surface on occasion.

Mars's surface looks almost Earth-like, but you wouldn't want to visit without a space suit. The air pressure is far less than that on top of Mount Everest, the temperature is usually well below freezing, the trace amounts of oxygen would not be nearly enough to breathe, and the lack of atmospheric ozone would leave you exposed to deadly ultraviolet radiation from the Sun.

Mars is the most studied planet besides Earth. More than a dozen spacecraft have flown past, orbited, or landed on Mars, and plans are in the works for many more missions. We may even send humans to Mars within the next few decades. By overturning rocks in ancient riverbeds or chipping away at ice in the polar caps, explorers will help us learn whether Mars has ever been home to life.



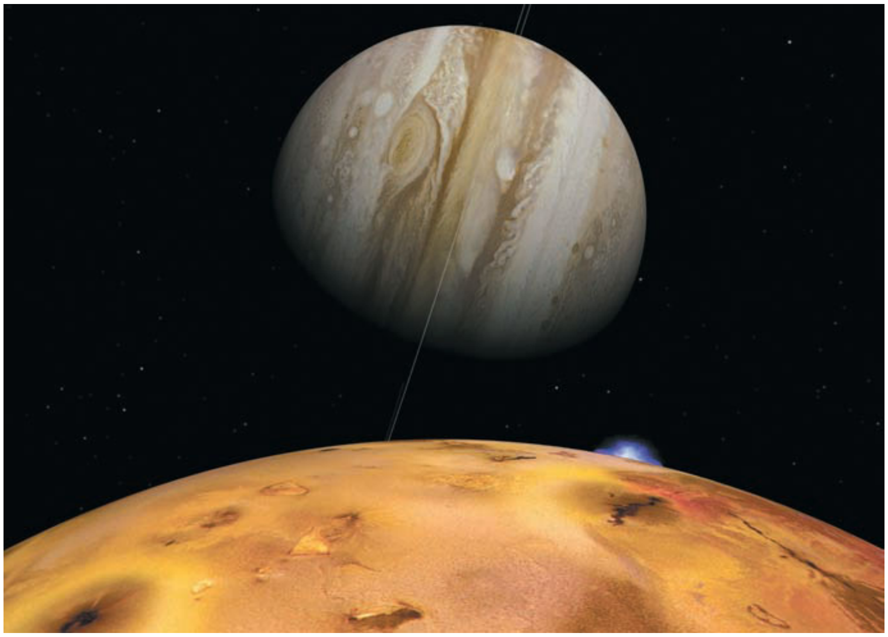


Figure 6.7

This image shows what it would look like to be orbiting near Jupiter's moon Io as Jupiter comes into view. Notice the Great Red Spot to the left of Jupiter's center. The extraordinarily dark rings discovered during the *Voyager* missions are exaggerated to make them visible. This computer visualization was created using data from both NASA's *Voyager* and *Galileo* missions. (From the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image created by ARC Science Simulations © 2001.)

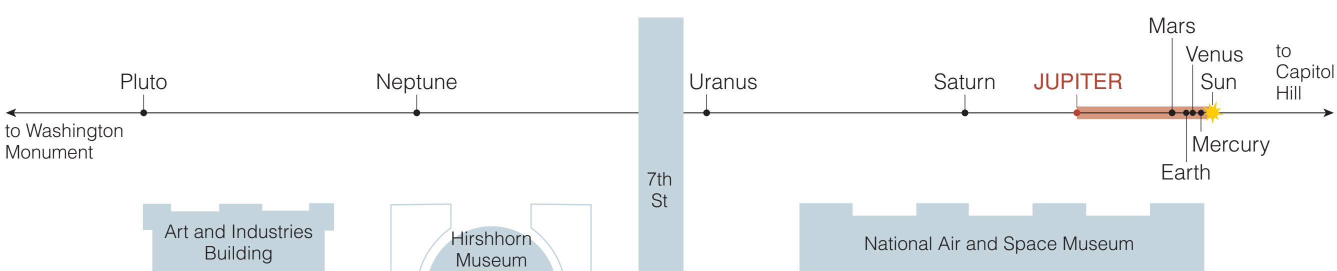
Jupiter

- Average distance from the Sun: 5.20 AU
- Radius 71,492 km = $11.2R_{\text{Earth}}$
- Mass: $318M_{\text{Earth}}$
- Average density: 1.33 g/cm^3
- Composition: mostly hydrogen and helium
- Cloud-top temperature: 125 K
- Moons: at least 63

To reach the orbit of Jupiter from Mars, we must traverse a distance that is more than double the total distance from the Sun to Mars, passing through the asteroid belt along the way. Upon our arrival, we find a planet much larger than any we have seen so far (Figure 6.7).

Jupiter is so different from the planets of the inner solar system that we must adopt an entirely new mental image of the term *planet.* Its mass is more than 300 times that of Earth, and its volume is more than 1000 times that of Earth. Its most famous feature—a long-lived storm called the Great Red Spot—is itself large enough to swallow two or three Earths. Like the Sun, Jupiter is made primarily of hydrogen and helium and has no solid surface. If we plunged deep into Jupiter, the increasing gas pressure would crush us long before we ever reached its core.

Jupiter reigns over dozens of moons and a thin set of rings (too faint to be seen in most photographs). Most of the moons are very small, but four are large enough that we'd probably consider them planets if they orbited the Sun independently. These four moons—Io, Europa, Ganymede, and Callisto—are often called the *Galilean moons,* because Galileo discovered them shortly after he first turned his telescope toward the heavens **[Section 3.3]**. They are also planetlike in having varied and interesting geology. Io is the most volcanically active world in the solar system. Europa has an icy crust that may hide a subsurface ocean of liquid water, making it a promising place to search for life. Ganymede and Callisto may also have subsurface oceans, and their surfaces have many features that remain mysterious.



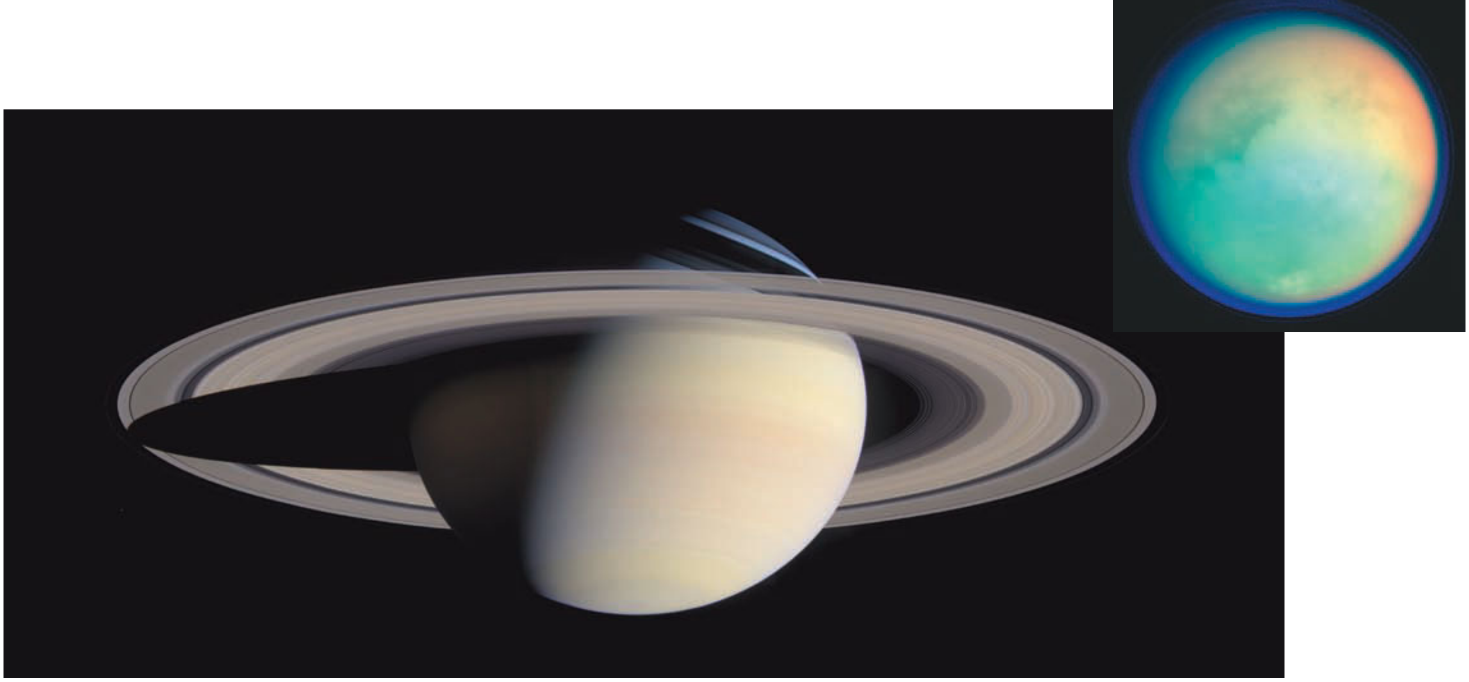


Figure 6.8

Cassini's view of Saturn. We see the shadow of the rings on Saturn's sunlit face, and the rings become lost in Saturn's shadow on the night side. The inset shows an infrared view of Titan, Saturn's large moon, shrouded in a thick, cloudy atmosphere.

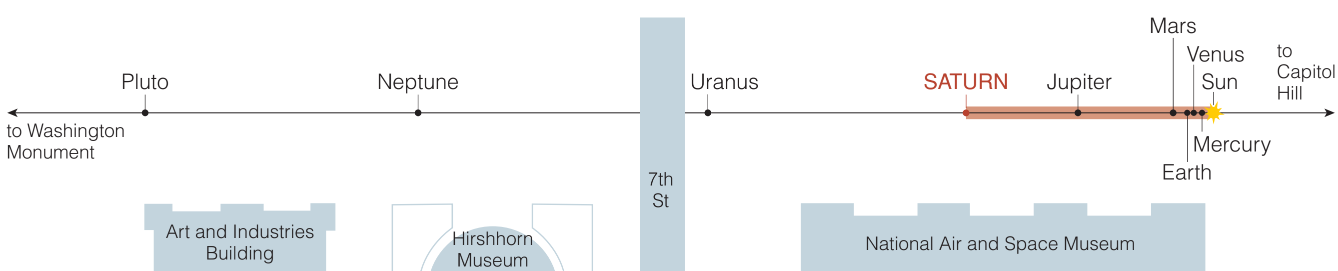
Saturn

- Average distance from the Sun: 9.54 AU
- Radius: 60,268 km = $9.4 R_{\text{Earth}}$
- Mass: $95.2 M_{\text{Earth}}$
- Average density: 0.70 g/cm^3
- Composition: mostly hydrogen and helium
- Cloud-top temperature: 95 K
- Moons: at least 60

The journey from Jupiter to Saturn is a long one: Saturn orbits nearly twice as far from the Sun as Jupiter. Saturn, the second-largest planet in our solar system, is only slightly smaller than Jupiter in diameter, but its lower density makes it considerably less massive (about one-third of Jupiter's mass). Like Jupiter, Saturn is made mostly of hydrogen and helium and has no solid surface.

Saturn is famous for its spectacular rings (Figure 6.8). Although all four of the giant outer planets have rings, only Saturn's rings can be seen easily through a small telescope. The rings may look solid from a distance, but in reality they are made of countless small particles, each of which orbits Saturn like a tiny moon. If you could wander into the rings, you'd find yourself surrounded by chunks of rock and ice that range in size from dust grains to city blocks. We are rapidly learning more about Saturn and its rings through observations made by the *Cassini* spacecraft, which has orbited Saturn since 2004.

Cassini has also taught us more about Saturn's moons, and has revealed that at least two are geologically active today: Enceladus, which has ice fountains spraying out from its southern hemisphere, and Titan, the only moon in the solar system with a thick atmosphere. Saturn and its moons are so far from the Sun that Titan's surface temperature is a frigid −180°C, making it far too cold for liquid water to exist. However, studies by *Cassini* and its *Huygens* probe, which landed on Titan in 2005, have revealed an erosion-carved landscape that looks remarkably Earth-like, except that it has been shaped by extremely cold liquid methane or ethane rather than liquid water. *Cassini* has even detected vast lakes of liquid methane or ethane on Titan's surface.



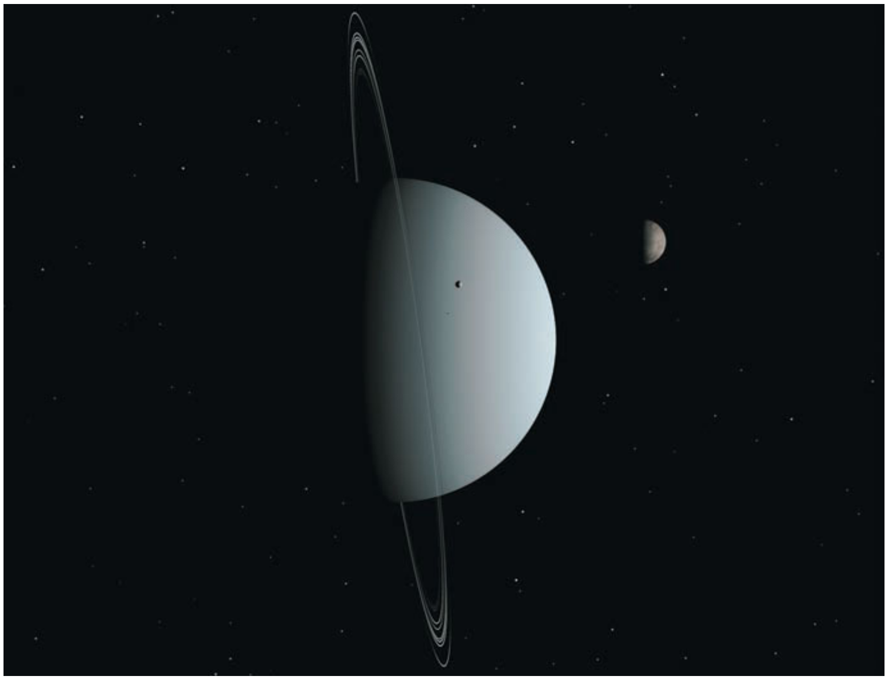


Figure 6.9

This image shows a view of Uranus from high above its moon Ariel. The ring system is shown, although it would actually be too dark to see from this vantage point. This computer simulation is based on data from NASA's *Voyager 2* mission. (From the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image created by ARC Science Simulations © 2001.)

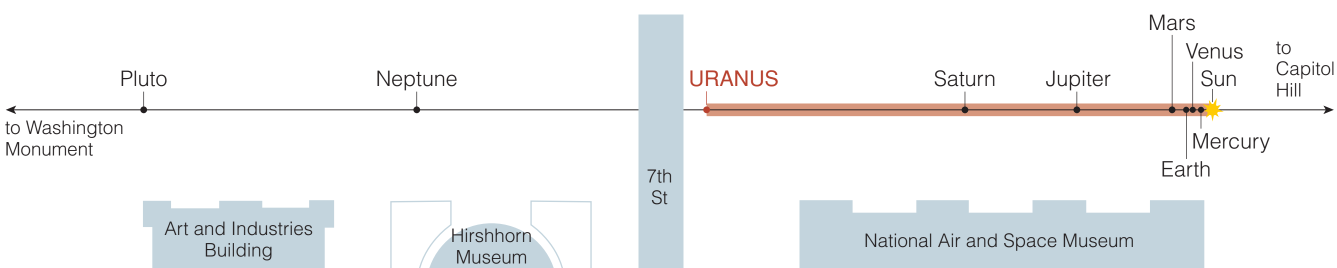
Uranus

- Average distance from the Sun: 19.2 AU
- Radius: 25,559 km = $4.0R_{\text{Earth}}$
- Mass: $14.5M_{\text{Earth}}$
- Average density: 1.32 g/cm^3
- Composition: hydrogen, helium, hydrogen compounds
- Cloud-top temperature: 60 K
- Moons: at least 27

It's another long journey to our next stop on the tour, as Uranus lies twice as far from the Sun as Saturn. Uranus (normally pronounced *YUR-uh-nus*) is much smaller than either Jupiter or Saturn but much larger than Earth. It is made largely of hydrogen, helium, and *hydrogen compounds* such as water (H_2O), ammonia (NH_3), and methane (CH_4). Methane gas gives Uranus its pale blue-green color (Figure 6.9). Like the other giants of the outer solar system, Uranus lacks a solid surface. More than two dozen moons orbit Uranus, along with a set of rings somewhat similar to those of Saturn but much darker and more difficult to see.

The entire Uranus system—planet, rings, and moon orbits—is tipped on its side compared to the rest of the planets. This extreme axis tilt may be the result of a cataclysmic collision that Uranus suffered as it was forming, and it gives Uranus the most extreme seasonal variations of any planet in our solar system. If you lived on a platform floating in Uranus's atmosphere near its north pole, you'd have continuous daylight for half of each orbit, or 42 years. Then, after a very gradual sunset, you'd enter into a 42-year-long night.

Only one spacecraft has visited Uranus: *Voyager 2*, which flew past all four of the giant outer planets before heading out of the solar system. Much of our current understanding of Uranus comes from that mission, though powerful new telescopes are also capable of studying it. Scientists would love an opportunity to study Uranus and its rings and moons in greater detail, but no missions to Uranus are currently under development.



