GLOBAL EDITION

Astronomy Today

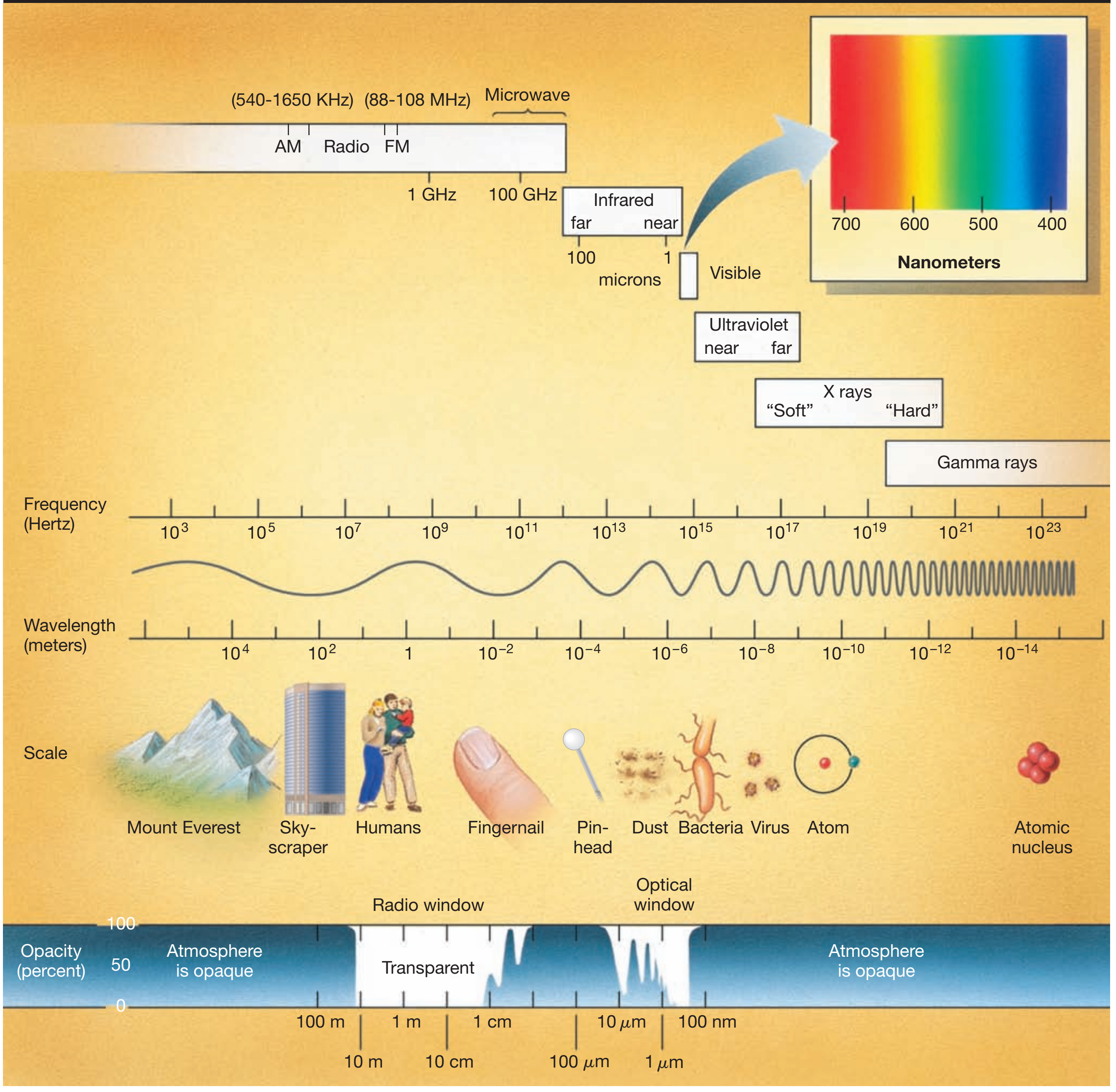
EIGHTH EDITION

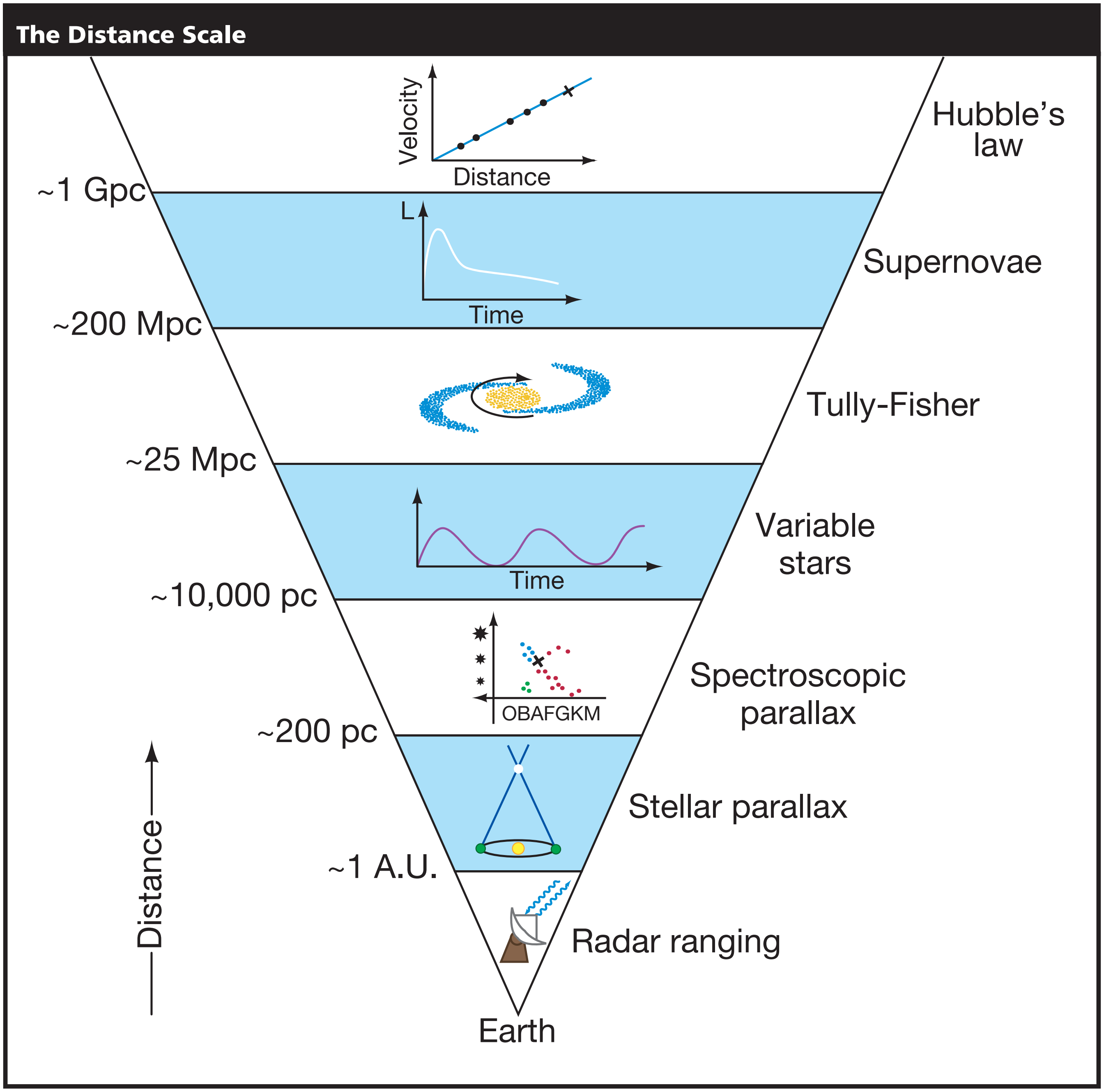
Eric Chaisson • Steve McMillan

ALWAYS LEARNING

PEARSON

The Entire Electromagnetic Spectrum




The Distance Scale
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Distance
Hubble's law
~1 Gpc
L
Time
Supernovae
~200 Mpc
Tully-Fisher
~25 Mpc
Time
Variable stars
~10,000 pc
OBAFGKM
Spectroscopic parallax
~200 pc
Stellar parallax
~1 A.U.
Radar ranging
Earth
Distance

Astronomy Today 8e
Global Edition

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Harvard University

Steve McMillan
Drexel University

PEARSON

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Brief Contents

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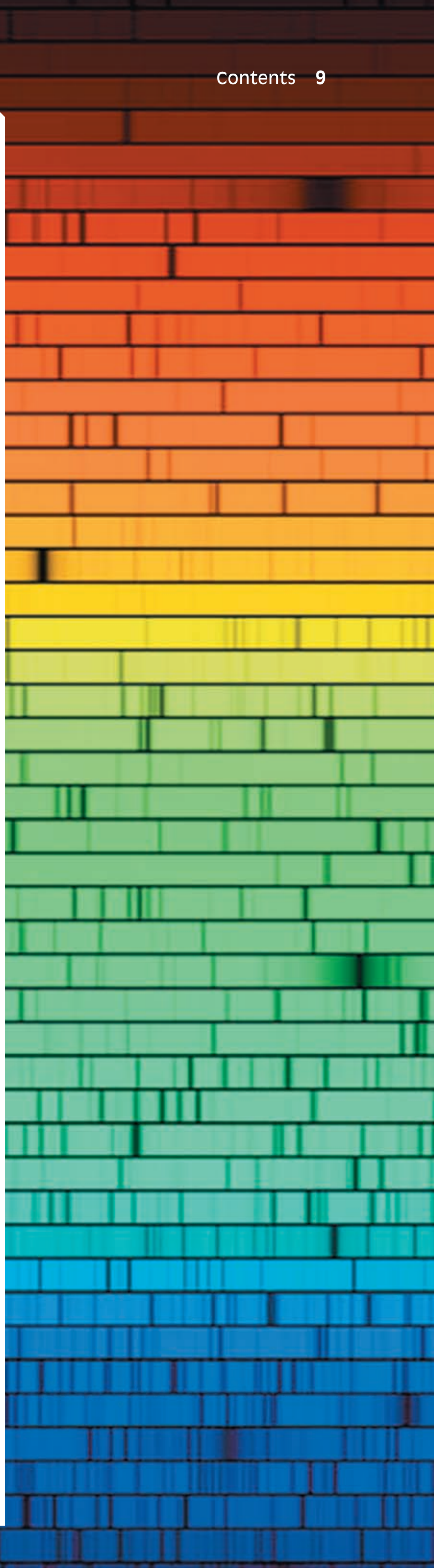
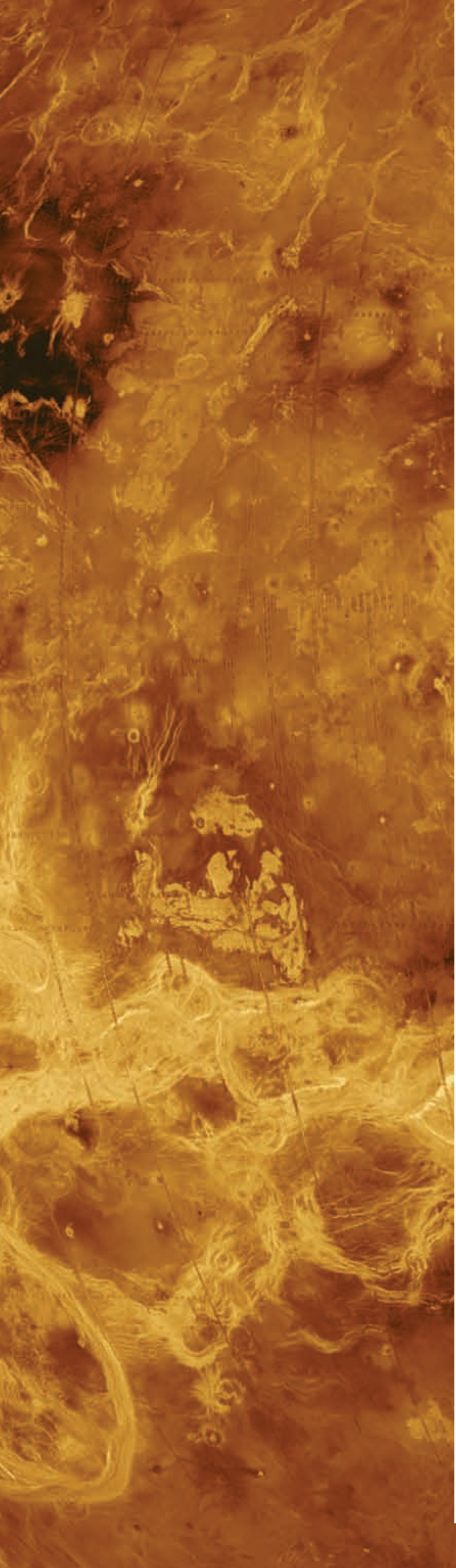




About the Authors

Eric Chaisson

Eric holds a doctorate in astrophysics from Harvard University, where he spent 10 years on the faculty of Arts and Sciences. For more than two decades thereafter, he served on the senior science staff at the Space Telescope Science Institute and held various professorships at Johns Hopkins and Tufts universities. He is now back at Harvard, where he teaches and conducts research at the Harvard-Smithsonian Center for Astrophysics. Eric has written 12 books on astronomy and has published nearly 200 scientific papers in professional journals.

Steve McMillan

Steve holds a bachelor's and master's degree in mathematics from Cambridge University and a doctorate in astronomy from Harvard University. He held postdoctoral positions at the University of Illinois and Northwestern University, where he continued his research in theoretical astrophysics, star clusters, and high-performance computing. Steve is currently Distinguished Professor of Physics at Drexel University and a frequent visiting researcher at Princeton's Institute for Advanced Study and Leiden University. He has published more than 100 articles and scientific papers in professional journals.

Preface

Astronomy is a science that thrives on new discoveries. Fueled by new technologies and novel theoretical insights, the study of the cosmos continues to change our understanding of the universe. We are pleased to have the opportunity to present in this book a representative sample of the known facts, evolving ideas, and frontier discoveries in astronomy today.

Astronomy Today has been written for students who have taken no previous college science courses and who will likely not major in physics or astronomy. It is intended for use in a one- or two-semester, nontechnical astronomy course. We present a broad view of astronomy, straightforwardly descriptive and without complex mathematics. The absence of sophisticated mathematics, however, in no way prevents discussion of important concepts. Rather, we rely on qualitative reasoning as well as analogies with objects and phenomena familiar to the student to explain the complexities of the subject without oversimplification. We have tried to communicate the excitement we feel about astronomy and to awaken students to the marvelous universe around us.

We are very gratified that the first seven editions of this text have been so well received by many in the astronomy education community. In using those earlier texts, many teachers and students have given us helpful feedback and constructive criticisms. From these, we have learned to communicate better both the fundamentals and the excitement of astronomy. Many improvements inspired by these comments have been incorporated into this new edition.

Focus of the Eighth Edition

From the first edition, we have tried to meet the challenge of writing a book that is both accurate and approachable. To the student, astronomy sometimes seems like a long list of unfamiliar terms to be memorized and repeated. Many new terms and concepts will be introduced in this course, but we hope students will also learn and remember how science is done, how the universe works, and how things are connected. In the eighth edition, we have taken particular care to show how astronomers know what they know, and to highlight both the scientific principles underlying their work and the process used in discovery.