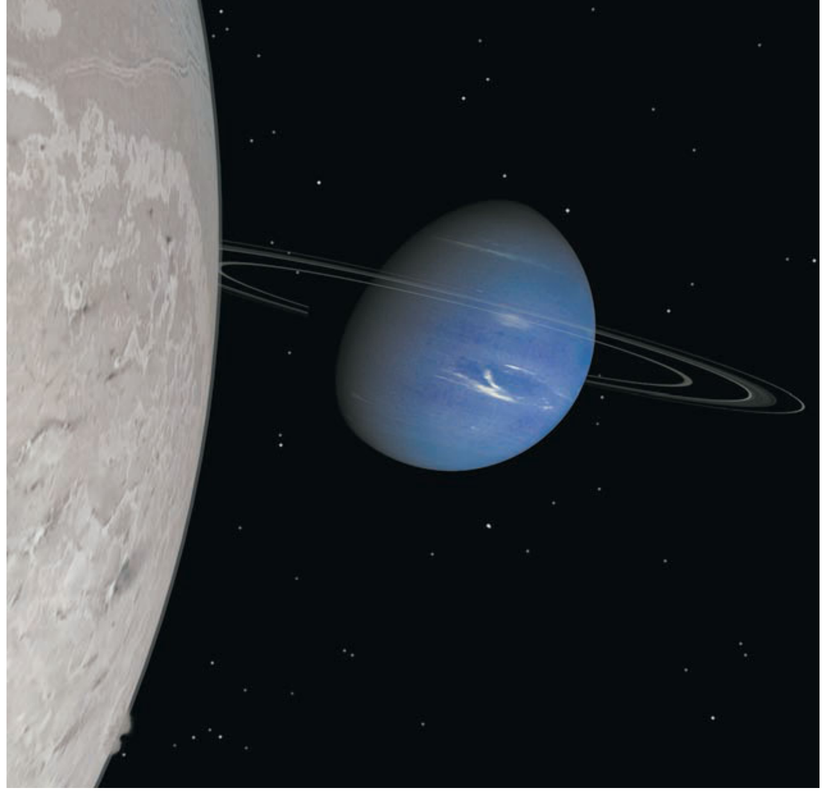


Figure 6.10

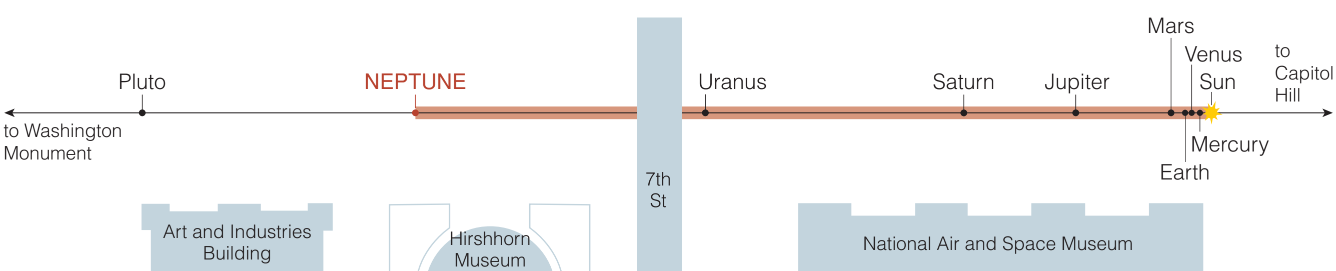
This image shows what it would look like to be orbiting Neptune's moon Triton as Neptune itself comes into view. The dark rings are exaggerated to make them visible in this computer simulation using data from NASA's *Voyager 2* mission. (From the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image created by ARC Science Simulations © 2001.)

• Neptune

- Average distance from the Sun: 30.1 AU
- Radius 24,764 km = $3.9R_{\text{Earth}}$
- Mass: $17.1M_{\text{Earth}}$
- Average density: 1.64 g/cm^3
- Composition: hydrogen, helium, hydrogen compounds
- Cloud-top temperature: 60 K
- Moons: at least 13

The journey from the orbit of Uranus to the orbit of Neptune is the longest yet in our tour, calling attention to the vast emptiness of the outer solar system. Nevertheless, Neptune looks nearly like a twin of Uranus, although it is more strikingly blue (Figure 6.10). It is slightly smaller than Uranus in size, but a higher density makes it slightly more massive even though the two planets share very similar compositions. Like Uranus, Neptune has been visited only by the *Voyager 2* spacecraft, and no additional missions are currently planned.

Neptune has rings and numerous moons. Its largest moon, Triton, is larger than Pluto and is one of the most fascinating moons in the solar system. Triton's icy surface has features that appear to be somewhat like geysers, although they spew nitrogen gas rather than water into the sky **[Section 8.2]**. Even more surprisingly, Triton is the only large moon in the solar system that orbits its planet "backward"—that is, in a direction opposite to the direction in which Neptune rotates. This backward orbit makes it a near certainty that Triton once orbited the Sun independently before somehow being captured into Neptune's orbit.



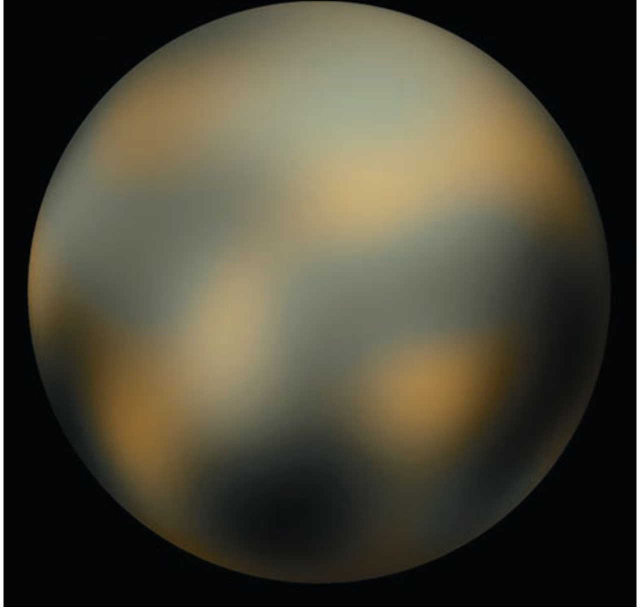


Figure 6.11

Pluto, as photographed by the Hubble Space Telescope.

• Pluto (and Other Dwarf Planets)

- Pluto's average distance from the Sun: 39.5 AU
- Radius: 1160 km = $0.18R_{\text{Earth}}$
- Mass: $0.0022M_{\text{Earth}}$
- Average density: 2.0 g/cm^3
- Composition: ices, rock
- Average surface temperature: 40 K
- Moons: 3

We conclude our tour at Pluto, which reigned for some 75 years as the ninth and last planet in our solar system. Pluto's average distance from the Sun lies as far beyond Neptune as Neptune lies beyond Uranus. Its great distance makes Pluto cold and dark. From Pluto, the Sun would be little more than a bright light among the stars. Pluto's largest moon, Charon, is locked together with it in synchronous rotation **[Section 4.4]**, so Charon would dominate the sky on one side of Pluto but never be seen from the other side.

We've known for decades that Pluto is much smaller and less massive than any of the other planets, and its orbit is much more eccentric and inclined to the ecliptic plane. Its composition of ice and rock is also quite different from that of any of those planets, although it is virtually identical to that of many known comets. Moreover, astronomers have discovered more than 1000 objects of similar composition orbiting in Pluto's general neighborhood, which is the region of our solar system known as the *Kuiper belt*. Pluto is not even the largest of these Kuiper belt objects: Eris, discovered in 2005, is slightly larger than Pluto.

Scientifically, these facts leave no room for doubt that both Pluto and Eris belong to a different class of objects than the first eight planets. They are just the largest known of hundreds of large iceballs—essentially large comets—located in the Kuiper belt. The only question has been one of words: Should Pluto and Eris be called "planets" or something else? In 2006, the International Astronomical Union (IAU) voted to classify Pluto and Eris as *dwarf planets*. The IAU definition (see Special Topic, page 12) also classifies several more objects as dwarf planets, including the largest asteroid, Ceres, and other objects that share the Kuiper belt with Pluto and Eris.

The great distances and small sizes of Pluto and other dwarf planets make them difficult to study, regardless of whether they are located in the asteroid belt or the Kuiper belt. As you can see in Figure 6.11, even the best telescopic views of Pluto reveal little detail. Better information should be coming soon. A spacecraft called *New Horizons,* launched in 2006, will fly past Pluto in mid-2015 and may then visit other objects of the Kuiper belt. Meanwhile, the *Dawn* spacecraft, launched in 2007, should give us our first good views of large asteroids in the asteroid belt beginning in about 2011, with a pass by Ceres in 2015 that will closely coincide with *New Horizons'* pass by Pluto.

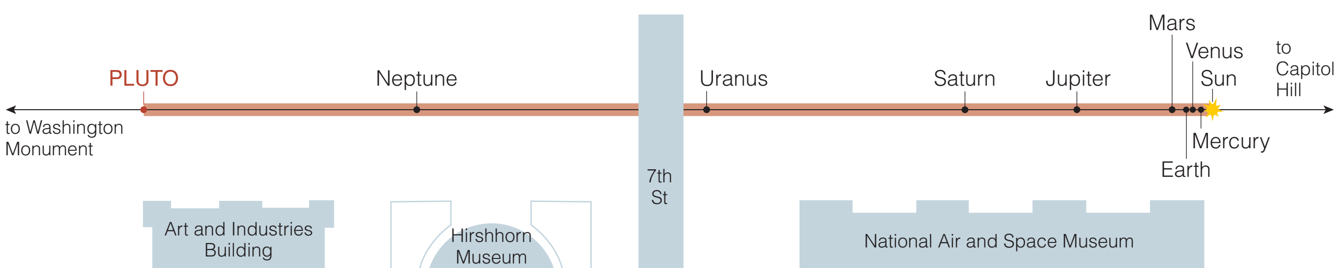
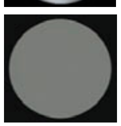


Table 6.1 *Planetary Data**

Photo	Planet	Relative Size	Average Distance from Sun (AU)	Average Equatorial Radius (km)	Mass (Earth = 1)	Average Density (g/m^3)	Orbital Period	Rotation Period	Axis Tilt	Average Surface (or Cloud-Top) Temperature†	Composition	Known Moons (2010)	Rings?
	Mercury		0.387	2440	0.055	5.43	87.9 days	58.6 days	0.0°	700 K (day) 100 K (night)	Rocks, metals	0	No
	Venus		0.723	6051	0.82	5.24	225 days	243 days	177.3°	740 K	Rocks, metals	0	No
	Earth		1.00	6378	1.00	5.52	1.00 year	23.93 hours	23.5°	290 K	Rocks, metals	1	No
	Mars		1.52	3397	0.11	3.93	1.88 years	24.6 hours	25.2°	220 K	Rocks, metals	2	No
	Jupiter		5.20	71,492	318	1.33	11.9 years	9.93 hours	3.1°	125 K	H, He, hydrogen compounds§	63	Yes
	Saturn		9.54	60,268	95.2	0.70	29.4 years	10.6 hours	26.7°	95 K	H, He, hydrogen compounds§	60	Yes
	Uranus		19.2	25,559	14.5	1.32	83.8 years	17.2 hours	97.9°	60 K	H, He, hydrogen compounds§	27	Yes
	Neptune		30.1	24,764	17.1	1.64	165 years	16.1 hours	29.6°	60 K	H, He, hydrogen compounds§	13	Yes
	Pluto		39.5	1160	0.0022	2.0	248 years	6.39 days	112.5°	40 K	Ices, rock	3	No
	Eris		67.7	1200	0.0028	2.3	557 years	1.08 days	78°	30 K	Ices, rock	1	?

*Including the dwarf planets Pluto and Eris; Appendix E gives a more complete list of planetary properties.

†Surface temperatures for all objects except Jupiter, Saturn, Uranus, and Neptune, for which cloud-top temperatures are listed.

§Includes water (H_2O), methane (CH_4), and ammonia (NH_3).

(continued from page 143)

In science, we always seek explanations for the existence of patterns like those evident in Figure 6.1 and the planetary tour. We will therefore devote most of this chapter to learning how our modern theory of solar system formation explains these and other features of the solar system. We will then see how recent discoveries of other planetary systems fit in with this theory, even as they have led us to refine some of its details.

The planets are tiny compared to the distances between them, but they exhibit clear patterns of composition and motion.

MA **Orbits and Kepler's Laws Tutorial, Lessons 2–4**

6.2 Clues to the Formation of Our Solar System

Let's begin by taking a more in-depth look at the general features of our solar system that must be explained by any successful theory of its origin. We can then discuss what theory best describes the major characteristics of our solar system and accounts for how it formed.

• What features of our solar system provide clues to how it formed?

We have already seen that our solar system is not a random collection of worlds but rather a family of worlds exhibiting many traits that would be difficult to attribute to coincidence. A valid theory of our solar system's formation must successfully account for these common traits. We could make a long list of such traits, but it is easier to develop a scientific theory by focusing on the more general structure of our solar system. For our purposes, four major features stand out:

1. **Patterns of motion among large bodies.** The Sun, planets, and large moons generally orbit and rotate in a very organized way.
2. **Two major types of planets.** The eight planets divide clearly into two groups: the small, rocky planets that are close together and close to the Sun, and the large, gas-rich planets that are farther apart and farther from the Sun.
3. **Asteroids and comets.** Between and beyond the planets, vast numbers of asteroids and comets orbit the Sun; some are large enough to qualify as dwarf planets. The locations, orbits, and compositions of these asteroids and comets follow distinct patterns.
4. **Exceptions to the rules.** The generally orderly solar system also has some notable exceptions. For example, only Earth has a large moon among the inner planets, and Uranus is tipped on its side. A successful theory must make allowances for exceptions even as it explains the general rules.

Because these four features are so important to our study of the solar system, let's investigate each of them in a little more detail.

Feature 1: Patterns of Motion Among Large Bodies If you look back at Figure 6.1, you'll notice several clear patterns of motion among the large bodies of our solar system. (In this context, a "body" is simply an individual object such as the Sun, a planet, or a moon.) For example:

- All planetary orbits are nearly circular and lie nearly in the same plane.
- All planets orbit the Sun in the same direction: counterclockwise as viewed from high above Earth's North Pole.
- Most planets rotate in the same direction in which they orbit, with fairly small axis tilts. The Sun also rotates in this direction.
- Most of the solar system's large moons exhibit similar properties in their orbits around their planets, such as orbiting in their planet's equatorial plane in the same direction that the planet rotates.

The Sun, planets, and large moons orbit and rotate in an organized way.

We consider these orderly patterns together as the first major feature of our solar system. As we'll see shortly, our theory of solar system formation explains these patterns as consequences of processes that occurred during the early stages of the birth of our solar system.

Table 6.2 *Comparison of Terrestrial and Jovian Planets*

Terrestrial Planets	Jovian Planets
Smaller size and mass	Larger size and mass
Higher density	Lower density
Made mostly of rock and metal	Made mostly of hydrogen, helium, and hydrogen compounds
Solid surface	No solid surface
Few (if any) moons and no rings	Rings and many moons
Closer to the Sun (and closer together), with warmer surfaces	Farther from the Sun (and farther apart), with cool temperatures at cloud tops

Feature 2: The Existence of Two Types of Planets

Our brief planetary tour showed that the four inner planets are quite different from the four large outer planets. We say that these two groups represent two distinct planetary classes: *terrestrial* and *jovian.*

Terrestrial planets **are small, rocky, and close to the Sun.** ***Jovian planets*** **are large, gas-rich, and far from the Sun.**

The **terrestrial planets** are the four planets of the inner solar system: Mercury, Venus, Earth, and Mars. (*Terrestrial* means "Earth-like.") These planets are relatively small and dense, with rocky surfaces and an abundance of metals deep in their interiors. They have few moons, if any, and no rings. We often count our Moon as a fifth terrestrial world, because its history has been shaped by the same processes that have shaped the terrestrial planets.

The **jovian planets** are the four large planets of the outer solar system: Jupiter, Saturn, Uranus, and Neptune. (*Jovian* means "Jupiter-like.") The jovian planets are much larger in size and lower in average density than the terrestrial planets, and they have rings and many moons. They lack solid surfaces and are made mostly of hydrogen, helium, and **hydrogen compounds**—compounds containing hydrogen, such as water (H_2O), ammonia (NH_3), and methane (CH_4). Because these substances are gases under earthly conditions, the jovian planets are sometimes called "gas giants." Table 6.2 contrasts the general traits of the terrestrial and jovian planets.

Figure 6.12

The asteroid Eros (photographed from the *NEAR* spacecraft). Its appearance is probably typical of most asteroids. Eros is about 40 kilometers in length, and like other small objects in the solar system, it is not spherical.

Feature 3: Asteroids and Comets

The third major feature of the solar system is the existence of vast numbers of small objects orbiting the Sun. These objects fall into two major groups: asteroids and comets.

Rocky asteroids and icy comets far outnumber the planets and their moons.

Asteroids are rocky bodies that orbit the Sun much like planets, but they are much smaller (Figure 6.12). Even the largest asteroids are much smaller than our Moon. Most known asteroids are found within the **asteroid belt** between the orbits of Mars and Jupiter (see Figure 6.1).

Comets are also small objects that orbit the Sun, but they are made largely of ices (such as water ice, ammonia ice, and methane ice) mixed with rock. You are probably familiar with the occasional appearance of comets in the inner solar system, where they may become visible to the naked eye with long, beautiful tails (Figure 6.13). These visitors, which may delight sky watchers for a few weeks or months, are actually quite rare among comets.

The vast majority of comets never visit the inner solar system. Instead, they orbit the Sun in one of the two distinct regions shown as Feature 3 in Figure 6.1. The first is a donut-shaped region beyond the orbit of Neptune that we call the **Kuiper belt** (*Kuiper* rhymes with *piper*). The Kuiper belt contains at least 100,000 icy objects, of which Pluto and Eris are the largest known. The second cometary region, called the **Oort cloud** (*Oort* rhymes with *court*), is much farther from the Sun and may contain a trillion comets. These comets have orbits randomly inclined to the ecliptic plane, giving the Oort cloud a roughly spherical shape.

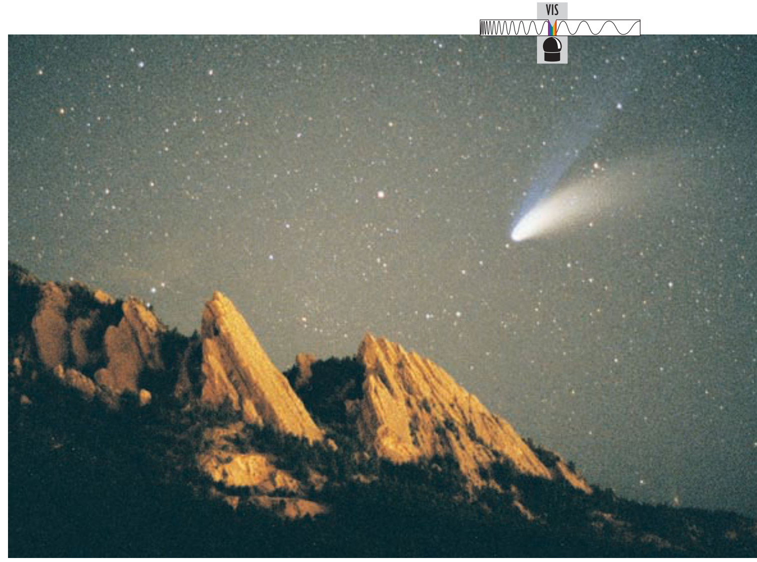


Figure 6.13

Comet Hale–Bopp, photographed over Boulder, Colorado, during its appearance in 1997.

Feature 4: Exceptions to the Rules The fourth key feature of our solar system is that there are a few notable exceptions to the general rules. Two such exceptions are the rotations of Uranus and Venus: While most of the planets rotate in the same direction as they orbit, Uranus rotates nearly on its side and Venus rotates "backward" (clockwise as viewed from high above Earth's North Pole). Similarly, while most large moons orbit their planets in the same direction as their planets rotate, many small moons have much more unusual orbits.

One of the most interesting exceptions concerns our own Moon. While the other terrestrial planets have either no moons (Mercury and Venus) or very tiny moons (Mars), Earth has one of the largest moons in the solar system.

A successful theory of solar system formation must allow for exceptions to the general rules.

• What theory best explains the features of our solar system?

After the Copernican revolution, many scientists speculated about the origin of the solar system. However, we generally credit two 18th-century scientists with proposing the hypothesis that ultimately blossomed into our modern scientific theory of the origin of the solar system. Around 1755, German philosopher Immanuel Kant proposed that our solar system formed from the gravitational collapse of an interstellar cloud of gas. About 40 years later, French mathematician Pierre-Simon Laplace put forth the same idea independently. Because an interstellar cloud is usually called a *nebula* (Latin for "cloud"), their idea became known as the *nebular hypothesis.*

The nebular hypothesis remained popular throughout the 19th century. By the early 20th century, however, scientists had found a few aspects of our solar system that the nebular hypothesis did not seem to explain well—at least in its original form as described by Kant and Laplace. While some scientists sought to modify the nebular hypothesis, others looked for entirely different explanations for how the solar system might have formed.

During the first half of the 20th century, the nebular hypothesis faced stiff competition from a hypothesis proposing that the planets represent debris from a near-collision between the Sun and another star. According to this *close encounter hypothesis,* the planets formed from blobs of gas that had been gravitationally pulled out of the Sun during the near-collision.

Today, the close encounter hypothesis has been discarded. It began to lose favor when calculations showed that it could not account for either the observed orbital motions of the planets or the neat division of the planets into two major categories (terrestrial and jovian). Moreover, the close encounter hypothesis required a highly improbable event: a near-collision between our Sun and another star. Given the vast separation between star systems in our region of the galaxy, the chance of such an encounter is so small that it would be difficult to imagine it happening even in the one case needed to make our own solar system. It certainly could not account for the many other planetary systems that we have discovered in recent years.

The nebular theory holds that our solar system formed from the gravitational collapse of a great cloud of gas, and it explains all the general features of our solar system.

While the close encounter hypothesis was losing favor, new discoveries about the physics of planet formation led to modifications of the nebular hypothesis. Using more sophisticated models of the processes that occur in a collapsing cloud of gas, scientists realized that the nebular hypothesis offered natural explanations for all four general features of our solar system. Indeed, so much evidence has accumulated in favor of the nebular hypothesis that it has achieved the status of a scientific *theory* **[Section 3.4]**—the **nebular theory** of our solar system's birth.

MA Formation of the Solar System Tutorial, Lessons 1–2

6.3 The Birth of the Solar System

We are now ready to examine the nebular theory in more depth. In this section, we'll see how it explains the first general feature of our solar system—orderly patterns of motion—and discuss why we expect similar patterns in other planetary systems.

• Where did the solar system come from?

The nebular theory begins with the idea that our solar system was born from a cloud of gas, called the **solar nebula,** that collapsed under its own gravity. But where did this gas come from?

Recall that the universe as a whole is thought to have been born in the Big Bang **[Section 1.1]**, which essentially produced only two chemical elements **[Section 1.1]**: hydrogen and helium. Heavier elements were produced later by massive stars and released into space when the stars died. The heavy elements then mixed with other interstellar gas to form new generations of stars (Figure 6.14).

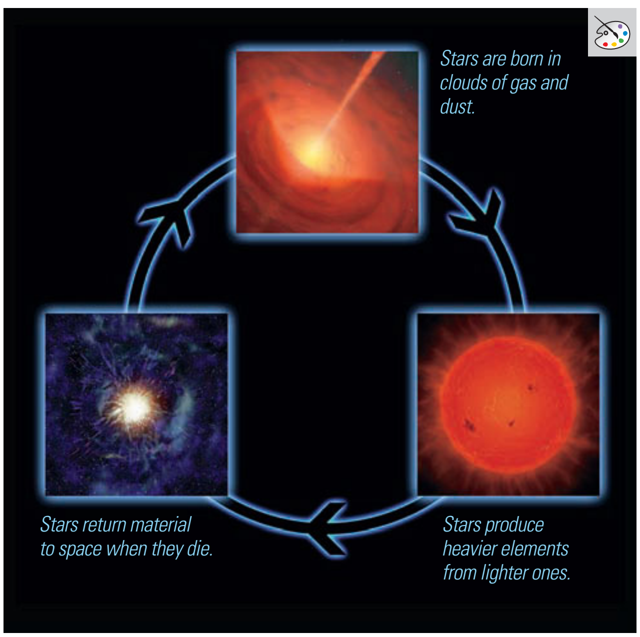


Figure 6.14 MA **interactive figure**

This figure (which is a portion of Figure 1.2) summarizes the galactic recycling process.

The gas that made up the solar nebula contained hydrogen and helium from the Big Bang and heavier elements produced by stars.

Despite billions of years of heavy element creation by stars, the overall chemical composition of the galaxy remains predominantly hydrogen and helium. By studying the composition of the Sun, of other stars of the same age, and of interstellar gas clouds, we have learned that the gas that made up the solar nebula contained (by mass) about 98% hydrogen and helium and 2% all other elements combined. The Sun still has this basic composition, while the planets tend to have higher proportions of heavy elements (for reasons we will discuss in Section 6.4).

think about it Could a solar system like ours have formed with the first generation of stars after the Big Bang? Explain.

Strong observational evidence supports this scenario. With telescopes we can witness stars in the process of formation today, and these forming stars are always found within interstellar clouds **[Section 12.1]**. Moreover, careful studies of gas in the Milky Way Galaxy have allowed us to put together a clear picture of the entire galactic recycling process **[Section 14.2]**, leaving little doubt that new stars are born from gas that has been recycled from prior generations of stars. As we saw in Chapter 1, we are "star stuff," because we and our planet are made of elements forged in stars that lived and died long ago.

• What caused the orderly patterns of motion in our solar system?

The solar nebula probably began as a large and roughly spherical cloud of very cold, low-density gas. Initially, this gas was so spread out—perhaps over a region a few light-years in diameter—that gravity alone may not have been strong enough to pull it together and start its collapse. Instead, the collapse may have been triggered by a cataclysmic event, such as the impact of a shock wave from the explosion of a nearby star (a supernova).

Once the collapse started, the law of gravity ensured that it would continue. Remember that the strength of gravity follows an inverse square law with distance **[Section 4.4]**. Because the mass of the cloud remained the same as it shrank, the strength of gravity increased as the diameter of the cloud decreased. For example, when the diameter decreased by half, the force of gravity increased by a factor of four.

Because gravity pulls inward in all directions, you might at first guess that the solar nebula would have remained spherical as it shrank. Indeed, the idea that gravity pulls in all directions explains why the Sun and the planets are spherical. However, we must also consider other physical laws that apply to a collapsing gas cloud in order to understand how orderly motions arose in the solar nebula.

Heating, Spinning, and Flattening As the solar nebula shrank in size, three important processes altered its density, temperature, and shape, changing it from a large, diffuse (spread-out) cloud to a much smaller spinning disk (Figure 6.15):

- **Heating.** The temperature of the solar nebula increased as it collapsed. Such heating represents energy conservation in action **[Section 4.3]**. As the cloud shrank, its gravitational potential energy was converted to the kinetic energy of individual gas particles falling inward. These particles crashed into one another, converting the kinetic energy of their inward fall to the random motions of thermal energy (see Figure 4.12b). The Sun formed in the center, where temperatures and densities were highest.
- **Spinning.** Like an ice skater pulling in her arms as she spins, the solar nebula rotated faster and faster as it shrank in radius. This increase in rotation rate represents conservation of angular momentum in action **[Section 4.3]**. The rotation of the cloud may have been imperceptibly slow before its collapse began, but the cloud's shrinkage made fast rotation inevitable. The rapid rotation

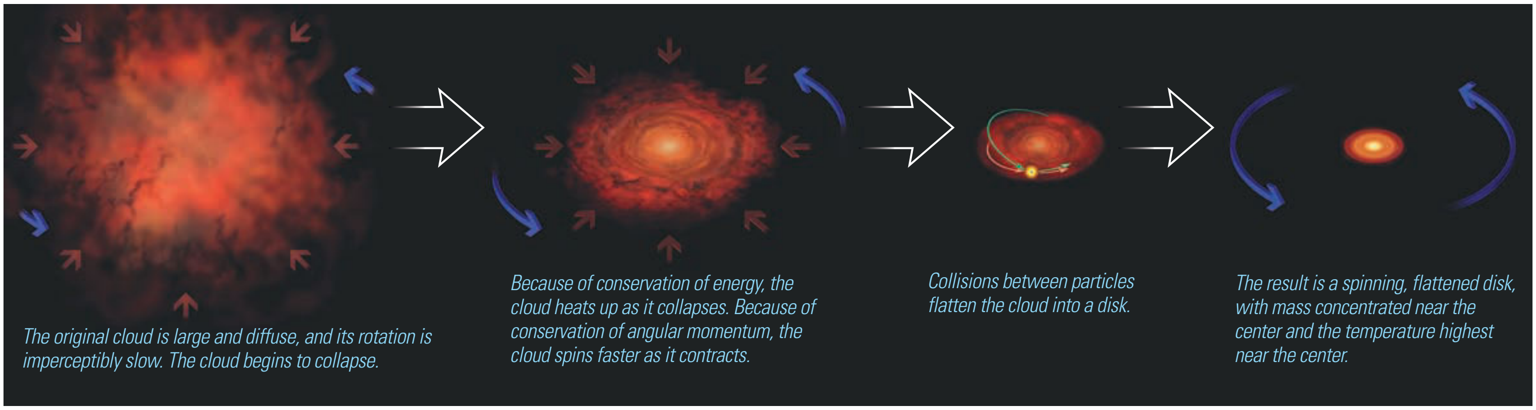


Figure 6.15 MA interactive figure

This sequence of illustrations shows how the gravitational collapse of a large cloud of gas causes it to become a spinning disk of matter. The hot, dense central bulge becomes a star, while planets can form in the surrounding disk.

helped ensure that not all the material in the solar nebula collapsed into the center: The greater the angular momentum of a rotating cloud, the more spread out it will be.

- **Flattening.** The solar nebula flattened into a disk. This flattening is a natural consequence of collisions between particles in a spinning cloud. A cloud may start with any size or shape, and different clumps of gas within the cloud may be moving in random directions at random speeds. These clumps collide and merge as the cloud collapses, and each new clump has the average velocity of the clumps that formed it. The random motions of the original cloud therefore become more orderly as the cloud collapses, changing the cloud's original lumpy shape into a rotating, flattened disk. Similarly, collisions between clumps of material in highly elliptical orbits reduce their eccentricities, making their orbits more circular.

The formation of the spinning disk explains the orderly motions of our solar system today. The planets all orbit the Sun in nearly the same plane because they formed in the flat disk. The direction in which the disk was spinning became the direction of the Sun's rotation and the orbits of the planets. Computer models show that planets would have tended to rotate in the same direction as they formed—which is why most planets rotate the same way—though the small sizes of planets compared to the entire disk allowed some exceptions to arise. The fact that collisions in the disk tended to make orbits more circular explains why most planets have nearly circular orbits.

The orderly motions of our solar system today are a direct result of the solar system's birth in a spinning, flattened cloud of gas.

see it for yourself You can demonstrate the development of orderly motion, much as it occurred in the solar system, by sprinkling pepper into a bowl of water and stirring it quickly in random directions. The water molecules constantly collide with one another, so the motion of the pepper grains will tend to settle into a slow rotation representing the average of the original, random velocities. Try the experiment several times, stirring the water differently each time. Do the random motions ever cancel out exactly, resulting in no rotation at all? Describe what occurs, and explain how this is similar to what took place in the solar nebula.

Testing the Model Because the same processes should affect other collapsing gas clouds, we can test our model by searching for disks around other forming stars. Observational evidence does indeed support our model of spinning, heating, and flattening.

The heating that occurs in a collapsing cloud of gas means the gas should emit thermal radiation **[Section 5.2]**, primarily in the infrared. We've detected infrared radiation from many nebulae where star systems appear to be forming. More direct evidence comes from flattened, spinning disks around other stars (Figure 6.16), some of which appear to be ejecting jets of material perpendicular to their disks **[Section 12.1]**. These jets are thought to result from the flow of material from the disk onto the forming star.

Other support for the model comes from computer simulations of the formation process. A simulation begins with a set of data representing the conditions we observe in interstellar clouds. Then, with the aid of a computer, we apply the laws of physics to predict the changes that should occur over time. These computer simulations successfully reproduce most of the general characteristics of motion in our solar system, suggesting that the nebular theory is on the right track.

Observations of disks around other stars support the idea that our own solar system was once a spinning disk of gas.

Additional evidence that our ideas about the formation of flattened disks are correct comes from many other structures in the universe. We expect flattening to occur anywhere that orbiting particles can collide, which explains why we find so many cases of flat disks, including the disks of spiral galaxies like the Milky Way, the disks of planetary rings, and the *accretion disks* that surround neutron stars and black holes in close binary star systems **[Section 13.3]**.

MA **Formation of the Solar System Tutorial, Lesson 3**

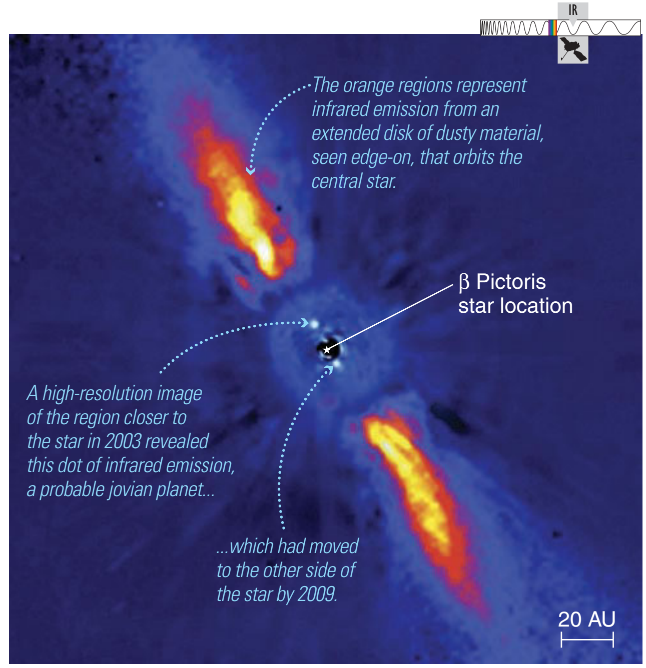
6.4 The Formation of Planets

The planets began to form after the solar nebula had collapsed into a flattened disk of perhaps 200 AU in diameter (about twice the present-day diameter of Pluto's orbit). In this section, we'll discuss planetary formation and address three major features of our solar system that we have not yet explained: the existence of two types of planets, the existence of asteroids and comets, and the exceptions to the rules.

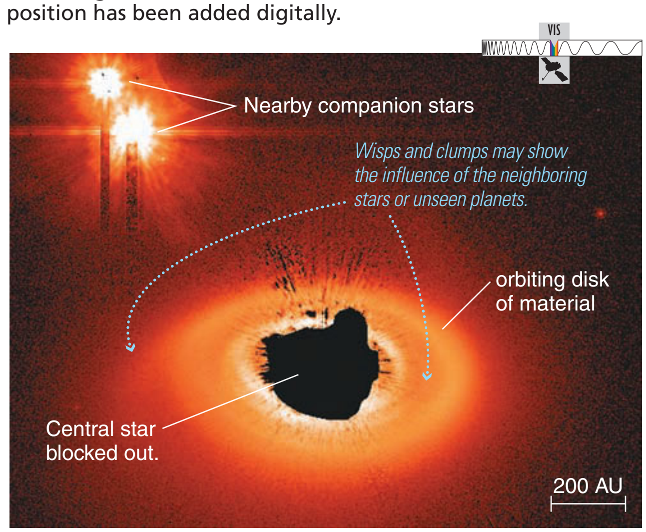
• Why are there two major types of planets?

The churning and mixing of gas in the solar nebula should have ensured that the nebula had the same composition throughout, so how did the terrestrial planets end up being so different in composition from the jovian planets? The key clue comes from their locations: The terrestrial planets formed in the warm, inner regions of the swirling disk, and the jovian planets formed in the colder, outer regions.

Condensation: Sowing the Seeds of Planets In the center of the collapsing solar nebula, gravity drew together enough material to form the Sun. In the surrounding disk, however, the gaseous material was too



a This infrared image composite from the European Southern Observatory shows a large debris disk orbiting the star Beta Pictoris and a probable jovian planet that has formed from the disk. Images were taken with the star itself blocked; the star's position has been added digitally.



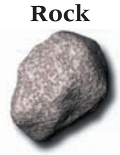
b This Hubble Space Telescope photo shows a disk around the star HD141569A. The colors are not real; a black-and-white image has been tinted red to bring out faint detail.

Figure 6.16

These photos show flattened, spinning disks of material around other stars.

Table 6.3 *Materials in the Solar Nebula*

A summary of the four types of materials present in the solar nebula. The squares represent the relative proportions of each type (by mass).

	Examples	*Typical condensation temperature*	*Relative abundance (by mass)*
Hydrogen and Helium Gas 	hydrogen, helium	do not condense in nebula	98%
Hydrogen Compounds 	water (H_2O) methane (CH_4) ammonia (NH_3)	<150 K	1.4%
Rock 	various minerals	500–1300 K	0.4%
Metals 	iron, nickel, aluminum	1000–1600 K	0.2%

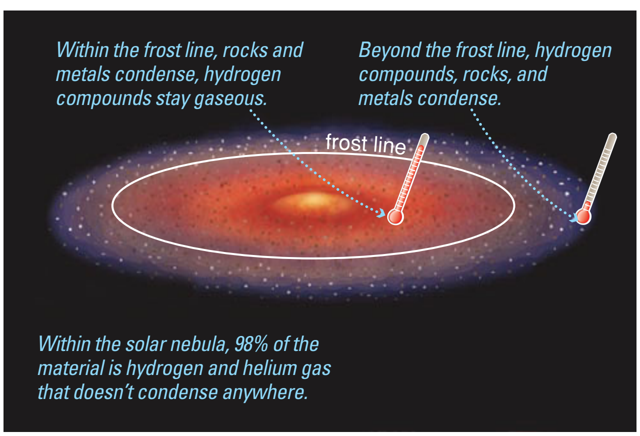


Figure 6.17 MA **interactive figure**

Temperature differences in the solar nebula led to different kinds of condensed materials, sowing the seeds for two different kinds of planets.

spread out for gravity alone to clump it together. Instead, material had to begin clumping in some other way and to grow in size until gravity could start pulling it together into planets. In essence, planet formation required the presence of "seeds"—solid bits of matter around which gravity could ultimately build planets.