New and Revised Material

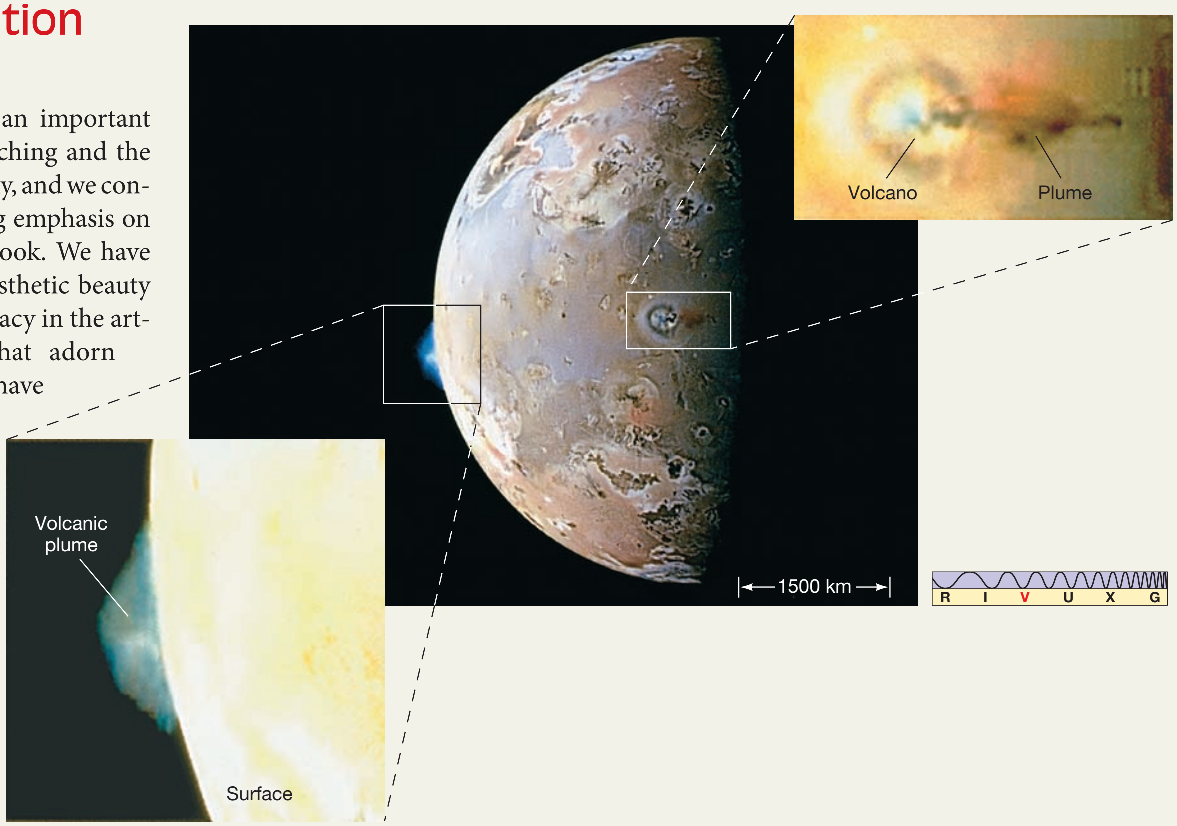
Astronomy is a rapidly evolving field and, in the three years since the publication of the seventh edition of *Astronomy Today,* has seen many new discoveries covering the entire spectrum of astronomical research. Almost every chapter in the eighth edition has been substantially updated with new information. Several chapters have also seen significant reorganization in order to streamline the overall presentation, strengthen our focus on the process of science, and reflect new understanding and emphases in contemporary astronomy.

In addition to updates throughout the text on the numbers and properties of the many astronomical objects, the many substantive changes include the following:

- A new *Discovery* box in Chapter 5 on the *ALMA* interferometric array.
- Significant revision in Chapter 5 of the discussion of infrared telescopes, including new coverage of *Herschel* and introduction of the *James Webb Space Telescope*.
- A new two-page box in Chapter 6 on planetary exploration.
- Incorporation and reorganization of the entire "standard" theory of solar system formation into Chapter 6, laying the groundwork for interpreting the planetary data presented in Part 2 and allowing Chapter 15 to focus on solar system details, irregularities, and exoplanets.
- Updated discussion in *Discovery 8-1* of *Chang'e*, *GRAIL*, and other recent lunar missions; new discussion of the *Prospector*, *LRO*, *and LCROSS* missions, with updated coverage of the search for lunar ice.
- Updated coverage in Chapter 8 of the lunar core and interior based on the latest *GRAIL* results.
- Updated discussion in Chapter 8 of surface features on Mercury, following the *Messenger* mission.
- Updated discussion in Chapter 8 of Mercury's inner and outer core and magnetic field and formation, in light of new *Messenger* data.
- Updated discussion in Chapter 9 of *Venus Express* findings and status.
- Updated discussion in Chapter 10 of the collision hypothesis as the origin of the northern Martian lowlands.
- Reorganized and updated discussion in Chapter 10 of liquid water on the Martian surface.
- Updated discussion in Chapter 10 on the *Spirit, Opportunity*, and *Phoenix* landers; new material on the *Curiosity* lander and its findings.
- Revised discussion in Chapter 10 of the origin of the Martian moons.
- Updated coverage of cometary impacts in *Discovery 11-1*, indicating that such impacts are commonplace in the solar system.

The Illustration Program

Visualization plays an important role in both the teaching and the practice of astronomy, and we continue to place strong emphasis on this aspect of our book. We have tried to combine aesthetic beauty with scientific accuracy in the artist's conceptions that adorn the text, and we have sought to present the best and latest imagery of a wide range of cosmic objects. Each illustration has been carefully crafted to enhance student learning; each is pedagogically sound and tied tightly to the nearby discussion of important scientific facts and ideas. This edition contains more than 100 revised figures that show the latest imagery and the results learned from them.



Compound Art It is rare that a single image, be it a photograph or an artist's conception, can capture all aspects of a complex subject. Wherever possible, multiple-part figures are used in an attempt to convey the greatest amount of information in the most vivid way:

- Visible images are often presented along with their counterparts captured at other wavelengths.
- Interpretive line drawings are often superimposed on or juxtaposed with real astronomical photographs, helping students to really "see" what the photographs reveal.
- Breakouts—often multiple ones—are used to zoom in from wide-field shots to close-ups so that detailed images can be understood in their larger context.

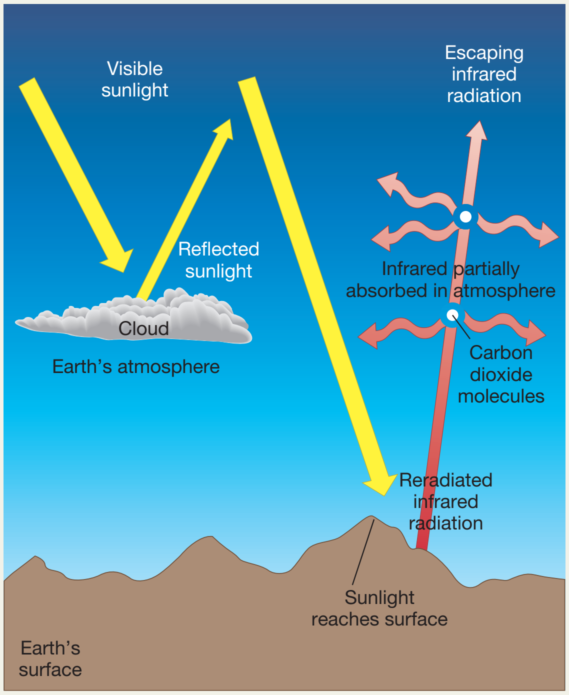
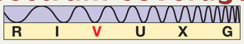
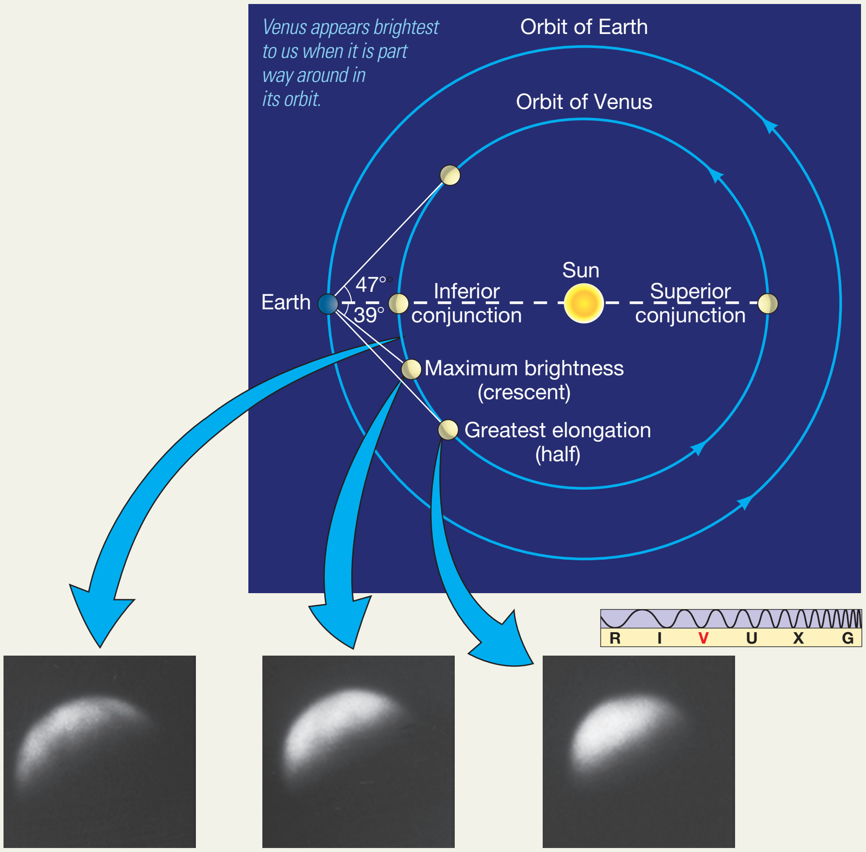


Figure Annotations (REVISED) The eighth edition incorporates the research-proven technique of strategically placing annotations (which always appear in blue type) within key pieces of art, fostering students' ability to read and interpret complex figures, focus on the most relevant information, and integrate written and visual knowledge.

Full Spectrum Coverage and Spectrum Icons 

Astronomers exploit the full range of the electromagnetic spectrum to gather information about the cosmos. Throughout this book, images taken at radio, infrared, ultraviolet, X-ray, or gamma-ray wavelengths are used to supplement visible-light images. As it is sometimes difficult (even for a professional) to tell at a glance which images are visible-light photographs and which are false-color images created with other wavelengths, each photo in the text is accompanied by an icon that identifies the wavelength of electromagnetic radiation used to capture the image.



- Revised discussion in Chapter 12 of storms on Saturn and new moons and features in Saturn's rings.
- Expanded coverage in Chapter 12 of *Cassini Solstice* observations of Titan and Enceladus.
- Updated discussion in Chapter 13 of Uranus's tilted spin axis and new imagery of weather patterns on Uranus and Neptune.
- New coverage in Chapter 14 of the *Dawn* mission to Vesta and Ceres.
- Updated coverage in Chapter 14 of Earth-crossing asteroids and asteroid near misses.
- Updated coverage in Chapter 14 of Pluto's moons and trans-Neptunian objects
- New *Discovery* box in Chapter 15 on the Alpha Centauri planetary system.
- Expanded coverage in Chapter 15 of exoplanet discoveries and properties and the *Kepler* candidates list.
- New discussion in Chapter 15 of Earths and super-Earths in the habitable zones of their parent stars.

- New coverage in Chapter 16 of the *Solar Dynamics Observatory* and its findings.
- Updated discussion in Chapter 19 of star cluster observations and formation.
- Revised discussion in Chapter 22 of gamma-ray bursts and hypernovae.
- Updated coverage in Chapter 23 of activity near the center of the Milky Way Galaxy.
- Significantly updated coverage in Chapter 25 of galaxies, including new discussion of inflow of gas from intergalactic space.
- Expanded discussion of tidal streams in the Milky Way halo.
- Significantly expanded coverage in Chapter 27 of baryon acoustic oscillations in the early universe and their connection to fluctuations in the microwave background.
- Updated discussion in Chapter 28 of the frequency of planetary systems and the numbers of habitable planets per system.
- Added 18 new Narrated Figure notations.
- Added helpful annotations so that now about half of the figures in the text employ this pedagogically useful tool.
- Added distance scales to many figures, helping students gain an understanding of the vastness of the universe.
- Replaced a number of older images for currency and clarity.
- Updated the art throughout the text.
- Added new table of contents for online material (Online Contents), which lists by chapter all the online assets the book delivers: Narrated Figures, Interactive Figures, Animation/Videos, and Self-Guided Tutorials.

Other Pedagogical Features

As with many other parts of our text, instructors have helped guide us toward what is most helpful for effective student learning. With their assistance, we have revised both our in-chapter and end-of-chapter pedagogical apparatus to increase its utility to students.

Learning Outcomes (NEW) Studies indicate that beginning students have trouble prioritizing textual material. For this reason, a few (typically five or six) well-defined Learning Outcomes are provided at the start of each chapter. These help students structure their reading of the chapter and then test their mastery of key concepts. The Learning Outcomes are numbered and keyed to the items in the Chapter Summary, which in turn refer back to passages in the text. This highlighting of the most important aspects of the chapter helps students prioritize information and also aids in their review. The Learning Outcomes are organized and phrased in such a way as to make them objectively testable, affording students a means of gauging their own progress.

Learning Outcomes

Studying this chapter will enable you to

1. Summarize the composition and physical properties of the interstellar medium.
2. Describe the characteristics of emission nebulae, and explain their significance in the life cycle of stars.
3. List the basic properties of dark interstellar clouds.
4. Specify the radio techniques used to probe the nature of interstellar matter.
5. Explain the nature and significance of interstellar molecules.

The Big Picture (REVISED) The Big Picture feature on every chapter opening spread encapsulates the overarching message that each chapter imparts, helping students see how chapter content is connected to a broad understanding of the universe.

The Big Picture Stars are everywhere in the nighttime sky. The naked eye can spot about 6000 of them, spread across 88 constellations. Millions more are visible even with binoculars or a small telescope. The total number of stars is impossible to count, and relatively few have been studied in detail. Yet, it is stars that tell us more about the fundamentals of astronomy than any other objects in the universe.

The Big Question (NEW) Each chapter now ends with a broad, open-ended query that is intended to ignite students' curiosity about the still-unanswered questions at the forefront of astronomical research. The Big Question builds on the material presented in the chapter and invites students to speculate on the larger scope of what they have just learned.

The Big Question Our Sun will expand as it ages, and it is destined to balloon rapidly into a red giant as it begins running out of fuel in about 5 billion years. A burning question, often asked and then quickly dismissed as being too remote in time is, will the red-giant Sun expand enough to engulf Earth? No one is certain. We do know that the Sun is losing lots of matter, thereby lessening its gravitational pull. Perhaps that will allow Earth to recede eventually to a relatively safe orbit.

Concept Checks We incorporate into each chapter a number of "Concept Checks"—key questions that require the reader to reconsider some of the material just presented or attempt to place it into a broader context. Answers to these in-chapter questions are provided at the back of the book.

CONCEPT Check

✔ Why do astronomers draw such a clear distinction between the inner and the outer planets?

Process of Science Checks Each chapter now also includes one or two "Process of Science Checks," similar to the Concept Checks but aimed specifically at clarifying the questions of how science is done and how scientists reach the conclusions they do. Answers to these in-chapter questions are also provided at the back of the book.

PROCESS OF SCIENCE Check

✔ In what sense are the comets we see *un*representative of comets in general?

Concept Links In astronomy, as in many scientific disciplines, almost every topic seems to have some bearing on almost every other. In particular, the connection between the astronomical material and the physical principles set forth early in the text is crucial. Practically everything in Chapters 6–28 of this text rests on the foundation laid in the first five chapters. For example, it is important that students, when they encounter the discussion of high-redshift objects in Chapter 25, recall not only what they just learned about Hubble's law in Chapter 24 but also refresh their memories, if necessary, about the inverse-square law (Chapter 17), stellar spectra (Chapter 4), and the Doppler shift (Chapter 3). Similarly, the discussions of the mass of binary-star components (Chapter 17) and of galactic rotation (Chapter 23) both depend on the discussion of Kepler's and Newton's laws in Chapter 2. Throughout, discussions of new astronomical objects and concepts rely heavily on comparison with topics introduced earlier in the text.

It is important to remind students of these links so that they recall the principles on which later discussions rest and, if necessary, review them. To this end, we have inserted "concept links" throughout the text—symbols that mark key intellectual bridges between material in different chapters. The links, denoted by the symbol ∞ together with a section reference, signal that the topic under discussion is related in some significant way to ideas developed earlier and provide direction to material to review before proceeding.

Key Terms Like all subjects, astronomy has its own specialized vocabulary. To aid student learning, the most important astronomical terms are boldfaced at their first appearance in the text. Boldfaced Key Terms in the Chapter Summary are linked with the page number where the term was defined. In addition, an expanded alphabetical glossary, defining each Key Term and locating its first use in the text, appears at the end of the book.

H–R Diagrams All of the book's H–R diagrams are drawn in a uniform format, using real data.

More Precisely Boxes These boxes provide more quantitative treatments of subjects discussed qualitatively in the text. Removing these more challenging topics from the main flow of the narrative and placing them within a separate modular element of the chapter design (so that they can be covered in class, assigned as supplementary material, or simply left as optional reading for those students who find them of interest) will allow instructors greater flexibility in setting the level of their coverage.

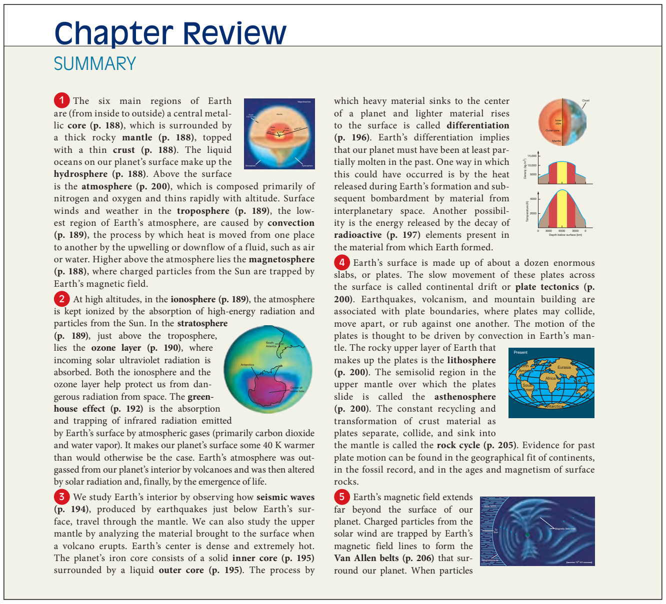
Discovery Boxes Exploring a wide variety of interesting supplementary topics, Discovery boxes provide the reader with insight into how scientific knowledge evolves and emphasizes the process of science.

End-of-Chapter Questions, Problems, and Activities (NEW) Many elements of the end-of-chapter material have seen substantial reorganization:

- Each chapter incorporates **Review and Discussion Questions,** which may be used for in-class review or for assignment. As with the Self-Test Questions, the material needed to answer Review Questions may be found within the chapter. The Discussion Questions explore particular topics more deeply, often asking for opinions, not just facts. As with all discussions, these questions usually have no single "correct" answer. Questions identified with a POS icon encourage students to explore the Process of Science, and each Learning Outcome is reflected in one of the Review and Discussion questions, marked by LO.
- Each chapter also contains **Conceptual Self-Test Questions** in a multiple-choice format, including select questions that are tied directly to a specific figure or diagram in the text, allowing students to assess their understanding of the chapter material. These questions are identified with a VIS icon. Answers to all these questions appear at the end of the book.
- The end-of-chapter material includes **Problems,** based on the chapter contents and requiring some numerical calculation. In many cases the problems are tied directly to quantitative statements made (but not worked out in detail) in the text. The solutions to the problems are not contained verbatim within the chapter, but the information necessary to solve them has been presented in the text. Answers to odd-numbered Problems appear at the end of the book.

- Also new to this edition, the end-of-chapter material now ends with collaborative and individual **Activities** relevant to the material presented in the text. These range from basic naked-eye and telescopic observing projects to opinion polls, surveys, group discussions, and astronomical research on the Web.

Chapter Review Summaries The Chapter Review Summaries, a primary review tool, are linked to the Learning Outcomes at the beginning of each chapter. Key Terms introduced in each chapter are listed again, in context and in boldface, along with key figures and page references to the text discussion.



Chapter Review

SUMMARY

1 The six main regions of Earth are (from inside to outside) a central metallic **core (p. 188)**, which is surrounded by a thick rocky **mantle (p. 188)**, topped with a thin **crust (p. 188)**. The liquid oceans on our planet's surface make up the **hydrosphere (p. 188)**. Above the surface is the **atmosphere (p. 200)**, which is composed primarily of nitrogen and oxygen and thins rapidly with altitude. Surface winds and weather in the **troposphere (p. 189)**, the lowest region of Earth's atmosphere, are caused by **convection (p. 189)**, the process by which heat is moved from one place to another by the upwelling or downflow of a fluid, such as air or water. Higher above the atmosphere lies the **magnetosphere (p. 188)**, where charged particles from the Sun are trapped by Earth's magnetic field.

2 At high altitudes, in the **ionosphere (p. 189)**, the atmosphere is kept ionized by the absorption of high-energy radiation and particles from the Sun. In the **stratosphere (p. 189)**, just above the troposphere, lies the **ozone layer (p. 190)**, where incoming solar ultraviolet radiation is absorbed. Both the ionosphere and the ozone layer help protect us from dangerous radiation from space. The **greenhouse effect (p. 192)** is the absorption and trapping of infrared radiation emitted by Earth's surface by atmospheric gases (primarily carbon dioxide and water vapor). It makes our planet's surface some 40 K warmer than would otherwise be the case. Earth's atmosphere was outgassed from our planet's interior by volcanoes and was then altered by solar radiation and, finally, by the emergence of life.

3 We study Earth's interior by observing how **seismic waves (p. 194)**, produced by earthquakes just below Earth's surface, travel through the mantle. We can also study the upper mantle by analyzing the material brought to the surface when a volcano erupts. Earth's center is dense and extremely hot. The planet's iron core consists of a solid **inner core (p. 195)** surrounded by a liquid **outer core (p. 195)**. The process by which heavy material sinks to the center of a planet and lighter material rises to the surface is called **differentiation (p. 196)**. Earth's differentiation implies that our planet must have been at least partially molten in the past. One way in which this could have occurred is by the heat released during Earth's formation and subsequent bombardment by material from interplanetary space. Another possibility is the energy released by the decay of **radioactive (p. 197)** elements present in the material from which Earth formed.

4 Earth's surface is made up of about a dozen enormous slabs, or plates. The slow movement of these plates across the surface is called continental drift or **plate tectonics (p. 200)**. Earthquakes, volcanism, and mountain building are associated with plate boundaries, where plates may collide, move apart, or rub against one another. The motion of the plates is thought to be driven by convection in Earth's mantle. The rocky upper layer of Earth that makes up the plates is the **lithosphere (p. 200)**. The semisolid region in the upper mantle over which the plates slide is called the **asthenosphere (p. 200)**. The constant recycling and transformation of crust material as plates separate, collide, and sink into the mantle is called the **rock cycle (p. 205)**. Evidence for past plate motion can be found in the geographical fit of continents, in the fossil record, and in the ages and magnetism of surface rocks.

5 Earth's magnetic field extends far beyond the surface of our planet. Charged particles from the solar wind are trapped by Earth's magnetic field lines to form the **Van Allen belts (p. 206)** that surround our planet. When particles

Instructor Resources

Instructor Guide Revised by James Heath (Austin Community College), this online guide provides: sample syllabi and course schedules; an overview of each chapter; pedagogical tips; useful analogies; suggestions for classroom demonstrations; writing questions, selected readings, and answers/solutions to the end-of-chapter Review and Discussion Questions and Problems; and additional references and resources.

Test Bank An extensive file of approximately 2800 test questions, newly compiled and revised for the eighth edition. The questions are organized and referenced by chapter section and by question type. The eighth edition Test Bank has been thoroughly revised and includes many new Multiple Choice and Essay questions for added conceptual emphasis. This Test Bank is available in both Microsoft® Word and TestGen® formats.

Instructor Resource Center The Pearson Instructor Resource Center contains the Instructor Guide and the Test Bank, which is available in both Microsoft® Word and TestGen® formats (for more details please visit www.pearsonglobaleditions.com/Chaisson).

Learner-Centered Astronomy Teaching: Strategies for ASTRO 101

Timothy F. Slater, *University of Wyoming*
Jeffrey P. Adams, *Millersville University*

Strategies for ASTRO 101 is a guide for instructors of the introductory astronomy course for nonscience majors. Written by two leaders in astronomy education research, this book details various techniques instructors can use to increase students' understanding and retention of astronomy topics, with an emphasis on making the lecture a forum for active student participation. Drawing from the large body of recent research to discover how students learn, this guide describes the application of multiple classroom-tested techniques to the task of teaching astronomy to predominantly nonscience students.
ISBN 0-13-046630-1

Peer Instruction for Astronomy

Paul J. Green, *Harvard-Smithsonian Center for Astrophysics*

Peer instruction is a simple yet effective method for teaching science. Techniques of peer instruction for introductory physics were developed primarily at Harvard and have aroused interest and excitement in the physics education community. This approach involves students in the teaching process, making science more accessible to them. This book is an important vehicle for providing a large number of thought-provoking, conceptual short-answer questions aimed at a variety of class levels. While significant numbers of such questions have been published for use in physics, *Peer Instruction for Astronomy* provides the first such compilation for astronomy.
ISBN 0-13-026310-9

Lecture-Tutorials for Introductory Astronomy, 3rd Edition

Edward E. Prather, *University of Arizona*
Timothy F. Slater, *University of Wyoming*
Jeffrey P. Adams, *Millersville University*
Gina Brissenden, *University of Arizona*

Funded by the National Science Foundation, *Lecture-Tutorials for Introductory Astronomy* is designed to help make large-lecture-format courses more interactive. The third edition features six new tutorials on the Greenhouse Effect; Dark Matter; Making Sense of the Universe and Expansion; Hubble's Law; Expansion, Lookback Times, and Distances; and The Big Bang. Each of the 44 Lecture-Tutorials is presented in a classroom-ready format that asks students to work in groups of two to three for between 10 and 15 minutes and requires no equipment. These lecture-tutorials challenge students with a series of carefully designed questions that spark classroom discussion and engage students in critical reasoning.
ISBN 0-321-82046-0

Acknowledgments

Throughout the many drafts that have led to this book, we have relied on the critical analysis of many colleagues. Their suggestions ranged from the macroscopic issue of the book's overall organization to the minutiae of the technical accuracy of each and every sentence. We have also benefited from much good advice and feedback from users of the first seven editions of the text. To these many helpful colleagues, we offer our sincerest thanks.

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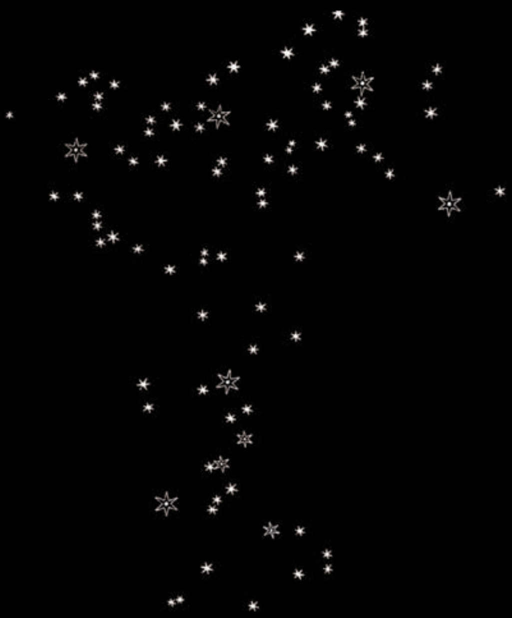
Astronomy Today 8e

Galileo's sketch of Saturn

PART ONE

Astronomy and the Universe



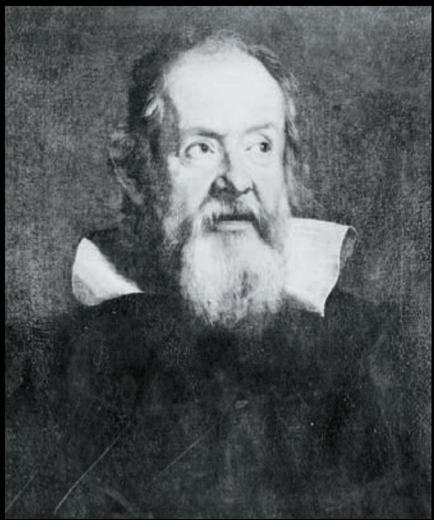
Galileo's sketch of Orion

It is often said that we live in a golden age of astronomy. Yet the dawn of the 21st century is actually the second such period of rich discovery and rapid exploration. The first era of stunning scientific growth began in the late Renaissance. Foremost among the early architects of modern astronomy was the Italian scientist Galileo Galilei (1564–1642). By turning his telescope to the heavens, he changed radically and forever our view of the universe in which we live.

Although he did not invent the telescope, in 1610 Galileo was the first to record what he saw when he aimed a small (5-cm-diameter) lens at the sky. His findings created nothing less than a revolution in astronomy. Viewing for the first time dark blemishes on the Sun, rugged mountains on the Moon, and whole new worlds orbiting Jupiter, he demolished the Aristotelian notion that the heavens were perfect and unchanging. It was with the philosophers of the day, as much as with the theologians, that Galileo had trouble. In championing the scientific method, he used a tool to test his ideas, and what he found disagreed greatly with the leading thoughts and beliefs of the time.

Galileo's advance was simple yet profound: He used a telescope to focus, magnify, and study radiation reaching Earth from the heavens—in particular, light from the Sun, the Moon, and the planets. Light is the most familiar kind of radiation to humans on Earth, since it enables us to get around on the surface of our planet. But light also enables telescopes to see objects deep in space, allowing us to probe farther than the eye can alone. With his simple optical telescope, Galileo changed completely the way that the oldest science—astronomy—is pursued.

Among other "wondrous things" he found were star clusters along the Milky Way, moons and rings around the outer planets, and colorful nebulae unlike anything seen before. Some of Galileo's sketches are reproduced here (left side) and are compared with modern views at right.



Galileo Galilei

Galileo's sketch of the Pleiades

Saturn in the ultraviolet *(STScI)*

Today, we are again in the midst of another period of unsurpassed scientific achievement—a revolution in which modern astronomers are revealing the invisible universe as Galileo once spied the visible universe. We have learned how to detect, measure, and analyze invisible radiation streaming to us from dark objects in space. And once again our perceptions are changing.

Astronomy no longer evokes visions of plodding intellectuals peering through long telescope tubes. Nor does the cosmos any longer refer to that seemingly inactive, immutable domain seen visually when we gaze at the nighttime sky. Modern astronomers now decipher a more vibrant, changing universe—one in which stars emerge and perish much like living things, galaxies spew forth vast quantities of energy, and life itself is thought to be a natural consequence of the evolution of matter.

New discoveries are rapidly advancing our understanding of the universe, but they also raise new questions. Astronomers will encounter many problems in the decades ahead, but this should neither dismay nor frustrate us, for it is precisely how science operates. Each discovery adds to our storehouse of information, generating a host of questions that lead in turn to more discoveries, and so on, causing an acceleration of basic knowledge.

Most notably, we are beginning to perceive the universe in all its multivaried ways. A single generation—not the generation of our parents and not that of our children, but our generation—has opened up the whole electromagnetic spectrum beyond visible light. And what we, too, have found are “wondrous things.”

Emerging largely from studies of the invisible universe, our view of the cosmos in its full splendor is one of many new scientific insights that we have recently been privileged to attain. Historians of the future may well regard our generation as the one that took a great leap forward, providing a whole new glimpse of our richly endowed universe. In all of history, there have been only two periods in which our perception of the universe has been so revolutionized within a single human lifetime. The first occurred four centuries ago at the time of Galileo; the second is now under way.

Orion in the infrared *(Caltech)*

Pleiades in the optical *(AURA)*

1

Charting the Heavens

THE FOUNDATIONS OF ASTRONOMY

Nature offers no greater splendor than the starry sky on a clear, dark night. Silent and jeweled with the constellations of ancient myth and legend, the night sky has inspired wonder throughout the ages—a wonder that leads our imaginations far from the confines of Earth and the pace of the present day and out into the distant reaches of space and cosmic time itself.

Astronomy, born in response to that wonder, is built on two of the most basic traits of human nature: the *need to explore* and the *need to understand*. Through the interplay of curiosity, discovery, and analysis—the keys to exploration and understanding—people have sought answers to questions about the universe since the earliest times. Astronomy is the oldest of all the sciences, yet never has it been more exciting than it is today.

The Big Picture Our subject is science, and that means rich details and specific ideas. Even so, we also need to keep in mind a larger, general perspective. And when it comes to astronomy, there is perhaps no grander feature of the cosmos than stars—they're everywhere in the nighttime sky, like those seen in the photo opposite. Roughly as many stars reside in the observable universe as there are grains of sand in all the beaches of the world—about a hundred sextillion, or 10^{23}.

LEFT: High overhead on a clear, dark night, we can see a rich band of stars known as the Milky Way—so-called for its resemblance to a milky band of countless stars. All these stars (and more) are part of a much larger system called the Milky Way Galaxy, of which our star, the Sun, is one member. This image shows the awesome splendor of the Milky Way shining above some of the big telescopes of the European Southern Observatory, a major astronomy facility high in the Chilean Andes. ***(ESO/Y. Beletsky)***

Learning Outcomes

Studying this chapter will enable you to

1. Arrange the basic levels of structure in the universe in order of increasing size.
2. Distinguish among scientific theories, hypotheses, and observations, and describe how scientists combine observation, theory, and testing in their study of the universe.
3. Describe the celestial sphere, and tell how astronomers use constellations and angular measurement to locate objects in the sky.
4. Describe how and why the Sun and the stars appear to change their positions from night to night and from month to month.
5. Explain how Earth's axial tilt causes the seasons, and why the seasons change over time.
6. Account for the changing appearance of the Moon, and explain how the relative motions of Earth, the Sun, and the Moon lead to eclipses.
7. Give an example of how simple geometric reasoning can be used to measure the distances and sizes of otherwise inaccessible objects.