Planet formation began around tiny "seeds" of solid metal, rock, or ice.

The basic process of seed formation was probably much like the formation of snowflakes in clouds on Earth: When the temperature is low enough, some atoms or molecules in a gas may bond and solidify. The general process in which solid (or liquid) particles form in a gas is called **condensation**—we say that the particles *condense* out of the gas. These particles start out microscopic in size, but they can grow larger with time.

Different materials condense at different temperatures. As summarized in Table 6.3, the ingredients of the solar nebula fell into four major categories:

- **Hydrogen and helium gas (98% of the solar nebula).** These gases never condense under the conditions present in a nebula.
- **Hydrogen compounds (1.4% of the solar nebula).** Materials such as water (H_2O), methane (CH_4), and ammonia (NH_3) can solidify into **ices** at low temperatures (below about 150 K under the low pressure of the solar nebula).
- **Rock (0.4% of the solar nebula).** Rocky material is gaseous at high temperatures but condenses into solid form at temperatures between about 500 K and 1300 K, depending on the type of rock.
- **Metals (0.2% of the solar nebula).** Metals such as iron, nickel, and aluminum are also gaseous at very high temperatures but condense into solid form at temperatures higher than rock—typically in the range of 1000 K to 1600 K.

Because hydrogen and helium gas made up 98% of the solar nebula's mass and did not condense, the vast majority of the nebula remained gaseous at all times. However, other materials could condense wherever the temperature allowed (Figure 6.17). Close to the forming Sun, where the temperature was above 1600 K, it was too hot for any material to condense. Near what is now Mercury's orbit, the temperature was low enough for metals and some types of rock to condense into tiny solid particles, but other types of rock and all the hydrogen compounds remained gaseous. More types of rock could condense, along with the metals, at the distances from the Sun where Venus, Earth, and Mars would form. In the region where the asteroid belt would eventually be located, temperatures were low enough to allow dark, carbon-rich minerals to condense, along with minerals containing small amounts of water. Hydrogen compounds could condense into ices only beyond the **frost line**—the minimum distance at which it was cold enough for ice to condense—which lay between the present-day orbits of Mars and Jupiter.

think about it Consider a region of the solar nebula in which the temperature was about 1300 K. Based on the data in Table 6.3, what fraction of the material in this region was gaseous? What were the solid particles in this region made of? Answer the same questions for a region with a temperature of 100 K. Would the 100 K region be closer to or farther from the Sun? Explain.

The frost line marked the key transition between the warm inner regions of the solar system where terrestrial planets formed and the cool outer regions where jovian planets formed. Inside the frost line, only metal and rock could condense into solid "seeds," which is why the terrestrial planets ended up being made of metal and rock. Beyond the frost line, where it was cold enough for hydrogen compounds to condense into ices, the solid seeds were built of ice along with metal and rock. Moreover, because hydrogen compounds were nearly three times as abundant in the nebula as metal and rock combined (see Table 6.3), the total amount of solid material was far greater beyond the frost line than within it. The stage was set for the birth of two types of planets: planets born from seeds of metal and rock in the inner solar system and planets born from seeds of ice (as well as metal and rock) in the outer solar system.

The solid seeds in the inner solar system were made only of metal and rock, but in the outer solar system they included the more abundant ices.

Building the Terrestrial Planets From this point, the story of the inner solar system seems fairly clear: The solid seeds of metal and rock in the inner solar system ultimately grew into the terrestrial planets we see today, but these planets ended up relatively small in size because rock and metal made up such a small amount of the material in the solar nebula.

The process by which small "seeds" grew into planets is called **accretion** (Figure 6.18). Accretion began with the microscopic solid particles that condensed from the gas of the solar nebula. These particles orbited the forming Sun with the same orderly, circular paths as the gas from which they condensed. Individual particles therefore moved at nearly the same speed as neighboring particles, so "collisions" were more like gentle touches. Although the particles were far too small to attract each other gravitationally at this point, they were able to stick together through electrostatic forces—the same "static electricity" that makes hair stick to a comb. Small particles thereby began to combine into larger ones. As the particles grew in mass, gravity began to aid in

common Misconceptions

Solar Gravity and the Density of Planets

You might think that it was the Sun's gravity that pulled the dense rocky and metallic materials to the inner part of the solar nebula, or that gases escaped from the inner nebula because gravity couldn't hold them. But this is not the case—all the ingredients were orbiting the Sun together under the influence of the Sun's gravity. The orbit of a particle or a planet does not depend on its size or density, so the Sun's gravity cannot be the cause of the different kinds of planets. Rather, the different temperatures in the solar nebula are the cause.

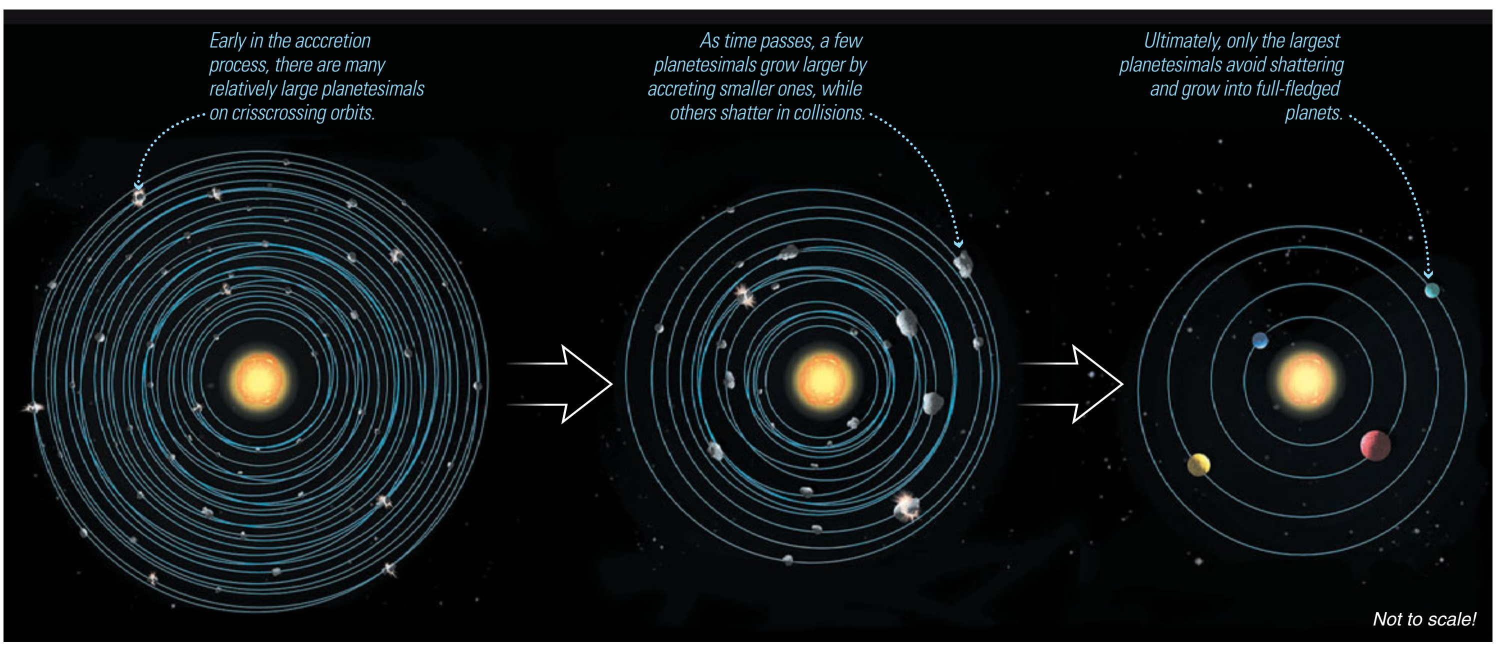


Figure 6.18

These diagrams show how planetesimals gradually accrete into terrestrial planets.

Figure 6.19

Shiny flakes of metal are clearly visible in this slice through a meteorite (a few centimeters across), mixed in among the rocky material. Such metallic flakes are just what we would expect to find if condensation really occurred in the solar nebula as described by the nebular theory.

the accretion process, accelerating their growth into boulders large enough to count as **planetesimals**, which means "pieces of planets."

The terrestrial planets were made from the solid bits of metal and rock that condensed in the inner solar system.

The planetesimals grew rapidly at first. As they grew larger, they had both more surface area to make contact with other planetesimals and more gravity to attract them. Some planetesimals probably grew to hundreds of kilometers in size in only a few million years—a long time in human terms, but only about $\frac{1}{1000}$ the present age of the solar system. However, once the planetesimals reached these relatively large sizes, further growth became more difficult.

Gravitational encounters **[Section 4.4]** between planetesimals tended to alter their orbits, particularly those of the smaller planetesimals. With different orbits crossing each other, collisions between planetesimals tended to occur at higher speeds and hence became more destructive. Such collisions tended to shatter planetesimals rather than help them grow. Only the largest planetesimals avoided being shattered and could grow into full-fledged planets.

Theoretical evidence in support of this model comes from computer simulations of the accretion process. Observational evidence comes from meteorites that appear to be surviving fragments from the period of condensation **[Section 9.1]**. These meteorites contain metallic grains embedded in rocky minerals (Figure 6.19), just as we would expect if metal and rock condensed in the inner solar system. Meteorites thought to come from the outskirts of the asteroid belt contain abundant carbon-rich materials, and some contain water—again, as we would expect for material that condensed in that region.

Making the Jovian Planets Accretion should have occurred similarly in the outer solar system, but condensation of ices meant both that there was more solid material and that this material contained ice in addition to metal and rock. The solid objects that reside in the outer solar system today, such as comets and the moons of the jovian planets, still show this ice-rich composition. However, the growth of icy planetesimals cannot be the whole story of jovian planet formation, because the jovian planets contain large amounts of hydrogen and helium gas.

The leading model for jovian planet formation holds that these planets formed as gravity drew gas around ice-rich planetesimals much more massive than Earth. Because of their large masses, these planetesimals had gravity strong enough to capture some of the hydrogen and helium gas that made up the vast majority of the surrounding solar nebula. This added gas made their gravity even stronger, allowing them to capture even more gas. Ultimately, the jovian planets accreted so much gas that they bore little resemblance to the icy seeds from which they started.

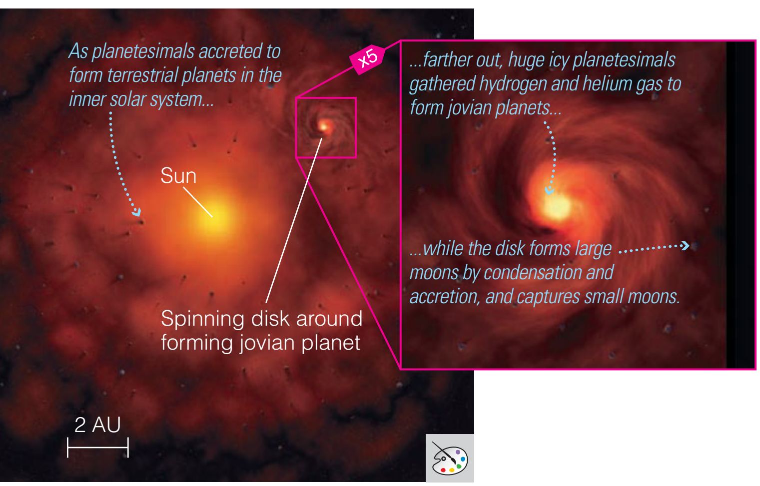


Figure 6.20

The forming jovian planets were surrounded by disks of gas, much like the disk of the entire solar nebula but smaller in size. According to the leading model, the planets grew as large, icy planetesimals that captured hydrogen and helium gas from the solar nebula. This painting shows the gas and planetesimals surrounding one jovian planet in the larger solar nebula.

The jovian planets began as large, icy planetesimals, which then captured hydrogen and helium gas from the solar nebula.

This model also explains most of the large moons of the jovian planets. The same processes of heating, spinning, and flattening that made the disk of the solar nebula should also have affected the gas drawn by gravity to the young jovian planets. Each jovian planet came to be surrounded by its own disk of gas, spinning in the same direction as the planet rotated (Figure 6.20). Moons that accreted from icy planetesimals within these disks therefore ended up with nearly circular orbits going in the same direction as their planet's rotation and lying close to their planet's equatorial plane.

Clearing the Nebula The vast majority of the hydrogen and helium gas in the solar nebula never became part of any planet. So what happened to it? Apparently, it was cleared away by a combination of radiation from the young Sun and the *solar wind*—a stream of charged particles continually blown outward in all directions from the Sun **[Section 10.1]**. Although the solar wind is fairly weak today, observations show that stars tend to have much stronger winds when they are young. The young Sun therefore should have had a strong solar wind—strong enough to have swept huge quantities of gas out of the solar system.

Remaining gas in the solar nebula was cleared away into space, ending the era of planet formation.

The clearing of the gas sealed the compositional fate of the planets. If the gas had remained longer, it might have continued to cool until hydrogen compounds could have condensed into ices even in the inner solar system. In that case, the terrestrial planets might have accreted abundant ice, and perhaps hydrogen and helium gas as well, changing their basic nature. At the other extreme, if the gas had been blown out much earlier, the raw materials of the planets might have been swept away before the planets could fully form. Although these extreme scenarios did not occur in our solar system, they may sometimes occur around other stars. Planet formation may also sometimes be interrupted when radiation from hot, neighboring stars drives away material in a solar nebula.

• Where did asteroids and comets come from?

The process of planet formation also explains the origin of the many asteroids and comets that populate our solar system (including those large enough to qualify as dwarf planets): They are "leftovers" from the era of planet formation. Asteroids are the rocky leftover planetesimals of the inner solar system, while comets are the icy leftover planetesimals of the outer solar system. We'll see in Chapter 9 why most asteroids ended up grouped in the asteroid belt while most comets ended up split between two regions (the Kuiper belt and the Oort cloud).

Rocky asteroids and icy comets are leftover planetesimals from the era of planet formation.

Evidence that asteroids and comets are leftover planetesimals comes from analysis of meteorites, spacecraft visits to comets and asteroids, and theoretical models of solar system formation. In fact, the nebular theory allowed scientists to make predictions about the locations of comets that weren't verified until decades later, when we discovered large comets orbiting in the vicinity of Neptune and Pluto.

The asteroids and comets that exist today probably represent only a small fraction of the leftover planetesimals that roamed the young solar system. The rest are now gone. Some of these "lost" planetesimals may have been flung into deep space by gravitational encounters, but many others must have collided with the planets. When impacts occur on solid worlds, they leave behind *impact craters* as scars. These impacts have transformed planetary landscapes, and, in the case of Earth, they have altered the course of evolution. For example, an impact is thought to have been responsible for the death of the dinosaurs **[Section 9.4]**.

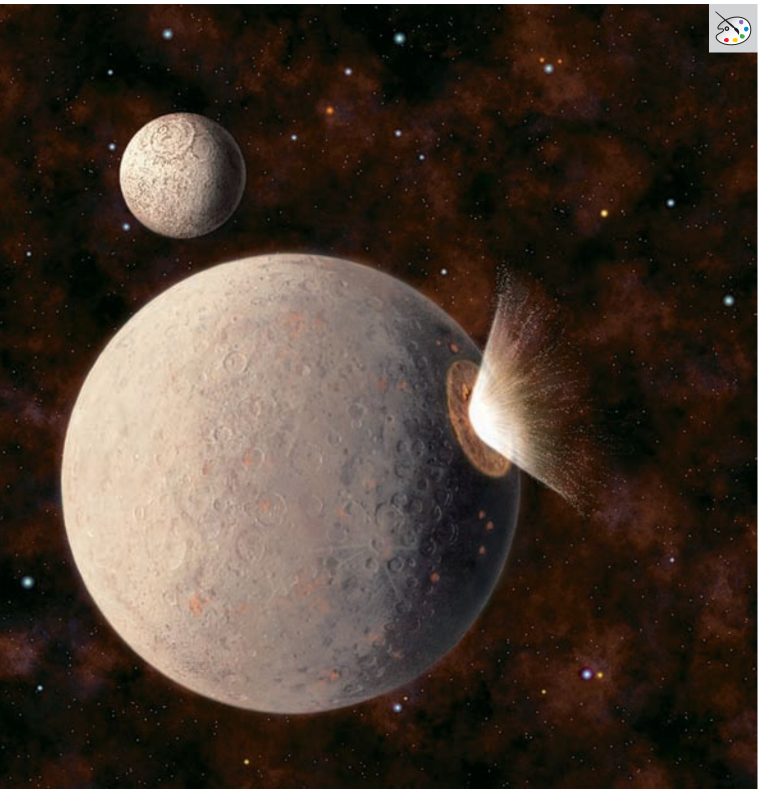


Figure 6.21

Around 4 billion years ago, Earth, its Moon, and the other planets were heavily bombarded by leftover planetesimals. This painting shows the young Earth and Moon, with an impact in progress on Earth.

Although impacts occasionally still occur, the vast majority of these collisions occurred in the first few hundred million years of our solar system's history, during the period we call the **heavy bombardment.** Every world in our solar system must have been pelted by impacts during the heavy bombardment (Figure 6.21), and most of the craters we see on the Moon and other worlds date from this period. These impacts did more than just batter the planets. They also brought materials from other regions of the solar system—a fact that is critical to our existence on Earth today.

Leftover planetesimals battered the planets during the solar system's first few hundred million years.