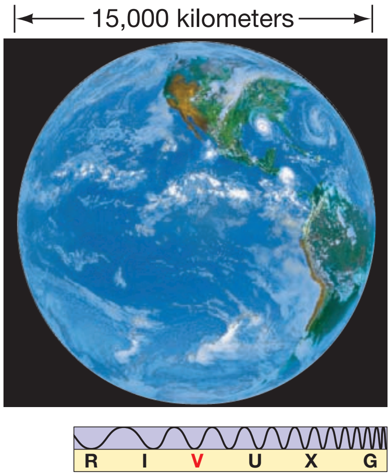
1.1 Our Place in Space

Of all the scientific insights attained to date, one stands out boldly: Earth is neither central nor special. We inhabit no unique place in the universe. Astronomical research, especially within the past few decades, strongly suggests that we live on what seems to be an ordinary rocky *planet* called Earth, one of eight known planets orbiting an average *star* called the Sun, a star near the edge of a huge collection of stars called the Milky Way Galaxy, which is one *galaxy* among billions of others spread throughout the observable universe. To begin to get a feel for the relationships among these very different objects, consult Figures 1.1 through 1.5.

We are connected to the most distant realms of space and time not only by our imaginations but also through a common cosmic heritage. Most of the chemical elements that make up our bodies (hydrogen, oxygen, carbon, and many more) were created billions of years ago in the hot centers of long-vanished stars. Their fuel supply spent, these giant stars died in huge explosions, scattering the elements created deep within their cores far and wide. Eventually, this matter collected into clouds of gas that slowly collapsed to give birth to new generations of stars. In this way, the Sun and its family of planets formed nearly 5 billion years ago. Everything on Earth embodies atoms from other parts of the universe and from a past far more remote than the beginning of human evolution. Elsewhere, other beings—perhaps with intelligence much greater than our own—may at this very moment be gazing in wonder at their own night sky. Our own Sun may be nothing more than an insignificant point of light to them—if it is visible at all. Yet if such beings exist, they must share our cosmic origin.

Simply put, the **universe** is the totality of all space, time, matter, and energy. **Astronomy** is the study of the universe. It is a subject unlike any other, for it requires us to profoundly change our view of the cosmos and to consider matter on scales totally unfamiliar from everyday experience. Look again at the galaxy in Figure 1.4. It is a swarm of about a hundred billion stars—more stars than the number of people who have ever lived on Earth. The entire assemblage is spread across a vast expanse of space 100,000 **light-years** in diameter. Although it sounds like a unit of time, a light-year is in fact the *distance* traveled by light in a year, at a speed of about 300,000 kilometers per second. Multiplying out, it follows that a light-year is equal to 300,000 kilometers/second × 86,400 seconds/day × 365 days or about 10 trillion kilometers, or roughly 6 trillion miles. Typical galactic systems are truly "astronomical" in size. For comparison, Earth's roughly 13,000-km diameter is less than one-twentieth of a light-*second*.

▲ **FIGURE 1.3 The Sun** The Sun is a star, a very hot ball of gas composed mainly of hydrogen and helium. Much bigger than Earth—more than 100 times larger in diameter—the Sun is held together by its own gravity. The dark blemishes are sunspots (see Chapter 16). *(AURA)*



▲ **FIGURE 1.2 Earth** Earth is a planet, a mostly solid object, although it has some liquid in its oceans and core and gas in its atmosphere. In this view, the North and South American continents are clearly visible, though most of the scene shows Pacific waters. *(NASA)*

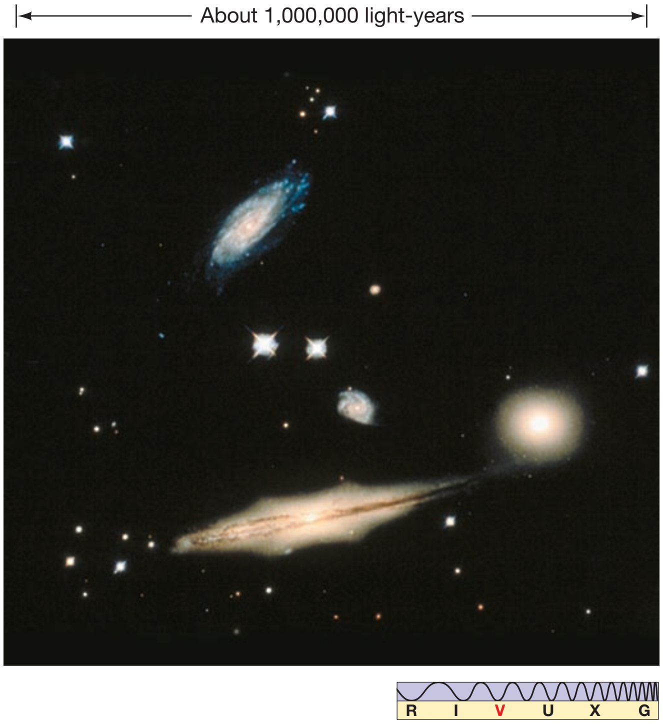
◀ **FIGURE 1.1 Humans** We know our own size and scale well—adult humans are typically 1.5 meters tall. Earth in the next figure is about 10 million times bigger. *(J. Lodriguss)*

The light-year is a unit introduced by astronomers to help them describe immense distances. We will encounter many such custom units in our studies. As discussed in more detail in Appendix 2, astronomers frequently augment the standard SI (Système Internationale) metric system with additional units tailored to the particular problem at hand.

▲ **FIGURE 1.4 Galaxy** A typical galaxy is a collection of a hundred billion stars, each separated by vast regions of nearly empty space. Our Sun is a rather undistinguished star near the edge of another such galaxy, called the Milky Way. *(R. Gendler/Science Source)*

A thousand (1000), a million (1,000,000), a billion (1,000,000,000), and even a trillion (1,000,000,000,000)—these words occur regularly in everyday speech. But let's take a moment to understand the magnitude of the numbers and appreciate the differences among them. One thousand is easy enough to understand: At the rate of one number per second, you could count to a thousand in 1000 seconds—about 16 minutes. However, if you wanted to count to a million, you would need more than 2 weeks of counting at the rate of one number per second, 16 hours per day (allowing 8 hours per day for sleep). To count from one to a billion at the same rate of one number per second and 16 hours per day would take nearly 50 years—the better part of an entire human lifetime.

In this book, we consider *distances* in space spanning not just billions of kilometers, but billions of light-years; *objects* containing not just trillions of atoms, but trillions of stars; and *time intervals* of not just billions of seconds or hours, but billions of years. You will need to become familiar—and comfortable—with such enormous numbers. A good way to begin is learning to recognize just how much larger than a thousand is a million, and how much larger still is a billion. Appendix 1 explains the convenient method used by scientists for writing and manipulating very large and very small numbers. If you are unfamiliar with this method, please read that appendix carefully—the *scientific notation* described there will be used consistently throughout our text, beginning in Chapter 2.



▲ **FIGURE 1.5 Galaxy Cluster** This photograph shows a typical cluster of galaxies, spread across roughly a million light-years of space. Each galaxy contains hundreds of billions of stars, probably planets, and possibly living creatures. *(NASA)*

Lacking any understanding of the astronomical objects they observed, early skywatchers made up stories to explain them: The Sun was pulled across the heavens by a chariot drawn by winged horses, and patterns of stars traced heroes and animals placed in the sky by the gods. Today, of course, we have a radically different conception of the universe. The stars we see are distant, glowing orbs hundreds of times larger than our entire planet, and the patterns they form span hundreds of light-years. In this first chapter we present some basic methods used by astronomers to chart the space around us. We describe the slow progress of scientific knowledge, from chariots and gods to today's well-tested theories and physical laws, and explain why we now rely on science rather than on myth to help us explain the universe.

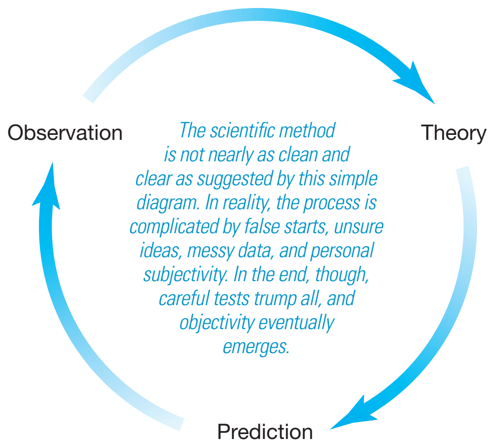
1.2 Scientific Theory and the Scientific Method

How have we come to know the universe around us and the cosmic perspective sketched in Figures 1.1–1.5? The earliest descriptions of the universe were based largely on imagination and mythology and made little attempt to explain the workings of the heavens in terms of earthly experience. However, some early scientists realized the importance of careful observation and testing to the formulation of their ideas. The success of their approach changed, slowly but surely, the way science was done and opened the door to a fuller understanding of nature. As the influence of logic and reasoned argument grew, the power of myth diminished. People began to inquire more critically about themselves and the universe. They realized that *thinking* about nature was no longer sufficient—*looking* at it was also necessary. Experiments and observations became a central part of the process of inquiry.

To be effective, a **theory**—the framework of ideas and assumptions used to explain some set of observations and make predictions about the real world—must be continually tested. Scientists accomplish this by using a theory to construct a **theoretical model** of a physical object (such as a planet or a star) or phenomenon (such as gravity or light) that accounts for its known properties. The model then makes further predictions about the object's properties, or perhaps how it might behave or change under new circumstances. If experiments and observations favor those predictions, the theory can be further developed and refined. If not, the theory must be reformulated or rejected, no matter how appealing it originally seemed. This approach to investigation, combining thinking and doing—that is, theory and experiment—is known as the **scientific method**. The process, combining theoretical reasoning with experimental testing, is illustrated schematically in Figure 1.6. It lies at the heart of modern science, separating science from pseudoscience, fact from fiction.

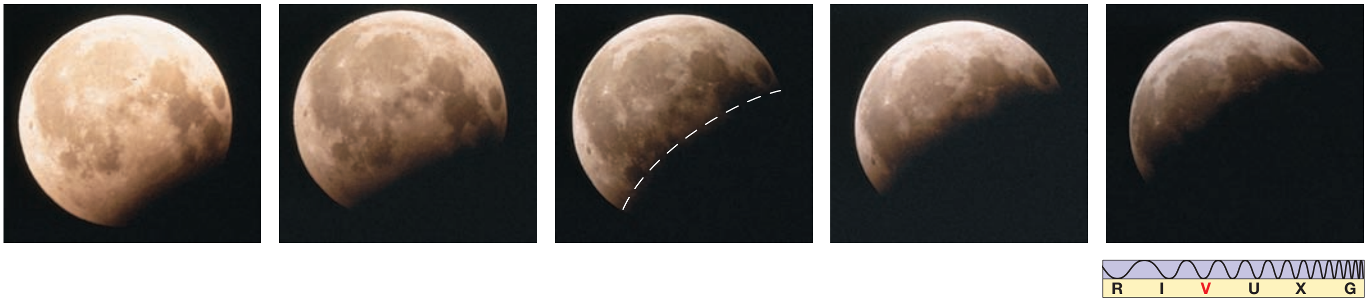
The notion that theories must be tested and may be proven wrong sometimes leads people to dismiss their importance. We have all heard the expression, "Of course, it's only a theory," used to deride or dismiss an idea that someone finds unacceptable. Don't be fooled! Gravity (see Section 2.7) is "only" a theory, but calculations based on it have guided human spacecraft throughout the solar system. Electromagnetism (Chapter 3) and quantum mechanics (Chapter 4) are theories, too, yet they form the foundation for technology. Facts about much of the universe are a dime a dozen. Theories are the intellectual "glue" that combine seemingly unrelated facts into a coherent and interconnected whole.

Notice that there is no end point to the process depicted in Figure 1.6. A theory can be invalidated by a single wrong prediction, but no amount of observation or experimentation can ever prove it "correct." Theories simply become more and more widely accepted as their predictions are repeatedly confirmed. Modern scientific theories share several important defining characteristics:



▲ **FIGURE 1.6 Scientific Method** Scientific theories evolve through a combination of observation, theoretical reasoning, and prediction, suggesting new observations. The process can begin at any point in the cycle, and it continues forever—or until the theory fails to explain an observation or makes a demonstrably false prediction.

- They must be *testable*—that is, they must admit the possibility that their underlying assumptions and their predictions can, in principle, be exposed to experimental verification. This feature separates science from, for example, religion, since, ultimately, divine revelations or scriptures cannot be challenged within a religious framework—we can't design an experiment to "verify the mind of God." Testability also distinguishes science from a pseudoscience such as astrology, whose underlying assumptions and predictions have been repeatedly tested and never verified, with no apparent impact on the views of those who continue to believe in it!
- They must continually be *tested*, and their consequences tested, too. This is the basic circle of scientific progress depicted in Figure 1.6.
- They should be *simple*. This is less a requirement than a practical outcome of centuries of scientific experience—the most successful theories tend to be the simplest ones that fit the facts. This viewpoint is often encapsulated in a principle known as *Occam's razor*: If two competing theories both explain the facts and make the same predictions, then the simpler one is better. Put another way—"Keep it simple!" A good theory should be no more complex than is absolutely necessary.
- Finally, most scientists have the additional bias that a theory should in some sense be *elegant*. When a



▲ **FIGURE 1.7 A Lunar Eclipse** These photographs show Earth's shadow (denoted by the dashed curve) sweeping across the Moon during a lunar eclipse. By observing this behavior, Aristotle reasoned that Earth was the cause of the shadow and concluded that Earth must be round. His theory has yet to be disproved. *(G. Schneider)*

clearly stated simple principle naturally ties together and explains several phenomena previously thought to be completely distinct, this is widely regarded as a strong point in favor of the new theory.

You may find it instructive to apply these criteria to the many physical theories—some old and well established, others much more recent and still developing—we will encounter throughout the text.

The birth of modern science is usually associated with the Renaissance, the historical period from the late 14th to the mid-17th century that saw a rebirth (*renaissance* in French) of artistic, literary, and scientific inquiry in European culture following the chaos of the Dark Ages. However, one of the first documented uses of the scientific method in an astronomical context was made by Aristotle (384–322 B.C.) some 17 centuries earlier. Aristotle is not normally remembered as a strong proponent of this approach—many of his best known ideas were based on pure thought, with no attempt at experimental test or verification. Nevertheless, his brilliance extended into many areas now thought of as modern science. He noted that, during a lunar eclipse (Section 1.6), Earth casts a curved shadow onto the surface of the Moon. Figure 1.7 shows a series of photographs taken during a recent lunar eclipse. Earth's shadow, projected onto the Moon's surface, is indeed slightly curved. This is what Aristotle must have seen and recorded so long ago.

Because the observed shadow seemed always to be an arc of the same circle, Aristotle theorized that Earth, the cause of the shadow, must be round. Don't underestimate the scope of this apparently simple statement. Aristotle also had to reason that the dark region was indeed a shadow and that Earth was its cause—facts we regard as obvious today, but far from clear 25 centuries ago. On the basis of this *hypothesis*—one possible explanation of the observed facts—he then predicted that any and all future lunar eclipses would show Earth's shadow to be curved, regardless of our planet's orientation. That prediction has been tested every time a lunar eclipse has occurred. It has yet to be proved wrong. Aristotle was not the first person to argue that Earth is round, but he was apparently the first to offer observational proof using this method.

This basic reasoning forms the basis of all modern scientific inquiry. Armed only with naked-eye observations of the sky (the telescope would not be invented for almost another 2000 years), Aristotle first made an observation. Next, he formulated a hypothesis to explain that observation. Then he tested the validity of his hypothesis by making predictions that could be confirmed or refuted by further observations. *Observation, theory, and testing*—these are the cornerstones of the scientific method, a technique whose power will be demonstrated again and again throughout our text.

Today, scientists throughout the world use an approach that relies heavily on testing ideas. They gather data, form a working hypothesis that explains the data, and then proceed to test the implications of the hypothesis using experiment and observation. Eventually, one or more "well-tested" hypotheses may be elevated to the stature of a physical law and come to form the basis of a theory of even broader applicability. The new predictions of the theory will in turn be tested, as scientific knowledge continues to grow. Experiment and observation are integral parts of the process of scientific inquiry. Untestable theories, or theories unsupported by experimental evidence, rarely gain any measure of acceptance in scientific circles. Used properly over a period of time, this rational, methodical approach enables us to arrive at conclusions that are mostly free of the personal bias and human values of any one scientist—it is designed to yield an objective view of the universe we inhabit.

PROCESS OF SCIENCE Check

✔ Can a theory ever become a "fact," scientifically speaking?

1.3 The "Obvious" View

To see how astronomers apply the scientific method to understand the universe around us, let's start with some very basic observations. Our study of the cosmos, the modern science of astronomy, begins with looking at the night sky. The overall appearance of the sky is not so different now from what our ancestors would have seen hundreds or thousands of years ago, but our *interpretation* of what we see has changed immeasurably as the science of astronomy has evolved and grown.

Constellations in the Sky

Between sunset and sunrise on a clear night, we can see about 3000 points of light. Including the view from the opposite side of Earth, nearly 6000 stars are visible to the unaided eye. A natural human tendency is to see patterns and relationships among objects even when no true connection exists, and people long ago connected the brightest stars into configurations called **constellations**, which ancient astronomers named after mythological beings, heroes, and animals—whatever was important to them. Figure 1.8 shows a constellation prominent in the nighttime sky from October through March: the hunter named Orion. Orion was a mythical Greek hero famed, among other things, for his amorous pursuit of the Pleiades, the seven daughters of the giant Atlas. According to Greek mythology, to protect the Pleiades from Orion, the gods placed them among the stars, where Orion still stalks them across the sky. Many constellations have similarly fabulous connections with ancient lore.

Perhaps not surprisingly, the patterns have a strong cultural bias—ancient Chinese astronomers saw mythical figures different from those seen by the Greeks, the Babylonians, and the people of other cultures, even though they were all looking at the same stars in the night sky. Interestingly, different cultures often made the same basic *groupings* of stars, despite widely varying interpretations of what they saw. For example, the group of seven stars known in North America as "the Dipper" is called "the Wagon" or "the Plough" in western Europe. The ancient Greeks regarded these same stars as the tail of "the Great Bear," the Egyptians saw them as the leg of an ox, the Siberians as a stag, and some Native Americans as a funeral procession.

Early astronomers had very practical reasons for studying the sky. Some constellations served as navigational guides. The star Polaris (part of the Little Dipper) indicates north, and the near constancy of its location in the sky, from hour to hour and night to night, has aided travelers for centuries. Other constellations served as primitive calendars to predict planting and harvesting seasons. For example, many cultures knew that the appearance of certain stars on the horizon just before daybreak signaled the beginning of spring and the end of winter.

In many societies, people came to believe that there were other benefits in tracing the regularly changing positions of heavenly bodies. The relative positions of stars and planets

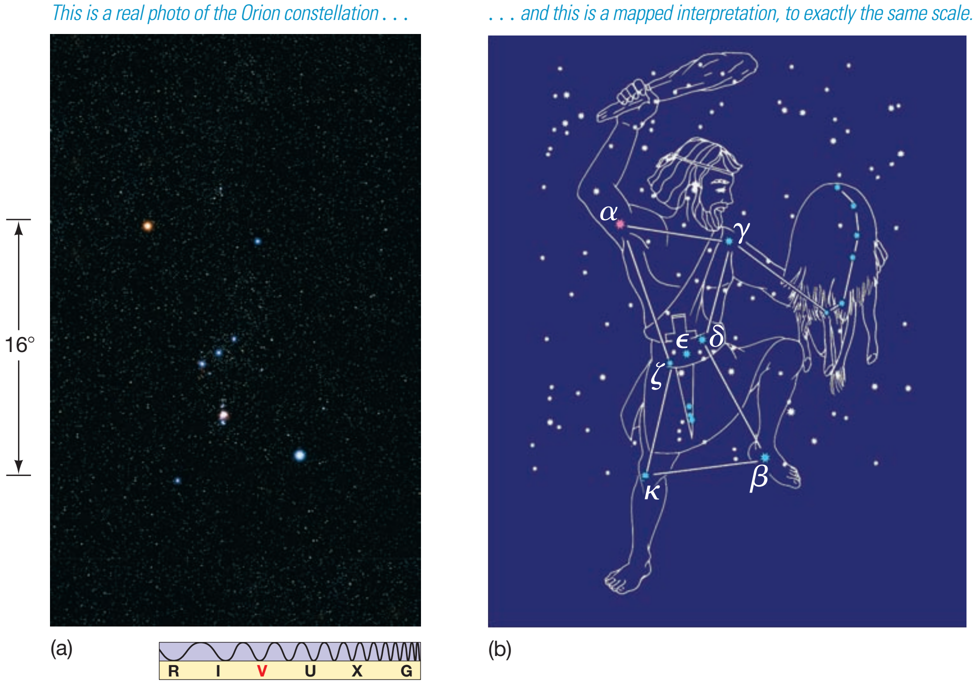
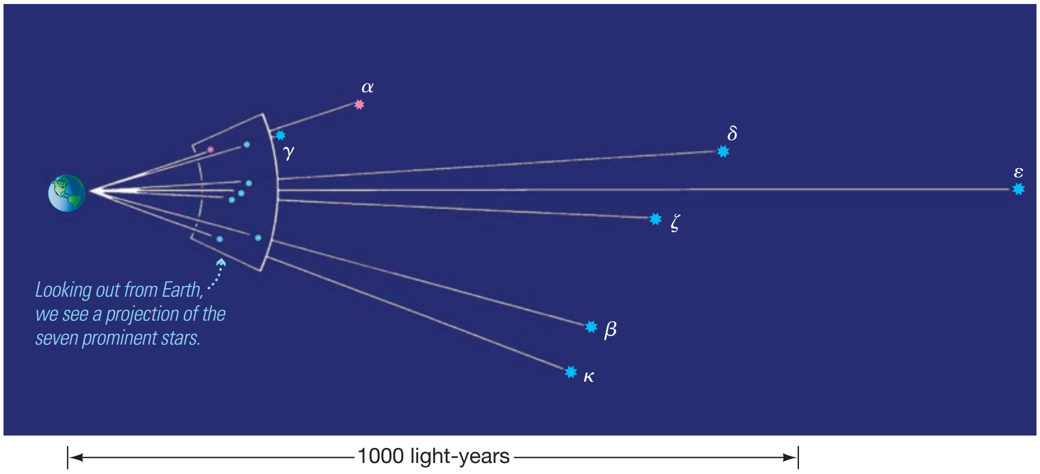


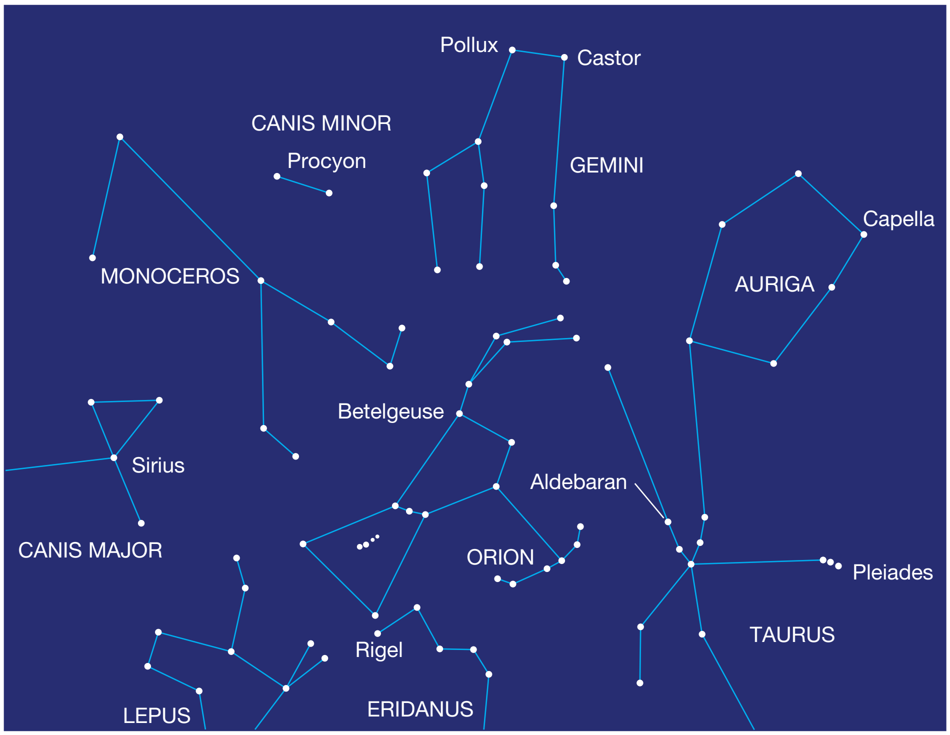
FIGURE 1.8 Constellation Orion (a) A photograph of the group of bright stars that make up the constellation Orion. (See the preface, p. 21, for an explanation of the icon at the bottom, which simply indicates that this image was made in visible light.) (b) The stars are connected to show the pattern visualized by the Greeks: the outline of a hunter. The Greek letters serve to identify some of the brighter stars in the constellation (see also Figure 1.9). You can easily find Orion in the northern winter sky by identifying the line of three bright stars in the hunter's "belt." *(P. Sanz/Alamy)*



◀ **FIGURE 1.9 Orion in 3-D** The true three-dimensional relationships among the most prominent stars in Orion. The distances were determined by the *Hipparcos* satellite in the 1990s. (See Chapter 17.)

at a person's birth were carefully studied by *astrologers,* who used the data to make predictions about that person's destiny. Thus, in a sense, astronomy and astrology arose from the same basic desire—to "see" into the future—and, indeed, for a long time they were indistinguishable from one another. Today, most people recognize that astrology is nothing more than an amusing diversion (although millions still study their horoscope in the newspaper every morning!). Nevertheless, the ancient astrological terminology—the names of the constellations and many terms used to describe the locations and motions of the planets—is still used throughout the astronomical world.

Generally speaking, as illustrated in Figure 1.9 for the case of Orion, the stars that make up any particular constellation are not actually close to one another in space, even by astronomical standards. They merely are bright enough to observe with the naked eye and happen to lie in roughly the same direction in the sky as seen from Earth. Still, the constellations provide a convenient means for astronomers to specify regions of the sky, much as geologists use continents or politicians use voting precincts to identify certain localities on planet Earth. Figure 1.10 shows how the conventionally defined constellations cover a portion of the sky in



◀ **FIGURE 1.10 Constellations Near Orion** The region of the sky conventionally associated with the constellation Orion, together with some neighboring constellations (labeled in all capital letters). Some prominent stars are also labeled in lowercase letters. The 88 constellations span the entire sky, so that every astronomical object lies in precisely one of them.

the vicinity of Orion. In all, there are 88 constellations, most of them visible from North America at some time during the year.

The Celestial Sphere

Over the course of a night, the constellations seem to move smoothly across the sky from east to west, but ancient skywatchers were well aware that the *relative* locations of stars remained unchanged as this nightly march took place.* It was natural for those observers to conclude that the stars must be firmly attached to a **celestial sphere** surrounding Earth—a canopy of stars resembling an astronomical painting on a heavenly ceiling. Figure 1.11 shows how early astronomers pictured the stars as moving with this celestial sphere as it turned around a fixed, unmoving Earth. Figure 1.12 shows how all stars appear to move in circles around a point very close to the star Polaris (better known as the Pole Star or North Star). To the ancients, this point represented the axis around which the entire celestial sphere turned.

Today we recognize that the apparent motion of the stars is the result of the spin, or **rotation**, not of the celestial sphere, but of Earth. Polaris indicates the direction—due north—in which Earth's rotation axis points. Even though we now know that the celestial sphere is an incorrect description of the heavens, we still use the idea as a convenient fiction that helps us visualize the positions of stars in the sky. The points where Earth's axis intersects the celestial sphere are called the **celestial poles**. In the Northern Hemisphere, the north celestial pole lies directly above Earth's North Pole. The extension of Earth's axis in the opposite direction defines the south celestial pole, directly above Earth's South Pole. Midway between the north and south celestial poles lies

**We now know that stars do in fact move relative to one another, but this proper motion across the sky is too slow to be discerned with the naked eye* *(see Section 17.1).*

Imagine yourself at the center of this sphere, looking out at the whole sky around you.

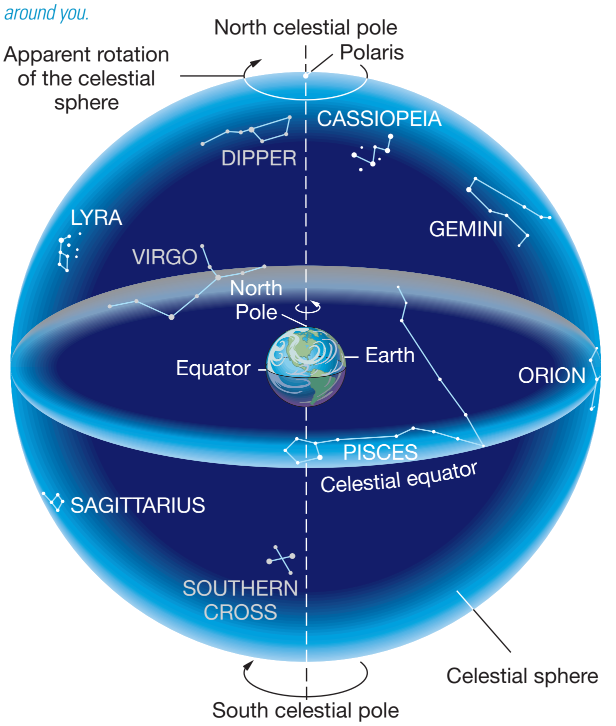
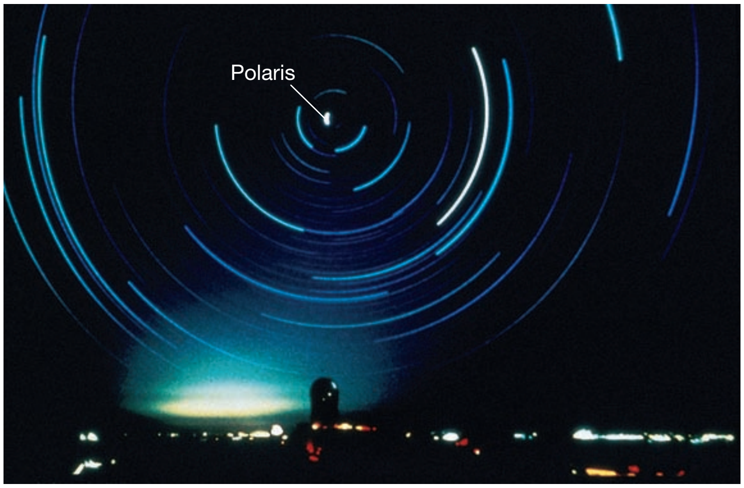


FIGURE 1.11 Celestial Sphere Planet Earth sits fixed at the hub of the celestial sphere. This is one of the simplest possible models of the universe, but it doesn't agree with the facts that astronomers now know about the universe.

The duration of this exposure is about 5 hours, . . .



. . . since each star traces out approximately 20 percent of a circle.

R I V U X G

FIGURE 1.12 Northern Sky This time-lapse photograph of the northern sky shows how each star traces out a curved trail across the night sky. The concentric circles are centered near the North Star, Polaris. *(AURA)* the **celestial equator**, representing the intersection of Earth's equatorial plane with the celestial sphere. These parts of the celestial sphere are marked on Figure 1.11.

When discussing the locations of stars "on the sky," astronomers naturally talk in terms of *angular* positions and separations. *More Precisely 1-1* presents some basic information on angular measure.

CONCEPT Check

✔ Why do astronomers find it useful to retain the fiction of the celestial sphere to describe the sky? What vital piece of information about stars is lost when we talk about their locations "on" the sky?

1.4 Earth's Orbital Motion

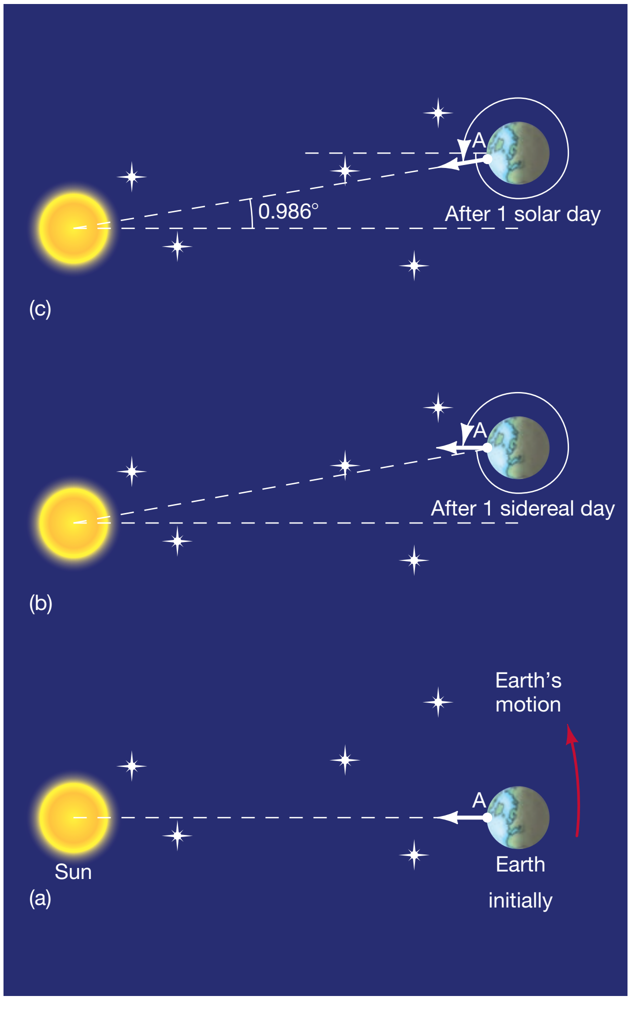
Day-to-Day Changes

We measure time by the Sun. Because the rhythm of day and night is central to our lives, it is not surprising that the period from one noon to the next, the 24-hour **solar day**, is our basic social time unit. The daily progress of the Sun and the other stars across the sky is known as *diurnal motion*. As we have just seen, it is a consequence of Earth's rotation. But the stars' positions in the sky do *not* repeat themselves exactly from one night to the next. Each night, the whole celestial sphere appears to be shifted a little relative to the horizon compared with the night before. The easiest way to confirm this difference is by noticing the stars that are visible just after sunset or just before dawn. You will find that they are in slightly different locations from those of the previous night. Because of this shift, a day measured by the stars—called a **sidereal day** after the Latin word *sidus,* meaning "star"—differs in length from a solar day. Evidently, there is more to the apparent motion of the heavens than simple rotation.