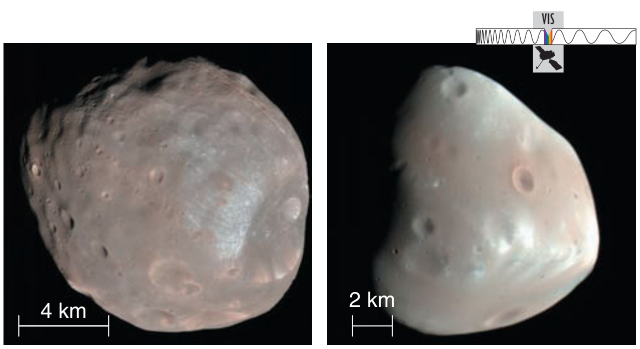
Remember that the terrestrial planets were built from planetesimals made of metal and rock. These planetesimals probably contained no water or other hydrogen compounds at all, because it was too hot for these compounds to condense in our region of the solar nebula. How, then, did Earth come to have the water that makes up our oceans and the gases that first formed our atmosphere? The likely answer is that water, along with other hydrogen compounds, was brought to Earth and other terrestrial planets by the impacts of water-bearing planetesimals that formed farther from the Sun. Remarkably, the water we drink and the air we breathe probably once were part of planetesimals that accreted beyond the orbit of Mars.

• How do we explain the existence of our Moon and other exceptions to the rules?

We have now explained all the major features of our solar system except for the exceptions to the rules, including our surprisingly large Moon. Today, we think that most of these exceptions arose from collisions or close gravitational encounters.

Captured Moons We have explained the orbits of most large jovian planet moons by their formation in a disk that swirled around the forming planet. But how do we explain moons with less orderly orbits, such as those that go in the "wrong" direction (opposite their planet's rotation) or that have large inclinations to their planet's equator? These moons are probably leftover planetesimals that originally orbited the Sun but were then captured into planetary orbit.

It's not easy for a planet to capture a moon. An object cannot switch from an unbound orbit (for example, an asteroid whizzing by Jupiter) to a bound orbit (for example, a moon orbiting Jupiter) unless it somehow loses orbital energy **[Section 4.4]**. For the jovian planets, captures probably occurred when passing planetesimals lost energy to drag in the extended and relatively dense gas that surrounded these planets as they formed. The planetesimals would have been slowed by friction with the gas, just as artificial satellites are slowed by drag in encounters with Earth's atmosphere. If friction reduced a passing planetesimal's orbital energy enough, it could have become an orbiting moon. Because of the random nature of the capture process, captured moons would not necessarily orbit in the same direction as their planet or in its equatorial plane. Most of the small moons of the jovian planets are a few kilometers across, supporting the idea that they were captured in this way. Mars may have similarly captured its two small moons, Phobos and Deimos, at a time when the planet had a much more extended atmosphere than it does today (Figure 6.22).



a Phobos **b** Deimos

Figure 6.22

The two moons of Mars are probably captured asteroids. Phobos is only about 13 kilometers across, and Deimos is only about 8 kilometers across—making each of these two moons small enough to fit within the boundaries of a typical large city. (Images from the *Mars Reconnaissance* orbiter.)

The Giant Impact Formation of Our Moon Capture processes cannot explain our own Moon, because it is much too large to have been captured by a small planet like Earth. We can also rule out the possibility that our Moon formed simultaneously with Earth, because if both had formed together, they would have accreted from planetesimals of the same type and should therefore have approximately the same composition and density. But this is not the case: The Moon's density is considerably lower than Earth's, indicating that it has a very different average composition. So how did we get our Moon? Today, the leading hypothesis suggests that it formed as the result of a **giant impact** between Earth and a huge planetesimal.

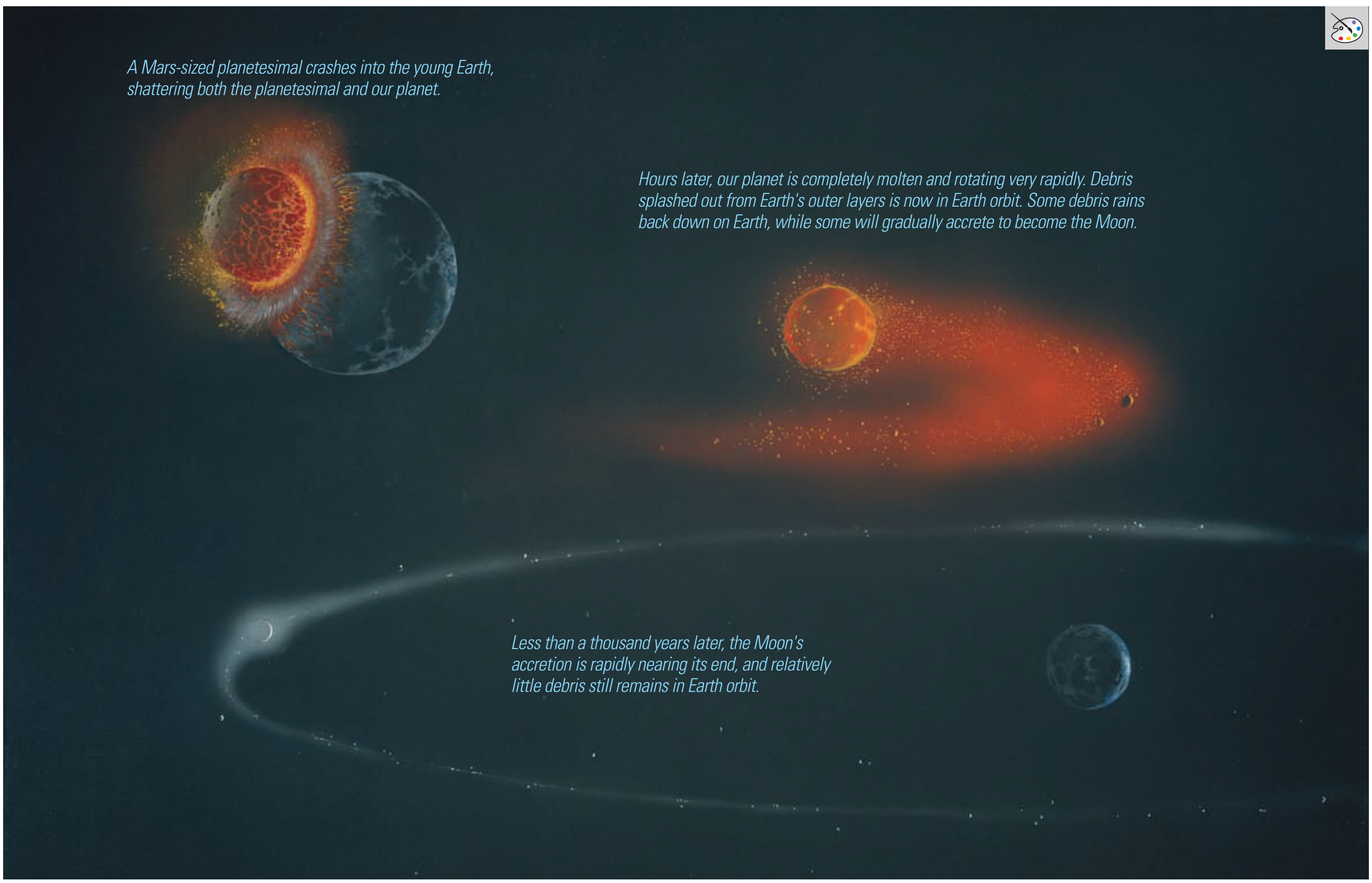
According to models, a few leftover planetesimals may have been as large as Mars. If one of these Mars-size objects struck a young planet, the blow might have tilted the planet's axis, changed the planet's rotation rate, or completely shattered the planet. The giant impact hypothesis holds that a Mars-size object hit Earth at a speed and angle that blasted Earth's outer layers into space. According to computer simulations, this material could have collected into orbit around our planet, and accretion within this ring of debris could have formed the Moon (Figure 6.23).

Our Moon is probably the result of a giant impact that blasted Earth's outer layers into orbit, where the material accreted to form the Moon.

Strong support for the giant impact hypothesis comes from two features of the Moon's composition. First, the Moon's overall

Figure 6.23

Artist's conception of the giant impact hypothesis for the formation of our Moon. The fact that ejected material came mostly from Earth's outer rocky layers explains why the Moon contains very little metal. The impact must have occurred more than 4.4 billion years ago, since that is the age of the oldest Moon rocks. As shown, the Moon formed quite close to a rapidly rotating Earth, but over billions of years, tidal forces have slowed Earth's rotation and moved the Moon's orbit outward **[Section 4.4]**.



composition is quite similar to that of Earth's outer layers—just as we should expect if it were made from material blasted away from those layers. Second, the Moon has a much smaller proportion of easily vaporized ingredients (such as water) than Earth. This fact supports the hypothesis because the heat of the impact would have vaporized these ingredients. As gases, they would not have participated in the process of accretion that formed the Moon.

Other Exceptions Giant impacts may also explain other exceptions to the general trends. For example, Pluto's moon Charon shows signs of having formed in a giant impact similar to the one thought to have formed our Moon, and Mercury's surprisingly high density may be the result of a giant impact that blasted away its outer, lower-density layers. Giant impacts could have also been responsible for tilting the axes of many planets (including Earth) and perhaps for tipping Uranus on its side. Venus's slow and backward rotation could also be the result of a giant impact, though some scientists suspect it is a consequence of processes attributable to Venus's thick atmosphere.

Although we cannot definitively explain these exceptions to the general rules, the overall lesson is clear: The chaotic processes that accompanied planet formation, including the many collisions that surely occurred, are *expected* to have led to at least a few exceptions. We therefore conclude that nebular theory can account for all four of the major features of our solar system. Figure 6.24 summarizes what we have discussed.

• When did the planets form?

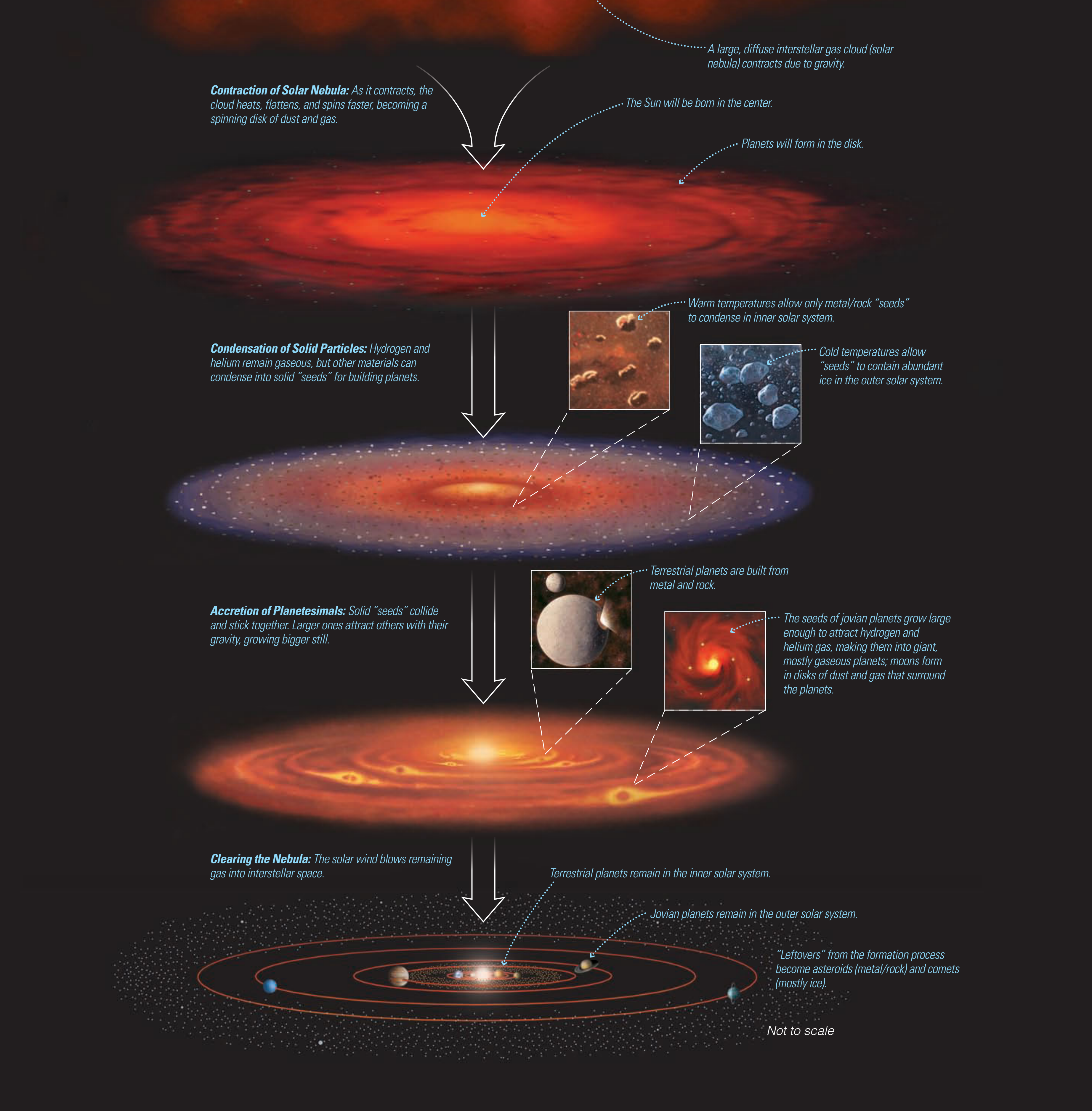
Computer models of planetary formation suggest that the entire process took no more than about 50 million years, and perhaps significantly less. But when did it all occur, and how do we know? The answer is that the planets began to form through accretion just over $4\frac{1}{2}$ billion years ago, a fact we learn by determining the age of the oldest rocks in the solar system.

Dating Rocks The most reliable method for measuring the age of a rock is **radiometric dating**, which relies on careful measurement of the proportions of various atoms and isotopes in the rock. The method works because some atoms undergo changes with time that allow us to determine how long they have been held in place within the rock's solid structure. By analyzing these changes we learn the amount of time that has passed since the atoms became locked together in their present arrangement, which in most cases means the time *since the rock last solidified.*

Remember that each chemical element is uniquely characterized by the number of protons in its nucleus. Different *isotopes* of the same element differ only in their number of neutrons [Section 5.1]. A **radioactive** isotope has a nucleus prone to spontaneous change, or *decay,* such as breaking apart or having one of its protons turn into a neutron. This decay always occurs at the same rate for any particular radioactive isotope, and scientists can measure these rates in the laboratory. We generally characterize decay rates by stating a **half-life**—the length of time it would take for half the nuclei in the collection to decay.

Figure 6.24

A summary of the proccess by which our solar system formed, according to the nebular theory.



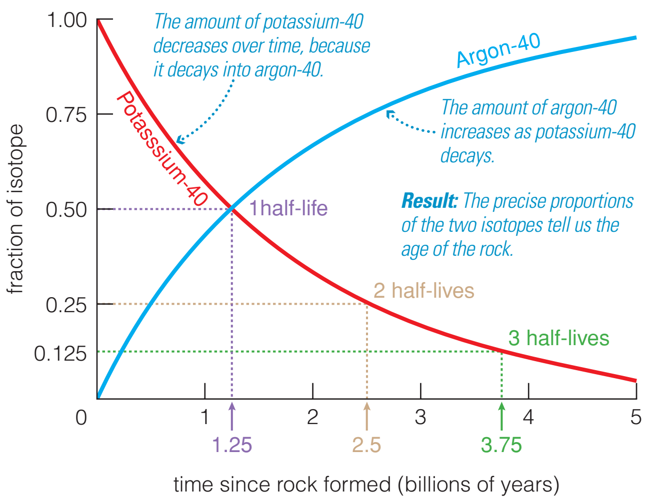


Figure 6.25

Potassium-40 is radioactive, decaying into argon-40 with a half-life of 1.25 billion years. The red curve shows the decreasing amount of potassium-40, and the blue curve shows the increasing amount of argon-40. The remaining amount of potassium-40 drops in half with each successive half-life.

For example, potassium-40 is a radioactive isotope with nuclei that decay when a proton turns into a neutron, changing the potassium-40 into argon-40. The half-life for this decay process is 1.25 billion years. (Potassium-40 also decays by other paths, but we focus only on decay into argon-40 to keep the discussion simple.) Now, consider a small piece of rock that contained 1 microgram of potassium-40 and no argon-40 when it formed (solidified) long ago. The half-life of 1.25 billion years means that half the original potassium-40 had decayed into argon-40 by the time the rock was 1.25 billion years old, so at that time the rock contained $\frac{1}{2}$ microgram of potassium-40 and $\frac{1}{2}$ microgram of argon-40. Half of this remaining potassium-40 had then decayed by the end of the next 1.25 billion years, so after 2.5 billion years the rock contained $\frac{1}{4}$ microgram of potassium-40 and $\frac{3}{4}$ microgram of argon-40. After three half-lives, or 3.75 billion years, only $\frac{1}{8}$ microgram of potassium-40 remained, while $\frac{7}{8}$ microgram had become argon-40. Figure 6.25 summarizes the gradual decrease in the amount of potassium-40 and the corresponding rise in the amount of argon-40.

We can determine the age of a rock through careful analysis of the proportions of various atoms and isotopes within it.

We can now see the essence of radiometric dating. Suppose you find a rock that contains equal numbers of atoms of potassium-40 and argon-40. If you assume that all the argon came from potassium decay (and if the rock shows no evidence of subsequent heating that could have allowed any argon to escape), then it must have taken precisely one half-life for the rock to end up with equal amounts of the two isotopes. You could therefore conclude that the rock is 1.25 billion years old. The only question is whether you are right in assuming that the rock lacked argon-40 when it formed. In this case, knowing a bit of "rock chemistry" helps. Potassium-40 is a natural ingredient of many minerals in rocks, but argon-40 is a gas that does not combine with other elements and did not condense in the solar nebula. If you find argon-40 gas trapped inside minerals, it must have come from radioactive decay of potassium-40.

Radiometric dating is possible with many other radioactive isotopes as well. In many cases, we can date a rock that contains more than one radioactive isotope, so agreement between the ages calculated from the different isotopes gives us confidence that we have dated the rock correctly. We can also check results from radiometric dating against those from other methods of measuring or estimating ages. For example, some fairly recent archaeological artifacts have original dates printed on them, and the dates agree with ages found by radiometric dating. We can validate the $4\frac{1}{2}$-billion-year radiometric age for the solar system as a whole by comparing it to an age based on detailed study of the Sun. Theoretical models of the Sun, along with observations of other stars, show that stars slowly expand and brighten as they age. The model ages are not nearly as precise as radiometric ages, but they confirm that the Sun is between about 4 and 5 billion years old. Overall, the technique of radiometric dating has been checked in so many ways and relies on such basic scientific principles that there is no longer any serious scientific debate about its validity.