The reason for the difference between a solar day and a sidereal day is sketched in Figure 1.13. It is a result of the fact that Earth moves in two ways simultaneously: It rotates on its central axis while at the same time **revolving** around the Sun. Each time Earth rotates once on its axis, it also moves a small distance along its orbit about the Sun. Earth therefore has to rotate through slightly more than 360° (see *More Precisely 1-1*) for the Sun to return to the same apparent location in the sky. Thus, the interval of time between noon one day and noon the next (a solar day) is slightly greater than one true rotation period (one sidereal day). Our planet takes 365 days to orbit the Sun, so the additional angle is 360°/365 = 0.986°. Because Earth, rotating at a rate of 15° per hour, takes about 3.9 minutes to rotate through this angle, the solar day is 3.9 minutes longer than the sidereal day (i.e., 1 sidereal day is roughly $23^{h}56^{m}$ long).

Seasonal Changes

Figure 1.14(a) illustrates the major stars visible from most locations in the United States on clear summer evenings. The brightest stars—Vega, Deneb, and Altair—form a conspicuous triangle high above the constellations Sagittarius and Capricornus, which are low on the southern horizon. In the winter sky, however, these stars are replaced as shown in Figure 1.14(b) by several other, well-known constellations, including Orion, Leo, and Gemini.



▲ **FIGURE 1.13 Solar and Sidereal Days** A sidereal day is Earth's true rotation period—the time taken for our planet to return to the same orientation in space relative to the distant stars. A solar day is the time from one noon to the next. The difference in length between the two is easily explained once we understand that Earth revolves around the Sun at the same time as it rotates on its axis. Frames (a) and (b) are 1 sidereal day apart. During that time, Earth rotates exactly once on its axis and also moves a little in its solar orbit—approximately 1°. Consequently, between noon at point A on one day and noon at the same point the next day, Earth actually rotates through about 361° (frame c), and the solar day exceeds the sidereal day by about 4 minutes. Note that the diagrams are not drawn to scale; the true 1° angle is in reality much smaller than shown here.

MORE PRECISELY 1-1

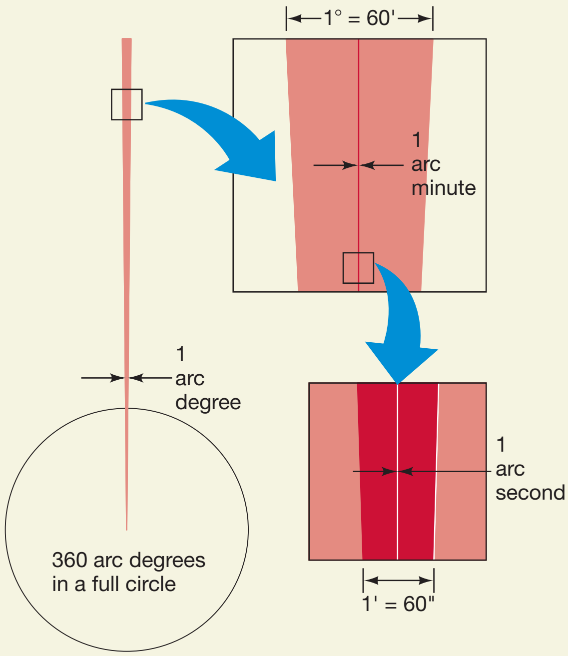
Angular Measure

Size and scale are often specified by measuring lengths and angles. The concept of length measurement is fairly intuitive to most of us. The concept of *angular measurement* may be less familiar, but it, too, can become second nature if you remember a few simple facts:

- A full circle contains 360 *degrees* (360°). Thus, the half-circle that stretches from horizon to horizon, passing directly overhead and spanning the portion of the sky visible to one person at any one time, contains 180°.
- Each 1° increment can be further subdivided into fractions of a degree, called *arc minutes*. There are 60 arc minutes (written 60′) in 1°. (The term "arc" is used to distinguish this angular unit from the unit of time.) Both the Sun and the Moon project an angular size of 30 arc minutes (half a degree) on the sky. Your little finger, held at arm's length, has a similar angular size, covering about a 40′ slice of the 180° horizon-to-horizon arc.
- An arc minute can be divided into 60 *arc seconds* (60″). Put another way, an arc minute is $\frac{1}{60}$ of a degree, and an arc second is $\frac{1}{60} \times \frac{1}{60} = \frac{1}{3600}$ of a degree. An arc second is an extremely small unit of angular measure—the angular size of a centimeter-sized object (a dime, say) at a distance of about 2 kilometers (a little over a mile).

The accompanying figure illustrates this subdivision of the circle into progressively smaller units.

Don't be confused by the units used to measure angles. Arc minutes and arc seconds have nothing to do with the measurement of time, and degrees have nothing to do with temperature. Degrees, arc minutes, and arc seconds are simply ways to measure the size and position of objects in the universe.



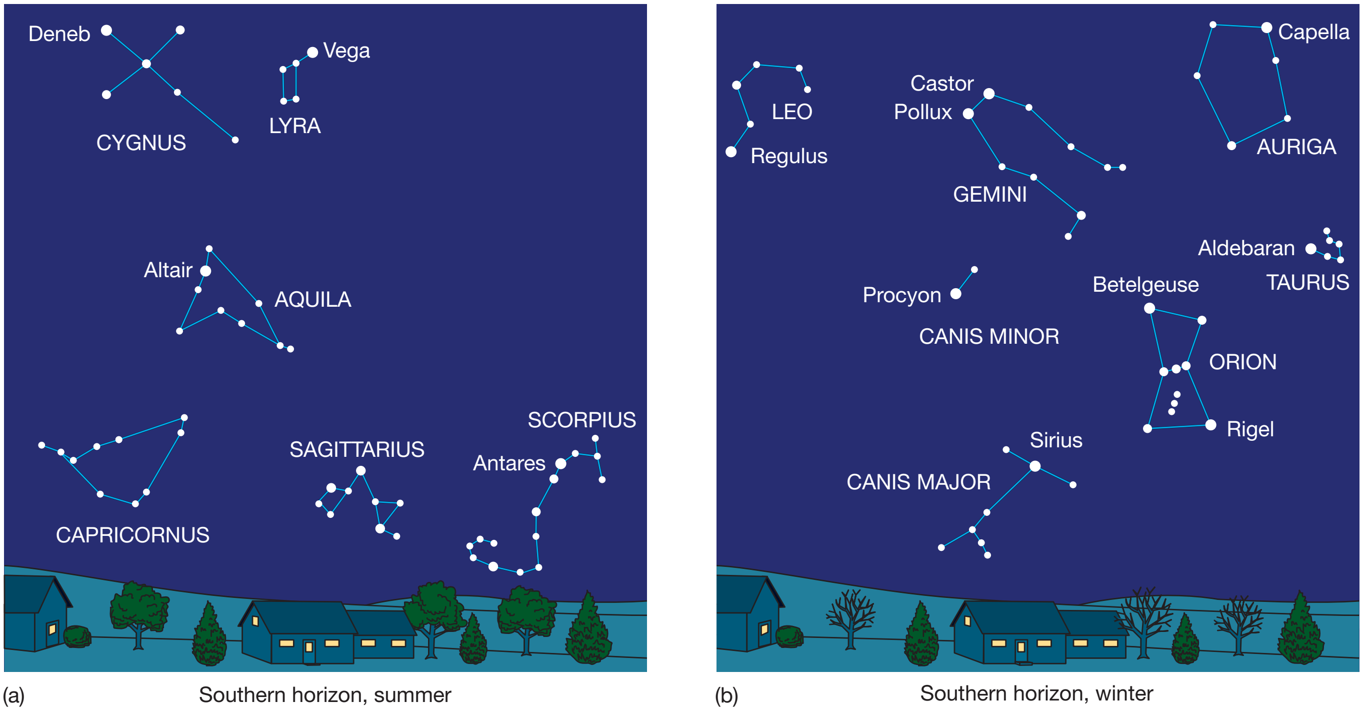
The angular size of an object depends both on its actual size and on its distance from us. For example, the Moon at its present distance from Earth has an angular diameter of 0.5°, or 30′. If the Moon were twice as far away, it would appear half as big—15′ across—even though its actual size would be the same. Thus, *angular size by itself is not enough to determine the actual diameter of an object—the distance to the object must also be known*. We return to this topic in more detail in *More Precisely 1-2*.

In the constellation Canis Major lies Sirius (the Dog Star), the brightest star in the sky. Year after year, the same stars and constellations return, each in its proper season. Every winter evening, Orion is high overhead; every summer, it is gone. (For more detailed maps of the sky at different seasons, consult the star charts at the end of the book.)

These regular seasonal changes occur because of Earth's **revolution** around the Sun: Earth's darkened hemisphere faces in a slightly different direction in space each evening. The change in direction is only about 1° per night (Figure 1.13)—too small to be easily noticed with the naked eye from one evening to the next, but clearly noticeable over the course of weeks and months, as illustrated in Figure 1.15.After 6 months, Earth has reached the opposite side of its orbit, and we face an entirely different group of stars and constellations at night. Because of this motion, the Sun appears (to an observer on Earth) to move relative to the background stars over the course of a year. This apparent motion of the Sun on the sky traces out a path on the celestial sphere known as the **ecliptic**.

The 12 constellations through which the Sun passes as it moves along the ecliptic—that is, the constellations we would see looking in the direction of the Sun if they weren't overwhelmed by the Sun's light—had special significance for astrologers of old. These constellations are collectively known as the **zodiac**.

As illustrated in Figure 1.16, the ecliptic forms a great circle on the celestial sphere, inclined at an angle of 23.5° to the celestial equator. In reality, as illustrated in Figure 1.17, the plane of the ecliptic is *the plane of Earth's orbit around the Sun*. Its tilt is a consequence of the *inclination* of our planet's rotation axis to the plane of its orbit.



▲ **FIGURE 1.14 Typical Night Sky** (a) A typical summer sky above the United States. Some prominent stars (labeled in lowercase letters) and constellations (labeled in all capital letters) are shown. (b) A typical winter sky above the United States.

The point on the ecliptic where the Sun is at its northernmost point above the celestial equator is known as the **summer solstice** (from the Latin words *sol,* meaning "sun," and *stare,* "to stand"). As indicated in Figure 1.17, it represents the location in Earth's orbit where our planet's North Pole comes closest to pointing in the direction of the Sun. This occurs on or near June 21—the exact date varies slightly from year to year because the actual length of a year is not a whole number of days. As Earth rotates, points north of the equator spend the greatest fraction of

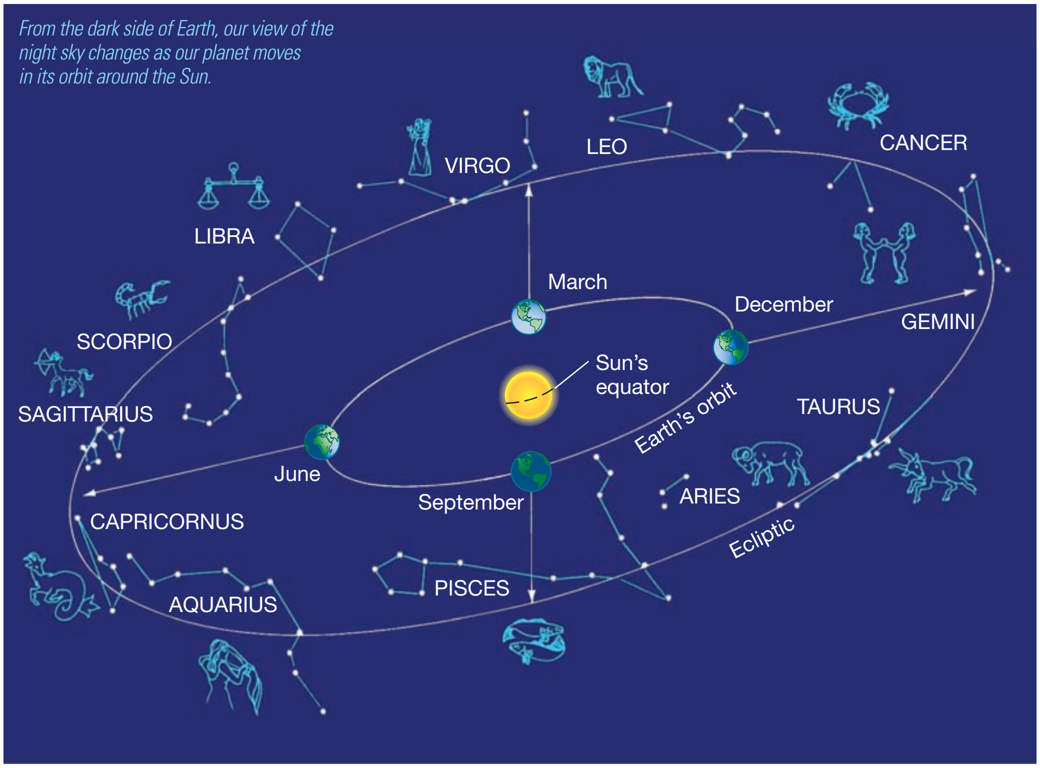
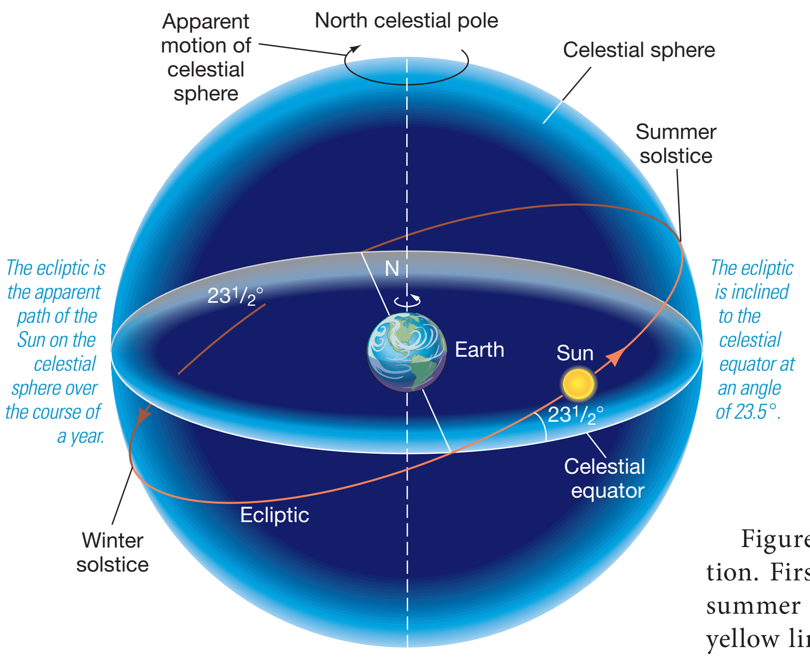


FIGURE 1.15
The Zodiac The night side of Earth faces a different set of constellations at different times of the year. The 12 constellations named here make up the astrological zodiac. The arrows indicate the most prominent zodiacal constellations in the night sky at various times of the year. For example, in June, when the Sun is "in" Gemini, Sagittarius and Capricornus are visible at night.



◀ **FIGURE 1.16 Ecliptic** The seasons result from the changing height of the Sun above the celestial equator. At the summer solstice, the Sun is at its northernmost point on its path around the ecliptic; it is therefore highest in the sky, as seen from Earth's Northern Hemisphere, and the days are longest. The reverse is true at the winter solstice. At the vernal and autumnal equinoxes, when the Sun crosses the celestial equator, day and night are of equal length.

their time in sunlight on that date, so the summer solstice corresponds to the longest day of the year in the Northern Hemisphere and the shortest day in the Southern Hemisphere.

Six months later, the Sun is at its southernmost point below the celestial equator (Figure 1.16)—or, equivalently, the North Pole points farthest from the Sun (Figure 1.17). We have reached the **winter solstice** (December 21), the shortest day in Earth's Northern Hemisphere and the longest in the Southern Hemisphere.

The tilt of Earth's rotation axis relative to the ecliptic is responsible for the **seasons** we experience—the marked difference in temperature between the hot summer and cold winter months. As illustrated in Figure 1.17, two factors combine to cause this variation. First, there are more hours of daylight during the summer than in winter. To see why this is, look at the yellow lines on the surfaces of the drawings of Earth in the figure. (For definiteness, they correspond to a latitude of 45 degrees—roughly that of the Great Lakes or the south of France.) A much larger fraction of the line is sunlit in the summertime, and more daylight means more solar heating. Second, as illustrated in the insets in Figure 1.17, when the Sun is high in the sky in summer, rays of sunlight striking Earth's surface are more concentrated—spread out over a smaller area—than in winter. As a result, the Sun feels hotter. Therefore summer, when the Sun is highest above the horizon and the days are longest, is generally much warmer than winter, when the Sun is low and the days are short.

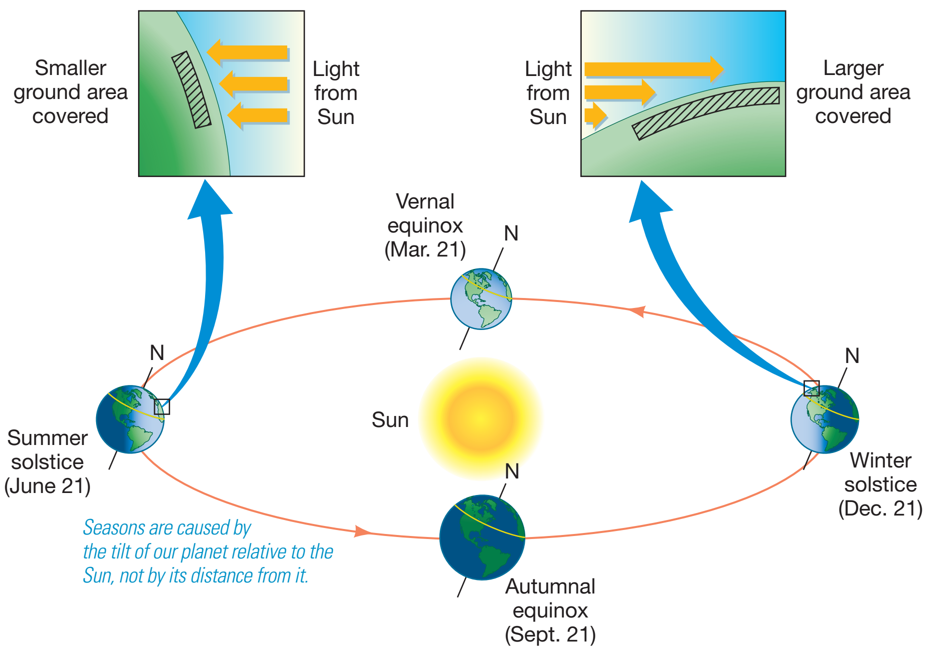
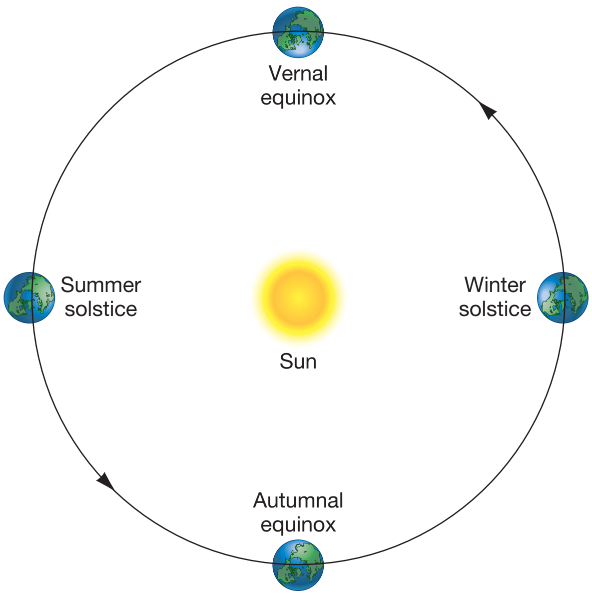


FIGURE 1.17 Seasons Earth's seasons result from the inclination of our planet's rotation axis with respect to its orbit plane. The summer solstice corresponds to the point on Earth's orbit where our planet's North Pole points most nearly toward the Sun. The opposite is true of the winter solstice. The vernal and autumnal equinoxes correspond to the points in Earth's orbit where our planet's axis is perpendicular to the line joining Earth and the Sun. The insets show how rays of sunlight striking the ground at an angle (e.g., during northern winter) are spread over a larger area than rays coming nearly straight down (e.g., during northern summer). As a result, the amount of solar heat delivered to a given area of Earth's surface is greatest when the Sun is high in the sky.



▲ **FIGURE 1.18 Earth's Orbit** Seen face on, Earth's orbit around the Sun is almost a perfect circle. The distance from Earth to the Sun varies only slightly over the course of a year and is *not* the cause of the seasonal temperature changes we experience on our planet.

A popular misconception is that the seasons have something to do with Earth's distance from the Sun. Figure 1.18 illustrates why this is *not* the case. It shows Earth's orbit "face on," instead of almost edge-on, as in Figure 1.17. Notice that the orbit is almost perfectly circular, so the distance from Earth to the Sun varies very little (in fact, by only about 3 percent) over the course of a year—not nearly enough to explain the seasonal changes in temperature. What's more, Earth is actually *closest* to the Sun in early January, the dead of winter in the Northern Hemisphere, so distance from the Sun cannot be the main factor controlling our climate.

The two points where the ecliptic intersects the celestial equator (Figure 1.16)—that is, where Earth's rotation axis is perpendicular to the Earth-Sun line (Figure 1.17)—are known as **equinoxes**. On those dates, day and night are of equal duration. (The word *equinox* derives from the Latin for "equal night.") In the fall (in the Northern Hemisphere), as the Sun crosses from the Northern into the Southern Hemisphere, we have the **autumnal equinox** (on September 21). The **vernal equinox** occurs in northern spring, on or near March 21, as the Sun crosses the celestial equator moving north. Because of its association with the end of winter and the start of a new growing season, the vernal equinox was particularly important to early astronomers and astrologers. It also plays an important role in human timekeeping: The interval of time from one vernal equinox to the next—365.2422 mean solar days—is 1 **tropical year**.

Long-Term Changes

Earth has many motions—it spins on its axis, it travels around the Sun, and it moves with the Sun through our Galaxy. We have just seen how some of these motions can account for the changing nighttime sky and the changing seasons. In fact, the situation is even more complicated. Like a spinning top that rotates rapidly on its own axis while that axis slowly revolves about the vertical, Earth's axis changes its *direction* over the course of time (although the angle between the axis and a line perpendicular to the plane of the ecliptic always remains close to 23.5°). Illustrated in Figure 1.19, this change is called **precession**. It is caused by torques (twisting forces) on Earth due to the gravitational pulls of the Moon and the Sun, which affect our planet in much the same way as the torque due to Earth's own gravity affects a top. During a complete cycle of precession—about 26,000 years—Earth's axis traces out a cone.

The time required for Earth to complete exactly one orbit around the Sun, relative to the stars, is called a **sidereal year**. One sidereal year is 365.256 mean solar days long—about 20 minutes longer than a tropical year. The reason for this slight difference is Earth's precession. Recall that the vernal equinox occurs when Earth's rotation axis is perpendicular to the line joining Earth and the Sun, and the Sun is crossing the celestial equator moving from south to north. In the absence of precession, this would occur exactly once per sidereal orbit, and the tropical and sidereal years would be identical. However, because of the slow precessional shift in the orientation of Earth's rotation axis, the instant when the axis is next perpendicular to the line from Earth to the Sun occurs slightly *sooner* than we would otherwise expect. Consequently, the vernal equinox drifts slowly westward ("backwards") around the zodiac over the course of the precession cycle.

The tropical year is the year that our calendars measure. If our timekeeping were tied to the sidereal year, the seasons would slowly march around the calendar as Earth precessed—13,000 years from now, summer in the Northern Hemisphere would be at its height in late February! By using the tropical year, we ensure that July and August will always be (northern) summer months. However, in 13,000 years' time, Orion will be a summer constellation.

CONCEPT Check

✔ In astronomical terms, what are *summer* and *winter*, and why do we see different constellations during those seasons?

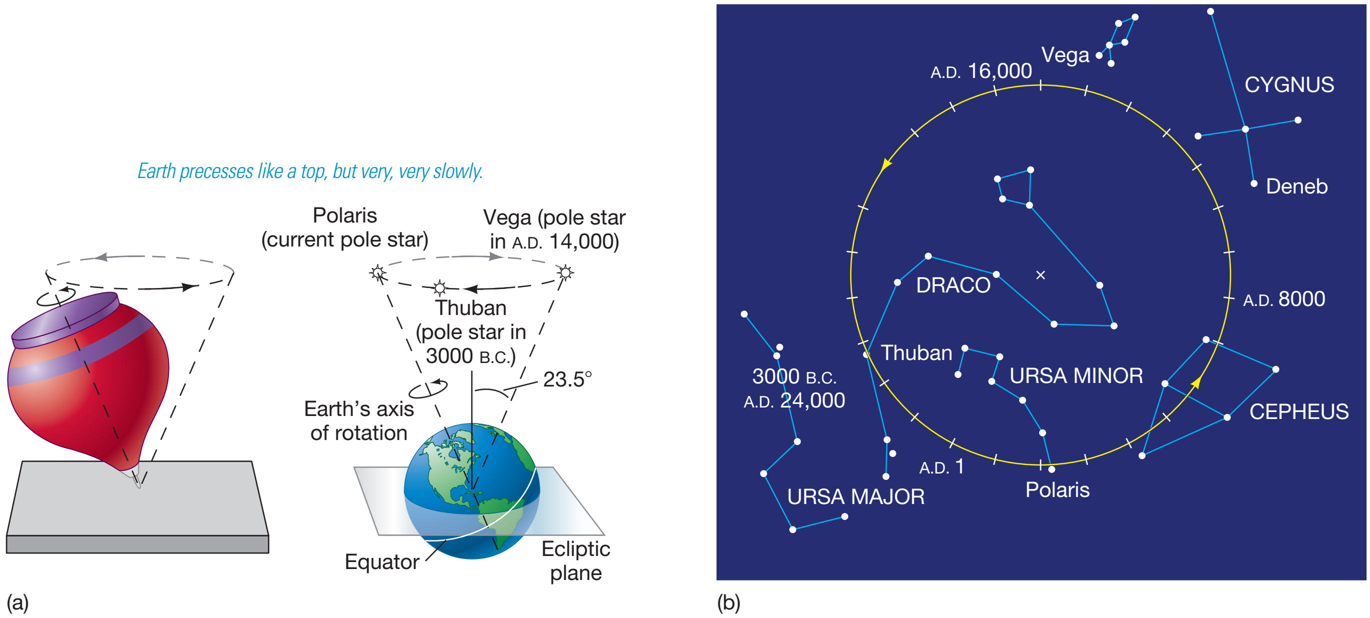


FIGURE 1.19 Precession (a) Earth's axis currently points nearly toward the star Polaris. About 12,000 years from now—almost halfway through one cycle of precession—Earth's axis will point toward a star called Vega, which will then be the "North Star." Five thousand years ago, the North Star was a star named Thuban in the constellation Draco. (b) The yellow circle shows the precessional path of the north celestial pole among some prominent northern stars. Tick marks indicate intervals of a thousand years.

1.5 The Motion of the Moon

The Moon is our nearest neighbor in space. Apart from the Sun, it is the brightest object in the sky. Like the Sun, the Moon appears to move relative to the background stars. Unlike the Sun, however, the Moon really does revolve around Earth. It crosses the sky at a rate of about 12° per day, moving through an angular distance equal to its own diameter—30 arc minutes—in about an hour.

Lunar Phases

The Moon's appearance undergoes a regular cycle of changes, or **phases**, taking roughly 29.5 days to complete. Figure 1.20 illustrates the appearance of the Moon at different times in this monthly cycle. Starting from the *new Moon*, which is all but invisible in the sky, the Moon appears to *wax* (or grow) a little each night and is visible as a growing *crescent* (photo 1 of Figure 1.20). One week after new Moon, half of the lunar disk can be seen (photo 2). This phase is known as a *quarter Moon*. During the next week, the Moon continues to wax, passing through the *gibbous* phase (photo 3) until, 2 weeks after new Moon, the *full Moon* (photo 4) is visible. During the next 2 weeks, the Moon *wanes* (or shrinks), passing in turn through the gibbous, quarter, crescent phases (photos 5–7) and eventually becoming new again.

The position of the Moon in the sky relative to the Sun, as seen from Earth, varies with lunar phase. For example, the full Moon rises in the east as the Sun sets in the west, while the first quarter Moon actually rises at noon, but may become visible only late in the day as the Sun's light fades and the Moon is already high in the sky. Some connections between the lunar phase and the rising and setting times of the Moon are indicated in Figure 1.20.

The Moon doesn't actually change its size and shape from night to night, of course. Its full circular disk is present at all times. Why, then, don't we always see a full Moon? The answer is that, unlike the Sun and the other stars, the Moon emits no light of its own. Instead, it shines by reflected sunlight. As illustrated in Figure 1.20, half of the Moon's surface is illuminated by the Sun at any instant. However, not all of the Moon's sunlit face can be seen because of the Moon's position with respect to Earth and the Sun. When the Moon is full, we see the entire "daylit" face because the Sun and the Moon are in opposite directions from Earth in the sky. In the case of a new Moon, the Moon and the Sun are in almost the same part of the sky, and the sunlit side of the Moon is oriented away from us. At new Moon, the Sun must be almost behind the Moon, from our perspective.

As the Moon revolves around Earth, our satellite's position in the sky changes with respect to the stars. In 1 **sidereal month** (27.3 days), the Moon completes one revolution and

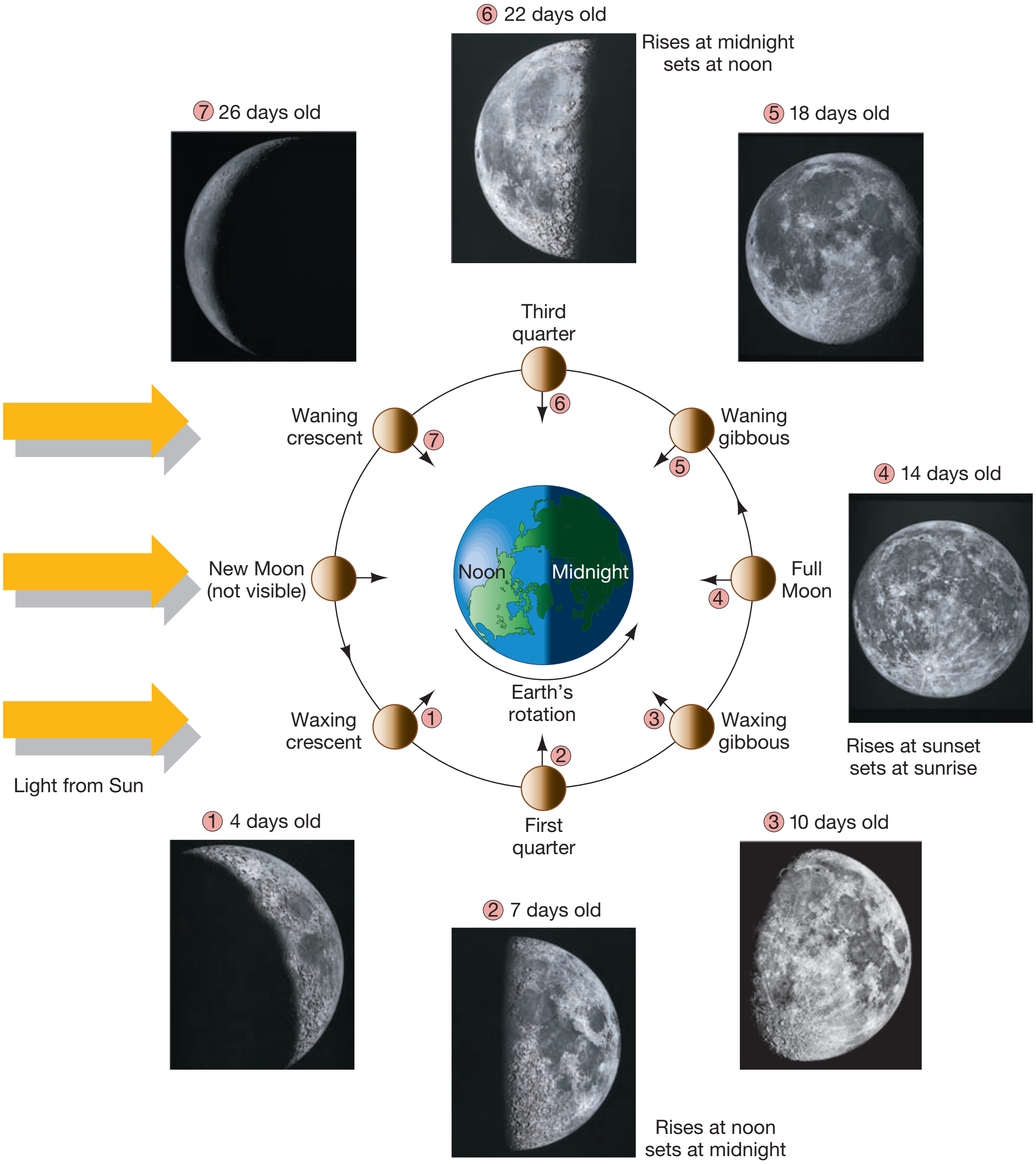


FIGURE 1.20 Lunar Phases Because the Moon orbits Earth, the visible fraction of the lunar sunlit face varies from night to night, although the Moon always keeps the same face toward our planet. (Note the location of the small, straight arrows, which mark the same point on the lunar surface at each phase shown.) The complete cycle of lunar phases, shown here starting at the waxing crescent phase and following the Moon's orbit counterclockwise, takes 29.5 days to complete. Rising and setting times for some phases are also indicated. *(UC/Lick Observatory)*

returns to its starting point on the celestial sphere, having traced out a great circle in the sky. The time required for the Moon to complete a full cycle of phases, 1 **synodic month**, is a little longer—about 29.5 days. The synodic month is a little longer than the sidereal month for the same reason that a solar day is slightly longer than a sidereal day: Because of Earth's motion around the Sun, the Moon must complete slightly more than one full revolution to return to the same phase in its orbit (Figure 1.21).