Earth Rocks, Moon Rocks, and Meteorites Radiometric dating tells us how long it has been since a rock solidified, which is not the same as the age of a planet as a whole. For example, we find rocks of many different ages on Earth. Some rocks are quite young because they formed recently from molten lava; others are much older. The oldest

Earth rocks are about 4 billion years old, and some small mineral grains are about 4.4 billion years old. Earth itself must be even older.

Moon rocks brought back by the *Apollo* astronauts date as far back as 4.4 billion years ago. Although they are older than Earth rocks, these Moon rocks must still be younger than the Moon itself. The ages of these rocks also tell us that the giant impact thought to have created the Moon must have occurred more than 4.4 billion years ago.

Age dating of meteorites that are unchanged since they condensed and accreted tells us that the solar system is about $4\frac{1}{2}$ billion years old.

To go all the way back to the origin of the solar system, we must find rocks that have not melted or vaporized since they first condensed in the solar nebula. Meteorites that have fallen to Earth are our source of such rocks. Many meteorites appear to have remained unchanged since they condensed and accreted in the early solar system. Careful analysis of radioactive isotopes in these meteorites shows that the oldest ones formed about 4.55 billion years ago, so this time must mark the beginning of accretion in the solar nebula. Because the planets apparently accreted within about 50 million (0.05 billion) years, Earth and the other planets formed about 4.5 billion years ago.

MA **Detecting Extrasolar Planets Tutorial, Lessons 1–3**

6.5 Other Planetary Systems

Just a couple of decades ago, the complete list of known planets in the universe consisted only of those in our own solar system. The nebular theory made it seem likely that planets existed around other stars, but technology was not yet at the point where we could test the idea. As we discussed in Chapter 1, seeing planets around other stars is equivalent to looking for dim ball points or marbles from a distance of thousands of kilometers away—with the star typically a billion times brighter than the planet. Remarkably, we can now detect many of these planets, and this fact has ushered in a new era in astronomy: We can engage in comparative study of planetary *systems,* which allows us to test and refine our ideas about the formation of stars and planets.

• How do we detect planets around other stars?

The first clear-cut discovery of a planet around another Sun-like star—a star called 51 Pegasi—came in 1995. Hundreds of additional extrasolar planets have been discovered since that time, using several planet-finding strategies. If we strip away the details, however, there are really only two basic ways to search for extrasolar planets:

1. Directly: Pictures or spectra of the planets themselves constitute direct evidence of their existence.
2. Indirectly: Precise measurements of a *star's* properties may indirectly reveal the effects of orbiting planets.

Almost all extrasolar planets detected to date have been found indirectly rather than through direct imaging.

Direct detection is preferable because it can tell us far more about the planet's properties, but to date nearly all detections have been indirect.

cosmic Calculations 6.1

Radiometric Dating

From the fact that the amount of a radioactive substance decays by half with each half-life, it is possible to derive a simple formula for the age of a rock. If you have measured the current amount of a radioactive substance and determined the original amount (by measuring the abundance of its decay products), and if you know its half-life, t_{half}, then the time t since the rock formed is

$$t = t_{\text{half}} \times \frac{\log_{10}\left(\dfrac{\text{current amount}}{\text{original amount}}\right)}{\log_{10}\left(\dfrac{1}{2}\right)}$$

Even if you are unfamiliar with logarithms, you can work with this formula by using the "log" button on your calculator.

Example: You chemically analyze a small sample of a meteorite. Potassium-40 and argon-40 are present in a ratio of approximately 0.85 unit of potassium-40 atoms to 9.15 units of gaseous argon-40 atoms. (The units are unimportant, because only the relative amounts of the parent and daughter materials matter.) How old is the meteorite?

Solution: Because no argon gas could have been present in the meteorite when it formed, the 9.15 units of argon-40 must originally have been potassium-40 that has decayed with a half-life of 1.25 billion years. The sample must therefore have started with $0.85 + 9.15 = 10$ units of potassium-40 (the original amount), of which 0.85 unit remains (the current amount). The formula now reads

$$t = 1.25 \text{ billion yr} \times \frac{\log_{10}\left(\dfrac{0.85}{10}\right)}{\log_{10}\left(\dfrac{1}{2}\right)} = 4.45 \text{ billion yr}$$

This meteorite solidified about 4.45 billion years ago.

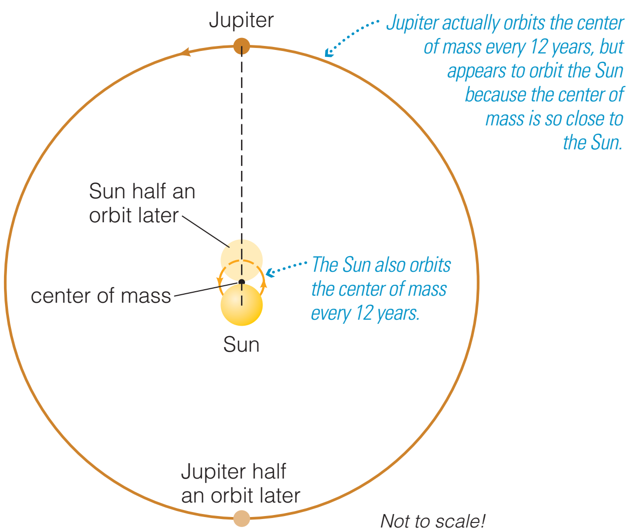


Figure 6.26

This diagram shows how both the Sun and Jupiter actually orbit around their mutual center of mass, which lies very close to the Sun. The diagram is not to scale; the sizes of the Sun and its orbit are exaggerated about 100 times compared to the size shown for Jupiter's orbit, and Jupiter's size is exaggerated even more.

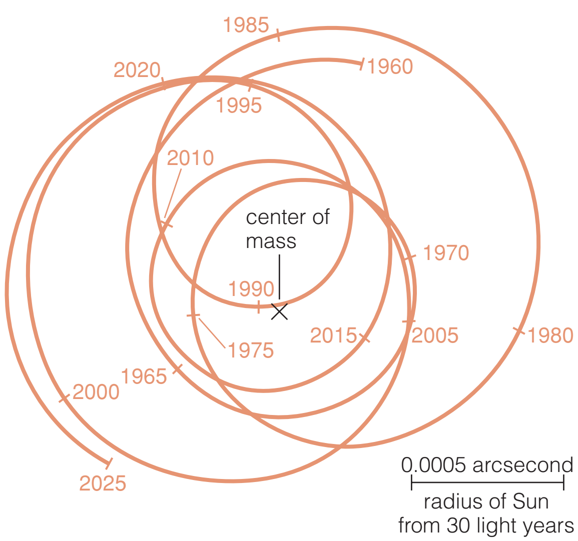


Figure 6.27

This diagram shows the orbital path of the Sun from 1960 to 2025 around the center of mass of our solar system, as it would appear if viewed face-on from a distance of 30 light-years away. The complex motion reveals the gravitational effects of the planets (primarily Jupiter and Saturn). The *astrometric technique* for detecting extrasolar planets works by looking for similar changes in the position of other stars. Notice that the entire range of motion during this period is only about 0.0015 arcsecond, which is almost 100 times smaller than the angular resolution of the Hubble Space Telescope.

think about it Do a quick Web search on "extrasolar planets" to find the current number of known extrasolar planets. How many have been found in the past year alone?

Gravitational Tugs Two indirect techniques—the *astrometric* and *Doppler* techniques—rely on observing stars in search of motion that we can attribute to gravitational tugs from orbiting planets. Although we usually think of a star as remaining still while planets orbit around it, that is only approximately correct. In reality, all the objects in a star system, including the star itself, orbit the system's *center of mass,* which is in essence the balance point for all the mass of the solar system. Because the Sun is far more massive than all the planets combined, the center of mass of our solar system lies close to the Sun—but not exactly at the Sun's center.

We can see how this fact allows us to discover extrasolar planets by imagining the viewpoint of extraterrestrial astronomers observing our solar system from afar. Let's start by considering only the influence of Jupiter, the most massive planet in our solar system (Figure 6.26). The center of mass between the Sun and Jupiter lies just outside the Sun's visible surface, so what we usually think of as Jupiter's 12-year orbit around the Sun is really a 12-year orbit around this center of mass. Because the Sun and Jupiter are always on opposite sides of the center of mass (otherwise it wouldn't be a "center"), the Sun must orbit this point with the same 12-year period. The Sun's orbit traces out a very small ellipse with each 12-year period, because the Sun's average orbital distance is barely larger than its own radius. Nevertheless, with sufficiently precise measurements, extraterrestrial astronomers could detect this orbital movement of the Sun and thereby deduce the existence of Jupiter—without having ever seen the planet. They could even determine Jupiter's mass from the orbital characteristics of the Sun as it goes around the center of mass. A more massive planet located at the same distance would pull the center of mass farther from the Sun's center, thereby giving the Sun a larger orbit and a faster orbital speed around the center of mass.

see it for yourself To see how a small planet can make a big star wobble, find a pencil and tape a heavier object (such as a set of keys) to one end and a lighter object (perhaps a small stack of coins) to the other end. Tie a string (or piece of floss) at the balance point—the center of mass—so that the pencil is horizontal; then tap the lighter object into "orbit" around the heavier object. What does the heavier object do, and why? How does your model correspond to a planet orbiting a star? You can experiment further with objects of different weights or shorter pencils; explain the differences you see.

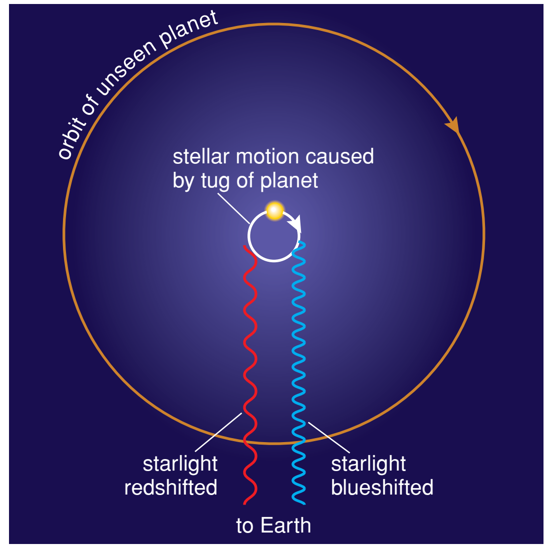
Orbiting planets exert gravitational tugs on their star, so we can detect the planets by observing the star's resulting "wobble" around its average position in the sky.

The other planets also exert gravitational tugs on the Sun, each adding a small additional effect to the effects of Jupiter. In principle, with sufficiently precise measurements of the Sun's orbital motion made over many decades, an extraterrestrial astronomer could deduce the existence of all the planets of our solar system (Figure 6.27). This is the essence of the **astrometric technique**, in which we make very precise measurements of stellar positions in the sky (*astrometric* means "measurement of the stars"). If a star "wobbles" gradually around its average position (the center of mass), we must be observing the influence of unseen planets. The primary difficulty with the astrometric technique is that we are looking for changes to position that are very small even for nearby stars, and these changes become smaller for more distant stars. In addition, the stellar motions are largest for massive planets orbiting *far* from their star, but the long orbital periods of such planets mean that it can take decades to notice the motion. As a result, the astrometric technique has been of only limited use to date, but astronomers hope it will prove successful with future space-based telescopes.

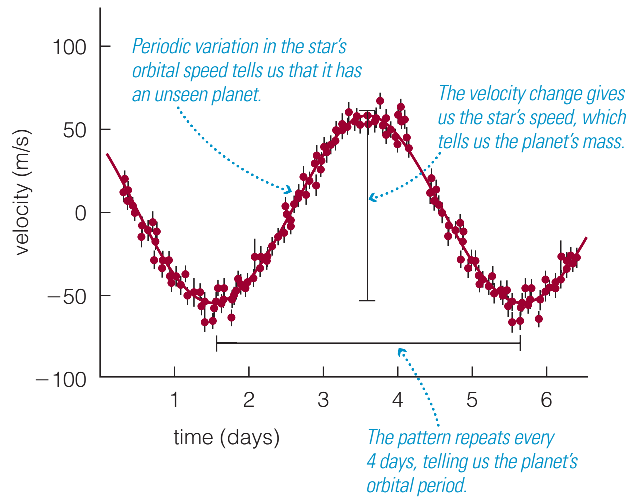
The **Doppler technique** searches for a star's orbital movement around the center of mass by looking for changing Doppler shifts in a star's spectrum **[Section 5.2]**. As long as a planet's orbit is *not* face-on to us, its gravitational influence will cause its star to move alternately with an orbital toward and away from us—motions that cause spectral lines to shift alternately toward the blue and red ends of the spectrum (Figure 6.28a). The 1995 discovery of a planet orbiting 51 Pegasi came when this star was found to have alternating blueshifts and redshifts within a period of four days (Figure 6.28b). The 4-day period of the star's motion must be the orbital period of its planet. We can then use this period with the star's mass and Newton's version of Kepler's third law **[Section 4.4]** to calculate the planet's orbital distance. (In Chapter 11, we'll see how the star's mass and other properties can be known.) The Doppler technique even allows us to estimate the planet's mass from the measured change in the star's velocity.* The data in Figure 6.28b thereby enabled us to learn that the planet orbiting 51 Pegasi is similar to Jupiter in mass but orbits only about 0.05 AU from its star—so close that its surface temperature is probably over 1000 K. It is therefore an example of what we call a **hot Jupiter,** because it has a Jupiter-like mass but a much higher surface temperature.

Alternating Doppler shifts in a star's spectrum, indicating back-and-forth motion, can also reveal the influence of orbiting planets.

The Doppler technique has been used for the vast majority of planet discoveries to date. In some cases, Doppler data are good enough to tell us whether the star has more than one planet. Remember that if two or more planets exert a noticeable gravitational tug on their star, the Doppler data will show the combined effect of these tugs. Dozens of multiple-planet systems have been identified, including one with five planets. Keep in mind, however, that the Doppler technique is best suited to identifying massive planets that orbit relatively close to their star, because the star's orbital speed depends on the strength of the gravitational tug, and gravity is strongest for massive planets with small orbital distances **[Section 4.4]**. This fact probably explains why most of the extrasolar planets discovered to date orbit relatively close to their stars—these planets are easier to find than planets orbiting far from their stars, which would have weaker gravitational effects and such long orbital periods that it might take decades of observations to detect them. It also explains why it is so difficult to detect planets with Earth-like masses: These planets would have such weak gravitational effects on their stars that we could not apply the Doppler technique to find them using current technology.



a Doppler shifts allow us to detect the slight motion of a star caused by an orbiting planet.



b A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

Figure 6.28 MA **interactive figure**

The Doppler technique for discovering extrasolar planets.

*The Doppler shift tells us the star's full orbital velocity only if we are viewing its planetary system edge-on; in all other cases, it gives us a lower limit on the star's velocity and therefore a lower limit to the planet's mass. However, statistical arguments show that in two out of three cases, the planet's true mass will be no more than double this lower limit.

Transits and Eclipses A third indirect way of detecting distant planets relies on searching for slight changes in a star's brightness that occur when a planet passes in front of or behind it. If we were to examine a large sample of stars with planets, a small number of them (<1%) would by chance be aligned in such a way that one or more of the star's planets pass directly between us and the star during each orbit. The result is a **transit**, in which the planet appears to move across the face of the star, causing a small, temporary dip in the star's brightness. Because a star's brightness can also vary for other reasons, we can assume that a transiting planet is the cause only if the dimming repeats with a regular period.

think about it What kind of planet is most likely to cause a transit across its star that we could observe from Earth: (a) a large planet close to its star? (b) a large planet far from its star? (c) a small planet close to its star? or (d) a small planet far from its star? Explain.

Figure 6.29 shows transit data for a planet orbiting the star HD189733. Transits occur every 2.2 days, telling us the planet's orbital period, and the 2.5% dips in the star's brightness tell us how the planet's radius compares to its star's radius. Half an orbit after a transit, a planet passes behind its star in what we call an **eclipse**. Observing an eclipse is much like observing a transit: In both cases, we actually measure the *combined* light from the star and planet, so in principle there can be a dip in brightness whenever either object blocks light from the other. However, because planets generally emit in the infrared, not in the visible [Section 5.2], the dips that occur during eclipses are usually measurable only at infrared wavelengths. For example, during eclipses in the HD189733 system, the infrared brightness drops by about 0.3%, telling us that the planet emits 0.3% as much infrared radiation as the star (see Figure 6.29). By combining this fact with the planet's radius measured during the transits, astronomers calculate the planet's temperature to be more than 1100 K.

If a planet happens to orbit edge-on as seen from Earth, it will periodically pass in front of its star, causing a dip in the star's brightness.

The primary limitation of the transit and eclipse methods is that they work only for the small fraction of planets whose orbits are nearly edge-on. But the method also has advantages, including the ability to take a spectrum of starlight transmitted through a planet's atmosphere. So far,

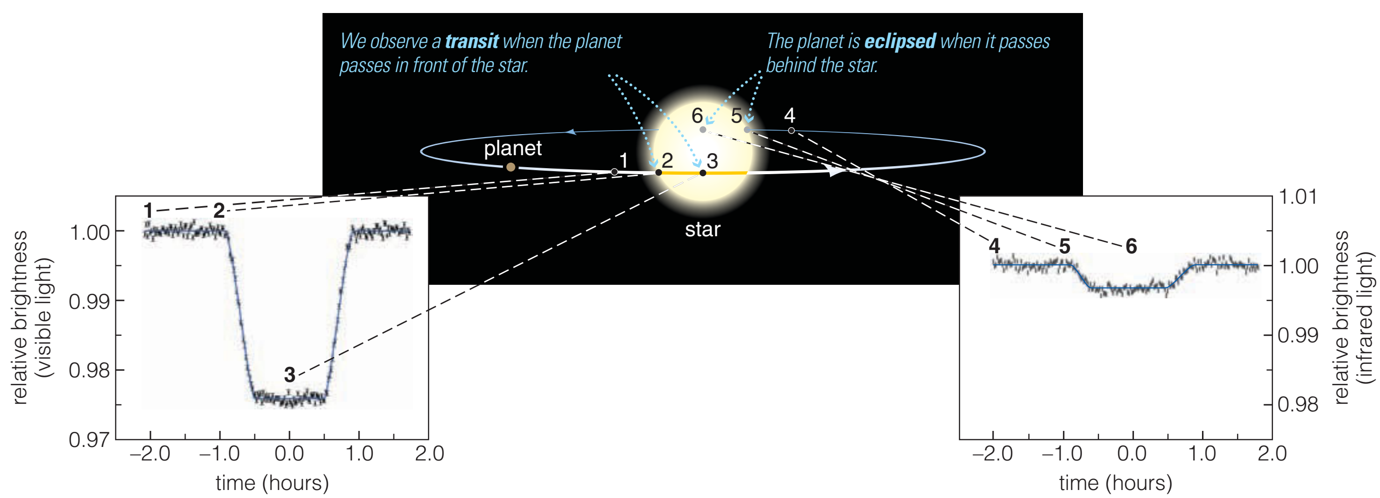


Figure 6.29 MA interactive figure

This diagram shows the planet orbiting the star HD189733. The graphs show how the star's brightness changes during transits and eclipses, which each occur once during every 2.2-day orbit. During a transit, the star's brightness drops for about 2 hours by 2.5%, which tells us how the planet's radius compares to the radius of its star. During an eclipse, the infrared signal drops by 0.3%, which tells us about the planet's thermal emission.

astronomers have confirmed the existence of hydrogen, water, methane, and even a hint of sodium in the atmospheres of extrasolar planets. The transit method can also be used to search simultaneously for planets around vast numbers of stars and to detect much smaller planets than is possible with the Doppler technique. NASA's *Kepler* mission, launched in 2009, is monitoring some 100,000 stars for transits. By mid-2010, *Kepler* had already found more than 700 candidates, some not much larger than Earth, but was still awaiting follow-up observations to distinguish planets from eclipsing or variable stars. If Earth-size planets are common, *Kepler* should detect dozens of them. A European Space Agency (ESA) spacecraft called *COROT* has also detected several transiting planets. In addition, small telescopes have been used to discover transiting planets, and it's relatively easy to confirm for yourself some of the transits already detected. What was once considered impossible can now be assigned as homework (see Problem 54 at the end of the chapter).

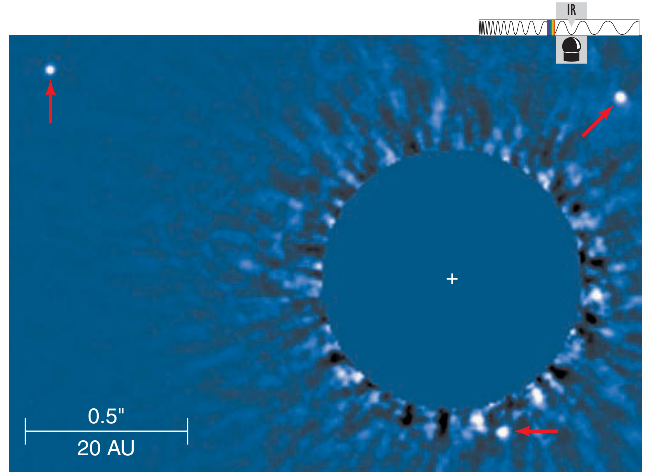


Figure 6.30

This infrared image from the Keck telescope shows three planets (indicated by red arrows) orbiting the star HR 8799. We know they are planets because they have all moved slightly since their discovery. The star itself, located at the + sign, was blocked during the exposure. These planets are much larger and farther from their star than the jovian planets in our solar system.

think about it Find the current status of the *Kepler* and *COROT* missions. What is the smallest planet discovered by either mission so far?

Direct Detection The indirect planet-hunting techniques we have discussed so far have started a revolution in planetary science by demonstrating that our solar system is just one of many planetary systems. However, these indirect techniques tell us relatively little about the planets themselves, aside from their orbital properties and their masses or radii. To learn more about their nature, we need to observe the planets themselves. Even low-resolution images can reveal important surface features, and spectra can tell us about their compositions and properties of their atmospheres.

Direct images and spectra allow us to learn much more about the nature of extrasolar planets.

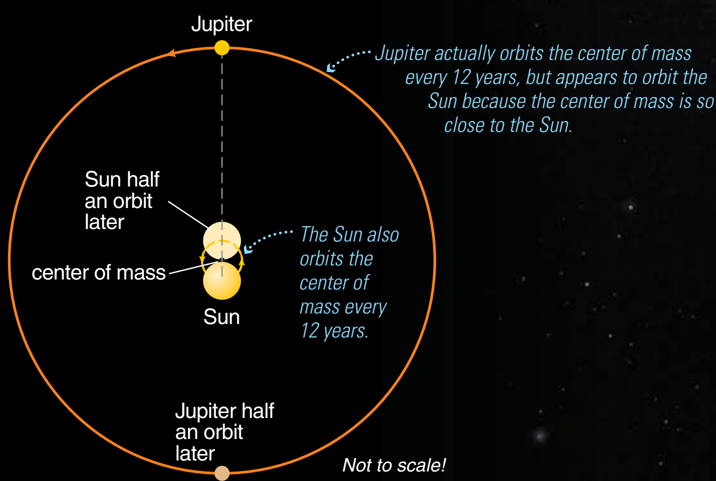
The great distances and the glare from stars make direct detection extremely difficult. Nevertheless, direct detection capabilities are rapidly improving, and we already have several images and spectra of extrasolar planets. Figure 6.30 shows a remarkable image of a three-planet system whose orbital plane appears nearly face-on. Astronomers are confident that the dots are planets because they observed them more than once and detected their orbital motion around their star. The planets are so young that they are still glowing from the heat of formation. (Figure 6.16 shows another directly detected jovian planet orbiting the star Beta Pictoris.) Figure 6.31 summarizes the major planet detection techniques.

Other Planet-Hunting Strategies The astonishing success of recent efforts to find extrasolar planets has led astronomers to think of many other possible ways of enhancing the search. For example, several planets have been detected using *gravitational lensing*, an effect predicted by Einstein's general theory of relativity that occurs when one object's gravity bends or brightens the light of a more distant object **[Section 16.2]**. While gravitational lensing is a useful technique, the geometry required for its application never repeats, giving no opportunity for follow-up observations. A different strategy looks for the gravitational effects of unseen planets on the disks of dust that surround many stars, while another method searches for the thermal emission from the impacts of accreting planetesimals. As we learn more about extrasolar planets, new search methods are sure to arise.

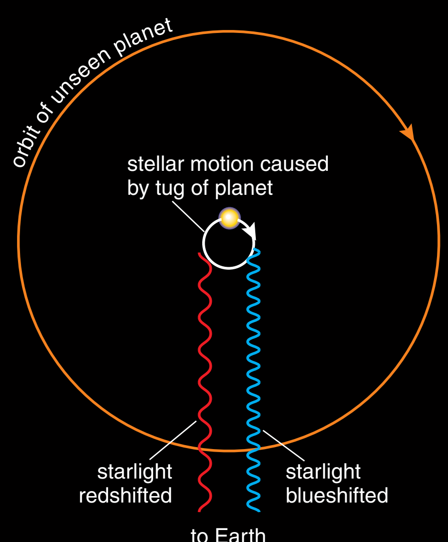
cosmic **Context** • **Figure 6.31. Detecting Extrasolar Planets**

The search for planets around other stars is one of the fastest growing and most exciting areas of astronomy. This figure summarizes major techniques that astronomers use to search for and study extrasolar planets.

1. **Gravitational Tugs:** We can detect a planet by observing the small orbital motion of its star as both the star and its planet orbit their mutual center of mass. The star's orbital period is the same as that of its planet, and the star's orbital speed depends on the planet's distance and mass. Any additional planets around the star will produce additional features in the star's orbital motion.

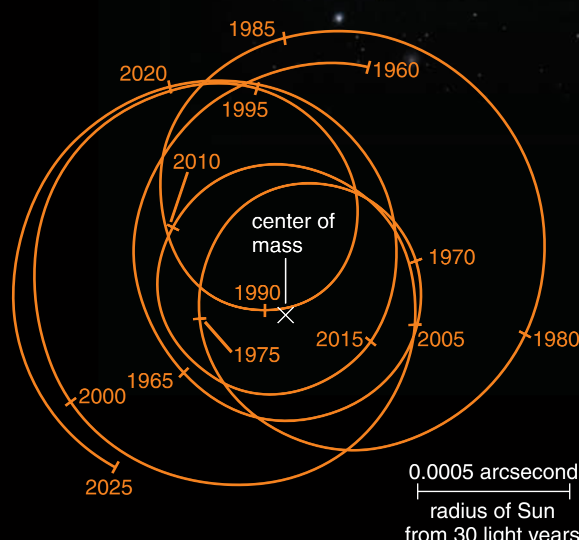


1a **The Doppler Technique:** As a star moves alternately toward and away from us around the center of mass, we can detect its motion by observing alternating Doppler shifts in the star's spectrum: a blueshift as the star approaches and a redshift as it recedes. This technique has revealed the vast majority of known extrasolar planets.



Current Doppler-shift measurements can detect an orbital velocity as small as 1 meter per second—walking speed.

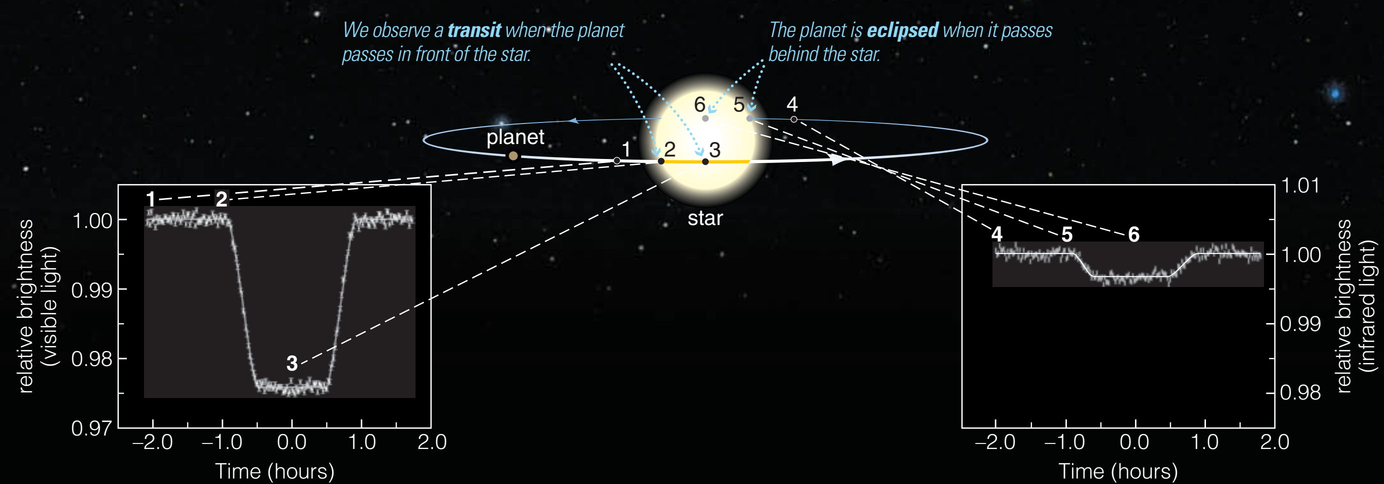
1b **The Astrometric Technique:** A star's orbit around the center of mass leads to tiny changes in the star's position in the sky. As we improve our ability to measure these tiny changes, we should discover many more extrasolar planets.



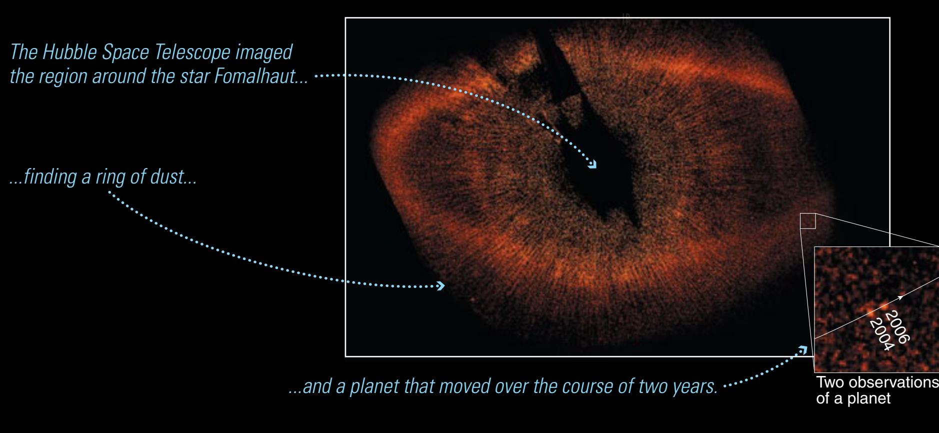
The change in the Sun's apparent position, if seen from a distance of 10 light years, would be similar to the angular width of a human hair at a distance of 5 kilometers.

Artist's conception of another planetary system, viewed near a ringed jovian planet.

② **Transits and Eclipses:** If a planet's orbital plane happens to lie along our line of sight, the planet will transit in front of its star once each orbit, while being eclipsed behind its star half an orbit later. The amount of starlight blocked by the transiting planet can tell us the planet's size, and changes in the spectrum can tell us about the planet's atmosphere.



③ **Direct Detection:** In principle, the best way to learn about an extrasolar planet is to observe directly either the visible starlight it reflects or the infrared light that it emits. Our technology is only beginning to reach the point where direct detection is possible, but someday we will be able to study both images and spectra of distant planets.



• How do extrasolar planets compare with planets in our solar system?

We have now discovered enough extrasolar planets that we can begin to search for patterns, trends, and groupings that might give us insight into how these planets compare to the planets of our own solar system. The first step in looking for patterns and trends is to organize the existing information. We will therefore begin by summarizing the known properties of extrasolar planets.

Orbits Much as Johannes Kepler first discovered the true layout of our own solar system based on orbital properties **[Section 3.3]**, we are now discovering the layouts of many other solar systems. Figure 6.32 shows the orbital parameters of hundreds of extrasolar planets. At least two important trends should jump out at you. First, notice that only a handful of these planets have orbits beyond about 5 AU, which is Jupiter's distance from our Sun. Most of the planets orbit very close to their host star; many of them orbit closer than Mercury orbits to our Sun. Second, notice that many of the orbits are elliptical instead of nearly circular like the orbits of planets in our own solar system.

Most extrasolar planets discovered to date have different orbital characteristics than planets in our solar system, but this may be a result of the search methods.

These data might seem to suggest that solar systems laid out like our own are quite rare. However, it is also possible that this result is a *selection effect* that occurs because most of these planets have been detected with the Doppler technique. Recall that the Doppler technique is best suited to identifying massive

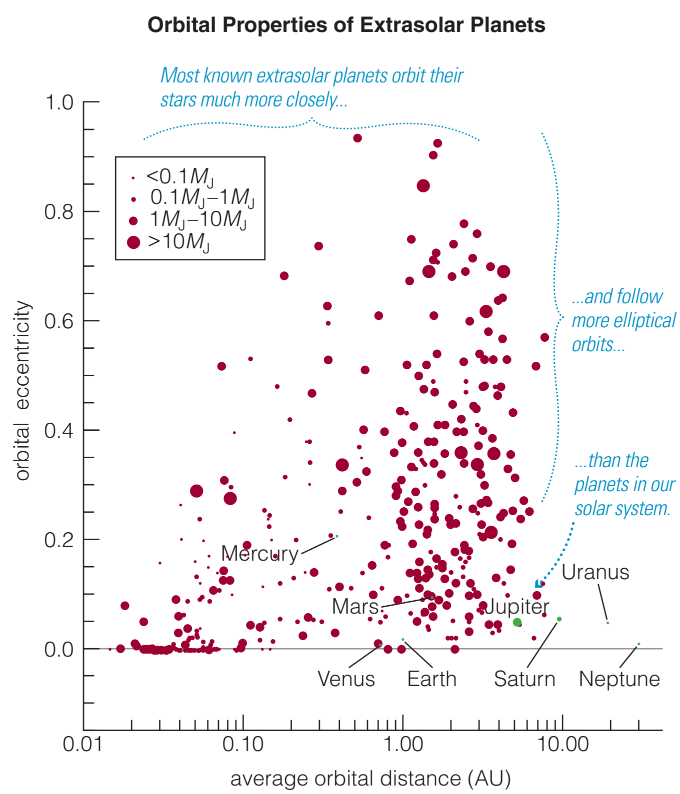


Figure 6.32

These data show orbital characteristics for all extrasolar planets with well-known properties as of 2010. Each dot represents a planet. The farther left a dot is, the closer the planet is to its star; the lower down, the more circular its orbit. Green dots are planets in our solar system.

planets that orbit relatively close to their star. Lower-mass planets are much more difficult to detect with this technique because of their weaker gravitational effects. Massive planets in more distant orbits are also difficult to detect, both because greater orbital distance means a weaker gravitational effect on the star and because long orbital periods can be identified only after many years of observation. We therefore say that the Doppler technique would tend to find, or *select*, massive planets orbiting close to their star, even if such planets are comparatively rare. Until we have more data from other detection techniques, we will not be sure whether orbits like those in our solar system are common or rare.

Another important discovery has come from systems in which we have identified more than one planet. In many of these systems, the planets seem to have orbital resonances with each other **[Section 8.2]**; for example, one planet may have an orbital period that is exactly twice as long as that of another planet. The data suggest that these orbital resonances help shape the overall layout of other planetary systems.

Masses Look again at Figure 6.32. The sizes of the dots indicate the approximate masses of these planets. Masses are even easier to see with a bar chart (Figure 6.33). Notice that most of the known extrasolar planets are more massive than Jupiter, and only a few are less massive than Uranus and Neptune. The smallest detected as of late 2010 is twice as massive as Earth (which has a mass of about 0.003 Jupiter mass). If we go by mass alone, it seems likely that most of the known extrasolar planets are jovian rather than terrestrial in nature. However, this may also be a selection effect that occurs because it is much easier to detect more massive planets.

Compositions We have even less data about the composition of extrasolar planets, because we have been able to obtain crude spectra in only a handful of cases so far. In one case, the spectrum showed evidence of water and methane, consistent with the idea that the planet is a jovian planet.

Sizes and Densities The masses of most known extrasolar planets suggest they are jovian in nature, but mass alone cannot rule out the possibility of "supersize" terrestrial planets—that is, very massive planets made of metal or rock. To distinguish between these possibilities, we also need to know a planet's size, from which we can calculate its density. If the planet is jovian, we expect it to have size and density values consistent with those found for the jovian planets in our solar system.

Unfortunately, we lack size data for the majority of extrasolar planets with measured masses, because they have been detected by the Doppler technique and their orbits are not oriented to produce transits. Nevertheless, we now have dozens of planets for which we know both sizes (from transits) and masses (from the Doppler technique) that can be used to calculate density.

In most of the cases for which we now have density data, planet masses and sizes are generally consistent with what we expect for jovian planets. In some cases, the densities are surprisingly low, but this may be because many of these planets are hot Jupiters. Since they orbit quite close to their stars, their surface temperatures are very

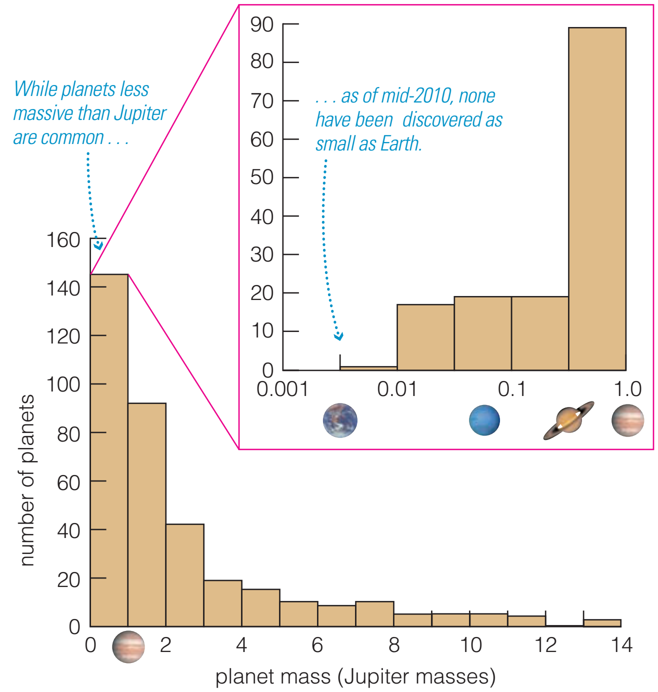
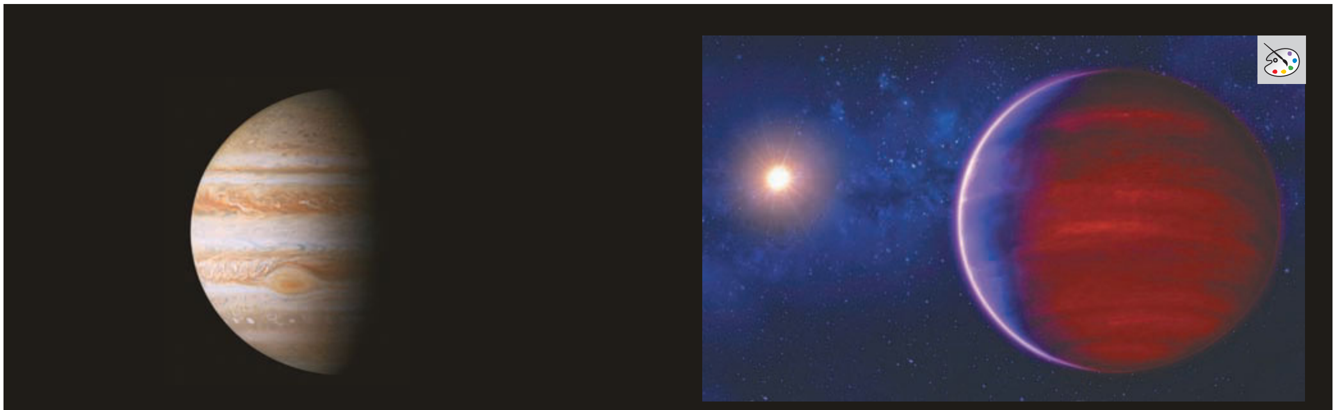


Figure 6.33

This bar chart shows the number of planets in different mass categories for all extrasolar planets with well-known masses as of 2010. Notice that the inset mass axis uses an exponential scale so that the wide range of masses can all fit on the graph.



Jupiter	Hot Jupiters orbiting other stars
Composed primarily of hydrogen and helium	Composed primarily of hydrogen and helium
5 AU from the Sun	As close as 0.03 AU to their stars
Orbit takes 12 Earth years	Orbit as short as 1.2 Earth days
Cloud top temperatures ≈ 130 K	Cloud top temperatures up to 1300 K
Clouds of various hydrogen compounds	Clouds of "rock dust"
Radius = 1 Jupiter radius	Radius up to 1.3 Jupiter radii
Mass = 1 Jupiter mass	Mass from 0.2 to 2 Jupiter masses
Average density = 1.33 g/cm^3	Average density as low as 0.2 g/cm^3
Moons, rings, magnetosphere	Moons, rings, magnetospheres: unknown

Figure 6.34

A summary of the expected similarities and differences between our solar system's Jupiter and extrasolar hot Jupiters orbiting Sun-like stars.

high, which may puff up their atmospheres and explain their low densities. Models have been used to predict several other interesting features of hot Jupiters, which are contrasted with features of our Jupiter in Figure 6.34.

Most known extrasolar planets are probably jovian, but we've also found "super Earths" likely made of metal and rock.

While most known extrasolar planets appear to be jovian, we have detected at least some "super Earths"—planets with Earth-like densities that are more massive than Earth. The first such discovery came in 2009, when the transiting planet COROT-7b was found to have a density of about 5 g/cm^3, comparable to Earth's. This planet's mass is about 5 Earth masses and its composition must be primarily rock and metal. Because this planet orbits very close to its star, its surface is probably molten. Even more intriguing is the planet GJ 1214b, which is 6.6 times Earth's mass and has a density of less than 2 g/cm^3. Such a low-mass planet cannot be jovian, so its low density must come from a mix of rock and water. It orbits very close to its star, so perhaps this planet is a "steam world," too hot to be habitable.

The Abundance of Planetary Systems Can we yet say anything about how common planetary systems are overall? Among the thousands of Sun-like stars that astronomers have so far examined in search of extrasolar planets, more than 1 in 10 show evidence of planets around them. While this could imply that planetary systems are relatively rare, a more likely hypothesis is that planets are present but more difficult to detect in the other 9 in 10 systems. In essence, we have been hunting for planets with "elephant traps"—and we have been catching elephants. The more common systems with smaller planets may simply be beyond the grasp of our current traps. By some estimates, as many as half of nearby stars possess a Neptune-sized or smaller planet not yet detected. In that case, hot Jupiters might actually be relatively rare, and known in large numbers only because they are easier to detect. Indeed, as technology has improved, we have begun to find systems that more closely resemble our own. The idea that terrestrial planets are common is supported by observations that reveal a correlation between the fraction of elements heavier than helium in a star and the chance that it has planets orbiting it. The more rocks, metals, and hydrogen compounds present in a solar nebula, the more likely the star is to have planets—just as we'd expect from the nebular theory.

see it for yourself It's impossible to see planets orbiting other stars with your naked eye, but you can see some of the stars known to have planets. As of 2010, the brightest star known to have a planet was Pollux, located in the constellation Gemini. Its planet has a mass three times that of Jupiter and orbits Pollux every $1\frac{1}{2}$ years. Use the star charts in Appendix I to find out if, when, and where you can observe Pollux tonight, and look for it if you can. Does knowing that Pollux has its own planetary system alter your perspective when you look at the night sky? Why or why not?

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

The discovery of extrasolar planets presents us with an opportunity to test our theory of solar system formation, and it has already presented challenges. For example, the nebular theory clearly predicts that jovian planets should form only in the cold outer regions of star systems and should have nearly circular orbits, so how can our theory account for hot Jupiters or planets with highly elliptical orbits?

One possibility that scientists must always consider is that something is fundamentally wrong with our model of solar system formation, and scientists have considered this possibility. However, more than a decade of re-examination has not turned up any obvious flaws in the basic theory. As a result, scientists now suspect that the hot Jupiters were indeed born with circular orbits far from their stars and that those that now have close-in or highly elliptical orbits underwent some sort of "planetary migration."

Hot Jupiters probably were born in their outer solar systems as the nebular theory predicts, but later migrated inward.

How might planetary migration occur? Our best guess is that it can be caused by waves passing through a gaseous disk (Figure 6.35). A planet's gravity and motion tend to disturb the otherwise evenly distributed disk material, generating waves that travel through the disk. The waves cause material to bunch up as they pass by, and these clumps exert their own gravitational pull on the planet, robbing it of energy and causing it to move inward.

Computer models confirm that waves in the nebula can cause young planets to spiral slowly toward their star. In our own solar system, this migration did not play a major role because the solar wind probably cleared out the gas before it could have much effect. But planets may form earlier in other solar systems, allowing time for jovian planets to migrate substantially inward. In some cases, the planets may form so early that they end up spiraling into their stars.

Another way to account for some of the observed extrasolar planet orbits invokes close encounters between young jovian planets. Such an

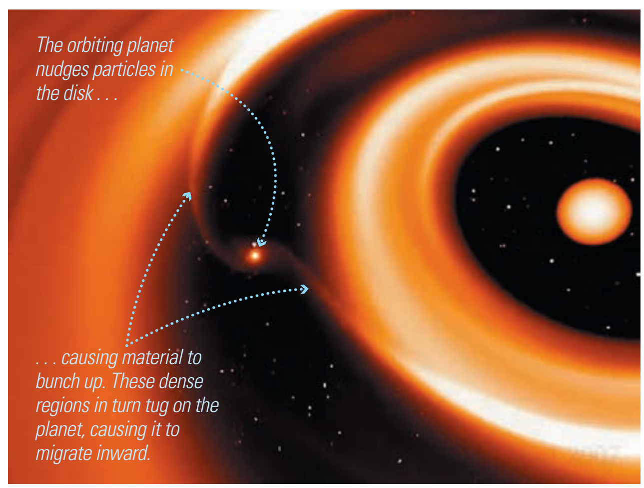


Figure 6.35

This figure shows a simulation of waves created by a planet embedded in a dusty disk of material surrounding its star; these waves may cause the planet to migrate inward.

encounter might send one planet out of the star system entirely while the other is flung inward into a highly elliptical orbit. Alternatively, a jovian planet could migrate inward as a result of multiple close encounters with much smaller planetesimals (as may have happened in our solar system) or jovian planets might periodically line up with one another in a way that would cause their orbits to become more elliptical. Models show that some of these interactions can tilt a planet's orbit sideways or even backwards, and observations have begun to show a few of these unusual planets.

The bottom line is that discoveries of extrasolar planets have shown us that the nebular theory is incomplete. It explains the formation of planets and the simple layout of a solar system such as ours, but it needs new features—such as planetary migration and gravitational encounters—to explain the differing layouts of other solar systems. A much wider range of solar system arrangements now seems possible than we had guessed before the discovery of extrasolar planets.

Planetary scientists are anxious to learn more, and over the past few years NASA and the European Space Agency have developed a series of plans for ambitious missions to try to find many more planets—including Earth-like planets, if they exist—and to study those planets through imaging and spectroscopy. However, budgetary pressures have placed all of those plans on hold for now.

think about it Look back at the discussion of the nature of science in Chapter 3, especially the definition of a scientific theory. Should the nebular theory qualify as a scientific theory even though we know that it needs modification to account for the orbits of planets in other solar systems? Does this mean that the theory was "wrong" as we understood it before? Explain.

the big picture

Putting Chapter 6 into Perspective

In this chapter, we've introduced the major features of our solar system and described the current scientific theory of its formation. We've seen how this theory explains the major features we observe and how it can be extended to other planetary systems. As you continue your study of the solar system, keep in mind the following "big picture" ideas:

- Our solar system is not a random collection of objects moving in random directions. Rather, it is highly organized, with clear patterns of motion and common traits among families of objects.
- We can explain the major features of our solar system with a theory that holds that the solar system formed from the gravitational collapse of an interstellar gas cloud.
- Most of the general features of the solar system were determined by processes that occurred very early in the solar system's history, which began some $4\frac{1}{2}$ billion years ago.
- Planet-forming processes are universal. Discoveries of planets around other stars have begun an exciting new era in planetary science.

summary of key concepts

6.1 A Brief Tour of the Solar System

• What does the solar system look like?

The planets are tiny compared to the distances between them. Our solar system consists of the Sun, the planets and their moons, and vast numbers of asteroids and comets. Each world has its own unique character, but there are many clear patterns among the worlds.

6.2 Clues to the Formation of Our Solar System

• What features of our solar system provide clues to how it formed?

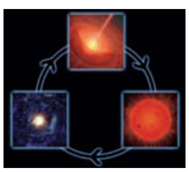
Four major features provide clues: (1) The Sun, planets, and large moons generally rotate and orbit in a very organized way. (2) The planets divide clearly into two groups: **terrestrial** and **jovian**. (3) The solar system contains vast numbers of asteroids and comets, some large enough to qualify as dwarf planets. (4) There are some notable exceptions to these general patterns.

• What theory best explains the features of our solar system?

The **nebular theory**, which holds that the solar system formed from the gravitational collapse of a great cloud of gas and dust, successfully explains all the major features of our solar system.

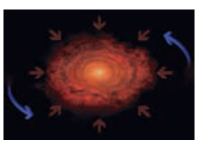
6.3 The Birth of the Solar System

• Where did the solar system come from?



The cloud of gas that gave birth to our solar system was the product of recycling of gas through many generations of stars within our galaxy. This gas consisted of 98% hydrogen and helium and 2% all other elements.

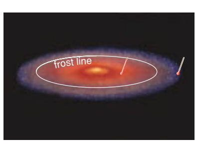
• What caused the orderly patterns of motion in our solar system?



A collapsing gas cloud tends to heat up, spin faster, and flatten out as it shrinks in size. Our solar system began as a spinning disk of gas and dust, so the orderly motions we observe today came from the orderly motion of this spinning disk.

6.4 The Formation of Planets

• Why are there two major types of planets?

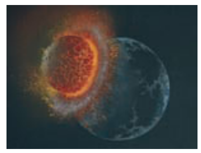


Planets formed around solid "seeds" that condensed from gas and then grew through accretion. In the inner solar system, temperatures were so high that only metal and rock could condense, which explains why terrestrial worlds are made of metal and rock. In the outer solar system, cold temperatures allowed more abundant ices to condense along with metal and rock. Icy planetesimals grew large enough for their gravity to draw in hydrogen and helium gas, forming the massive jovian planets.

• Where did asteroids and comets come from?

Asteroids are the rocky leftover planetesimals of the inner solar system, and comets are the icy leftover planetesimals of the outer solar system.

• How do we explain the existence of our Moon and other exceptions to the rules?



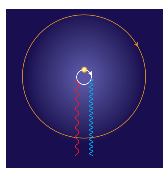
Most of the exceptions probably arose from collisions or close encounters with leftover planetesimals. Our Moon is most likely the result of a **giant impact** between a Mars-size planetesimal and the young Earth.

• When did the planets form?

The planets began to accrete in the solar nebula about 4.55 billion years ago, a fact we determine from radiometric dating of the oldest meteorites.

6.5 Other Planetary Systems

• How do we detect planets around other stars?



So far, we are best able to detect extrasolar planets indirectly by observing the planet's effects on the star it orbits. Most discoveries to date have been made with the **Doppler technique**, in which Doppler shifts reveal the gravitational tug of a planet (or planets) on a star. We can also search for **transits** and **eclipses** in which a system becomes slightly dimmer as a planet passes in front of or behind its star.

• How do extrasolar planets compare with planets in our solar system?

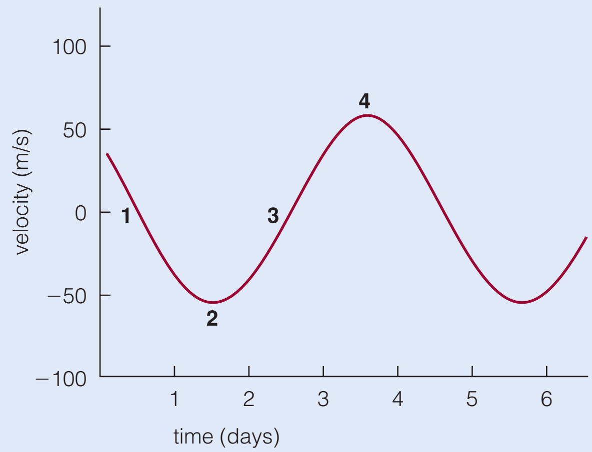
Most known extrasolar planets have masses that suggest they are jovian; limited density and composition data support this idea. Many orbit surprisingly close to their stars, making them **hot Jupiters**, and many have highly elliptical orbits. A few "super Earths"—planets larger than Earth but likely made of metal and rock—have also been discovered.

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

Our basic theory of solar system formation seems to be sound, but we have had to modify it to allow for planetary migration and gravitational encounters.

visual skills check

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. Answers are provided in Appendix J. For additional practice, try the Chapter 6 Visual Quiz at www.masteringastronomy.com.



This plot, based on Figure 6.28b, shows the periodic variations in the Doppler shift of a star caused by a planet orbiting around it. Positive velocities mean the star is moving away from Earth, and negative velocities mean the star is moving toward Earth. (You can assume that the orbit appears edge-on from Earth.) Answer the following questions based on the information in the graph.

1. How long does it take the star and planet to complete one orbit around their center of mass?
2. What maximum velocity does the star attain?
3. Match the *star's* position at points 1, 2, 3, and 4 in the plot with the descriptions below.
   a. headed straight toward Earth
   b. headed straight away from Earth
   c. closest to Earth
   d. farthest from Earth
4. Match the *planet's* position at points 1, 2, 3, and 4 in the plot with the descriptions in question 3.
5. How would the plot change if the planet were more massive?
   a. It would not change, because it describes the motion of the star, not the planet.
   b. The peaks and valleys would get larger (greater positive and negative velocities) because of larger gravitational tugs.
   c. The peaks and valleys would get closer together (shorter period) because of larger gravitational tugs.

exercises and problems

Mastering ASTRONOMY

For instructor-assigned homework go to www.masteringastronomy.com.

Review Questions

1. Briefly describe the layout of the solar system as it would appear from beyond the orbit of Neptune.
2. For the Sun and each of the planets in our solar system, describe at least two features that you find interesting.
3. What are the four major features of our solar system that provide clues to how it formed? Describe each one briefly.
4. What are the basic differences between *terrestrial* and *jovian* planets? Which planets in our solar system fall into each group?
5. What is the *nebular theory,* and why is it widely accepted by scientists today?
6. What do we mean by the *solar nebula?* What was it made of, and where did it come from?
7. Describe each of the three key processes that led the solar nebula to take the form of a spinning disk. What observational evidence supports this scenario?
8. List the four categories of materials in the solar nebula by their condensation properties and abundance. Which ingredients are present in terrestrial planets? In jovian planets? Explain why.
9. What was the *frost line* in the solar nebula? Explain how temperature differences led to the formation of two distinct types of planets.
10. Briefly describe the process by which terrestrial planets are thought to have formed. How was the formation of jovian planets similar?