Eclipses

From time to time—but only at new or full Moon—the Sun and the Moon line up precisely as seen from Earth, and we observe the spectacular phenomenon known as an **eclipse**. When the Sun and the Moon are in exactly *opposite* directions, as seen from Earth, Earth's shadow sweeps across the Moon, temporarily blocking the Sun's light and darkening the Moon in a **lunar eclipse**, as illustrated in Figure 1.22.

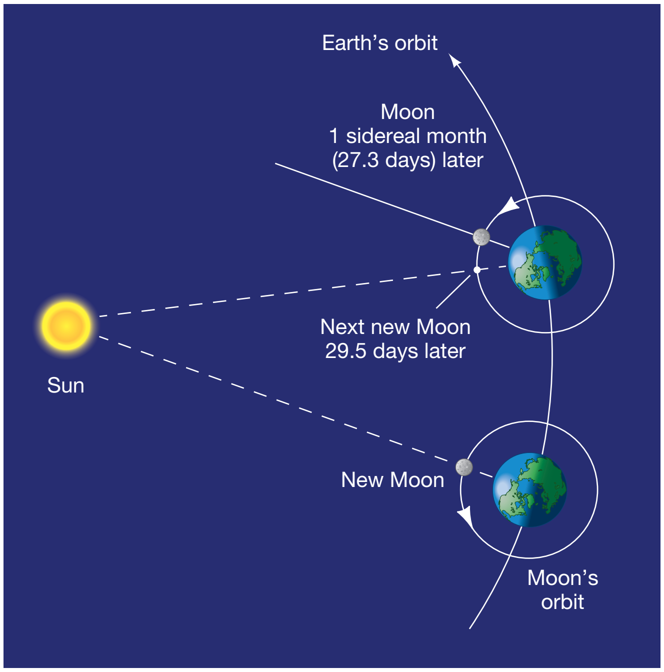


FIGURE 1.21 Sidereal Month The difference between a *synodic* and a *sidereal* month stems from the motion of Earth relative to the Sun. Because Earth orbits the Sun in 365 days, in the 29.5 days from one new Moon to the next (1 synodic month), Earth moves through an angle of approximately 29°. Thus, the Moon must revolve more than 360° between new Moons. The sidereal month, which is the time taken for the Moon to revolve through exactly 360°, relative to the stars, is about 2 days shorter.

From Earth, we see the curved edge of Earth's shadow cut into the face of the full Moon and slowly eat its way into the lunar disk. Usually, the alignment of the Sun, Earth, and Moon is imperfect, so the shadow never completely covers the Moon. Such an occurrence is known as a **partial lunar eclipse**. Occasionally, however, the entire lunar surface is obscured in a **total lunar eclipse**, such as that shown in the inset of Figure 1.22. Total lunar eclipses last only as long as is needed for the Moon to pass through Earth's shadow—no more than about 100 minutes. During that time, the Moon often acquires an eerie, deep red coloration—the result of a small amount of sunlight reddened by Earth's atmosphere (for the same reason that sunsets appeared—see *More Precisely 7-1*) and refracted (bent) onto the lunar surface, preventing the shadow from being completely black.

When the Moon and the Sun are in exactly the *same* direction, as seen from Earth, an even more awe-inspiring event occurs. The Moon passes directly in front of the Sun, briefly turning day into night in a **solar eclipse**. In a *total solar eclipse,* when the alignment is perfect, planets and some stars become visible in the daytime as the Sun's light is reduced to nearly nothing. We can also see the Sun's ghostly outer atmosphere, or *corona* (Figure 1.23).* In a *partial solar eclipse,* the Moon's path is slightly "off center," and only a portion of the Sun's face is covered. In either case, the sight of the Sun apparently being swallowed up by the black disk of the Moon is disconcerting even today. It must surely have inspired fear in early observers. Small wonder that the ability to predict such events was a highly prized skill.

Unlike a lunar eclipse, which is simultaneously visible from all locations on Earth's night side, a total solar eclipse

**Actually, although a total solar eclipse is undeniably a spectacular occurrence, the visibility of the corona is probably the most important astronomical aspect of such an event today. It enables us to study this otherwise hard-to-see part of our Sun (see Chapter 16).*

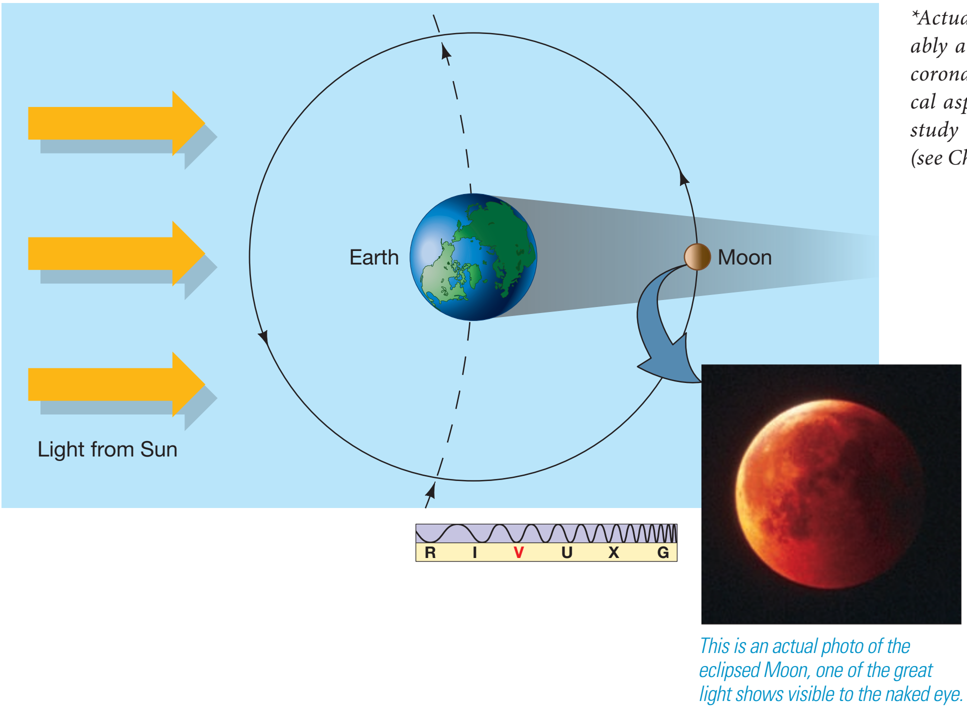
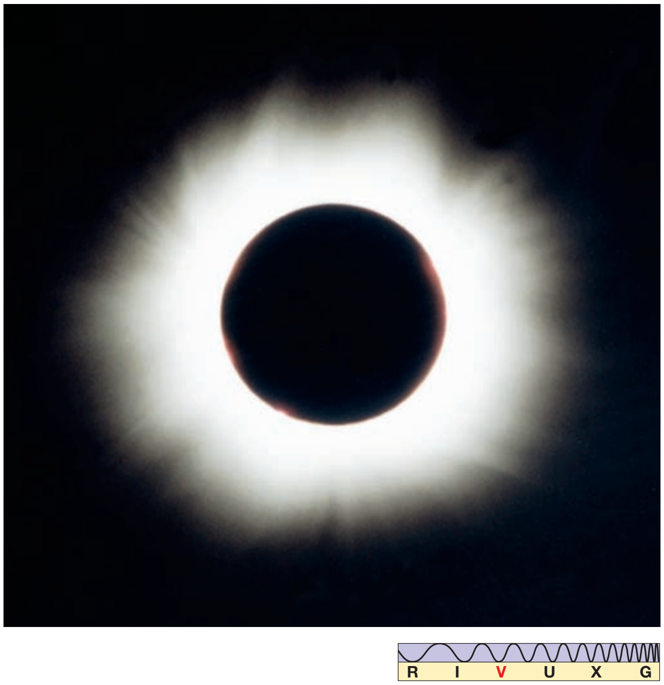


FIGURE 1.22 Lunar Eclipse When the Moon passes through Earth's shadow, we see a darkened, copper-colored Moon, as shown by the partial eclipse in the inset photograph. The red coloration is caused by sunlight deflected by Earth's atmosphere onto the Moon's surface. *(Inset: G. Schneider)*



▲ **FIGURE 1.23 Total Solar Eclipse** During a total solar eclipse, the Sun's corona becomes visible as an irregularly shaped halo surrounding the blotted-out disk of the Sun. This was the August 1999 eclipse, as seen from the banks of the Danube River near Sofia, Bulgaria. *(B. Angelov)*

can be seen from only a small portion of Earth's daytime side. The Moon's shadow on Earth's surface is about 7000 kilometers wide—roughly twice the diameter of the Moon. Outside of that shadow, no eclipse is seen. However, within the central region of the shadow, called the **umbra**, the eclipse is total. Within the shadow, but outside the umbra, in the **penumbra**, the eclipse is partial, with less and less of the Sun obscured the farther one travels from the shadow's center.

The connections among the umbra, the penumbra, and the relative locations of Earth, Sun, and Moon are illustrated in Figure 1.24. The umbra is always very small. Even under the most favorable circumstances, its diameter never exceeds 270 kilometers. Because the shadow sweeps across Earth's surface at over 1700 kilometers per hour, the duration of a total eclipse at any given point on our planet can never exceed 7.5 minutes.

The Moon's orbit around Earth is not exactly circular. Thus, the Moon may be far enough from Earth at the moment of an eclipse that its disk fails to fully cover the disk of the Sun, even though their centers coincide. In that case, there is no region of totality—the umbra never reaches Earth, and a thin ring of sunlight can be seen surrounding the Moon. Such an occurrence, called an **annular eclipse**, is illustrated in Figure 1.24(c) and shown more clearly in Figure 1.25. Roughly half of all solar eclipses are annular.

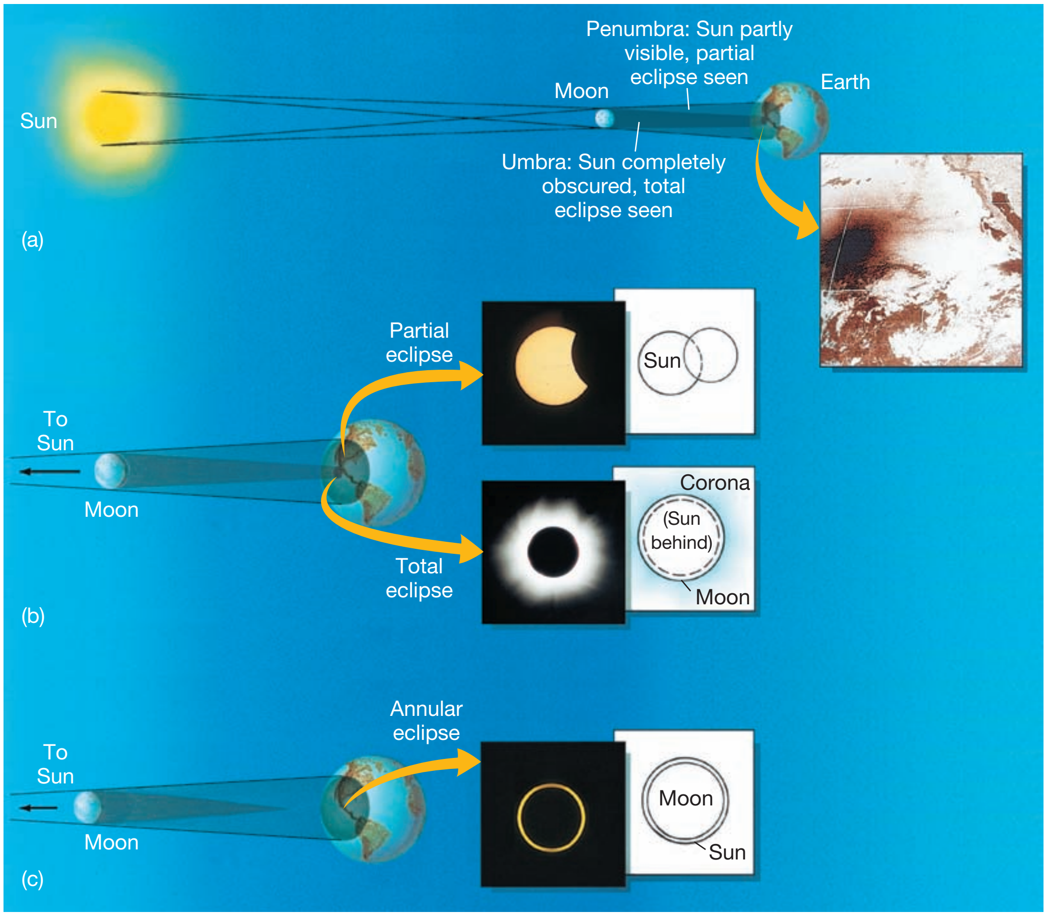


FIGURE 1.24 Types of Solar Eclipse (a) The Moon's shadow consists of two parts: the umbra, where no sunlight is seen, and the penumbra, where a portion of the Sun is visible. (b) If we are in the umbra, we see a total eclipse; in the penumbra, we see a partial eclipse. (c) If the Moon is too far from Earth at the moment of the eclipse, the umbra does not reach Earth and there is no region of totality; instead, an annular eclipse is seen. (Note that these figures are not drawn to scale.) *(Insets: NOAA; G. Schneider)*

▲ **FIGURE 1.25 Annular Solar Eclipse** During an annular solar eclipse, the Moon fails to completely hide the Sun, so a thin ring of light remains. No corona is seen in this case because even the small amount of the Sun still visible completely overwhelms the corona's faint glow. This was the December 1973 eclipse, as seen from Algiers. (The gray fuzzy areas at the top left and right are clouds in Earth's atmosphere.) *(G. Schneider)*

Eclipse Seasons

Why isn't there a solar eclipse at every new Moon and a lunar eclipse at every full Moon? That is, why doesn't the Moon pass directly between Earth and the Sun once per orbit and directly through Earth's shadow 2 weeks later?

The answer is that the Moon's orbit is slightly inclined to the ecliptic (at an angle of 5.2°), so the chance that a new (or full) Moon will occur just as the Moon happens to cross the plane of the ecliptic (with Earth, Moon, and Sun perfectly aligned) is quite low. Figure 1.26 illustrates some possible configurations of the three bodies. If the Moon happens to lie above or below the plane of the ecliptic when new (or full), a solar (or lunar) eclipse cannot occur. Such a configuration is termed *unfavorable* for producing an eclipse. In a *favorable* configuration, the Moon is new or full just as it crosses the plane of the ecliptic, and eclipses are seen. Unfavorable configurations are much more common, so eclipses are relatively rare events.

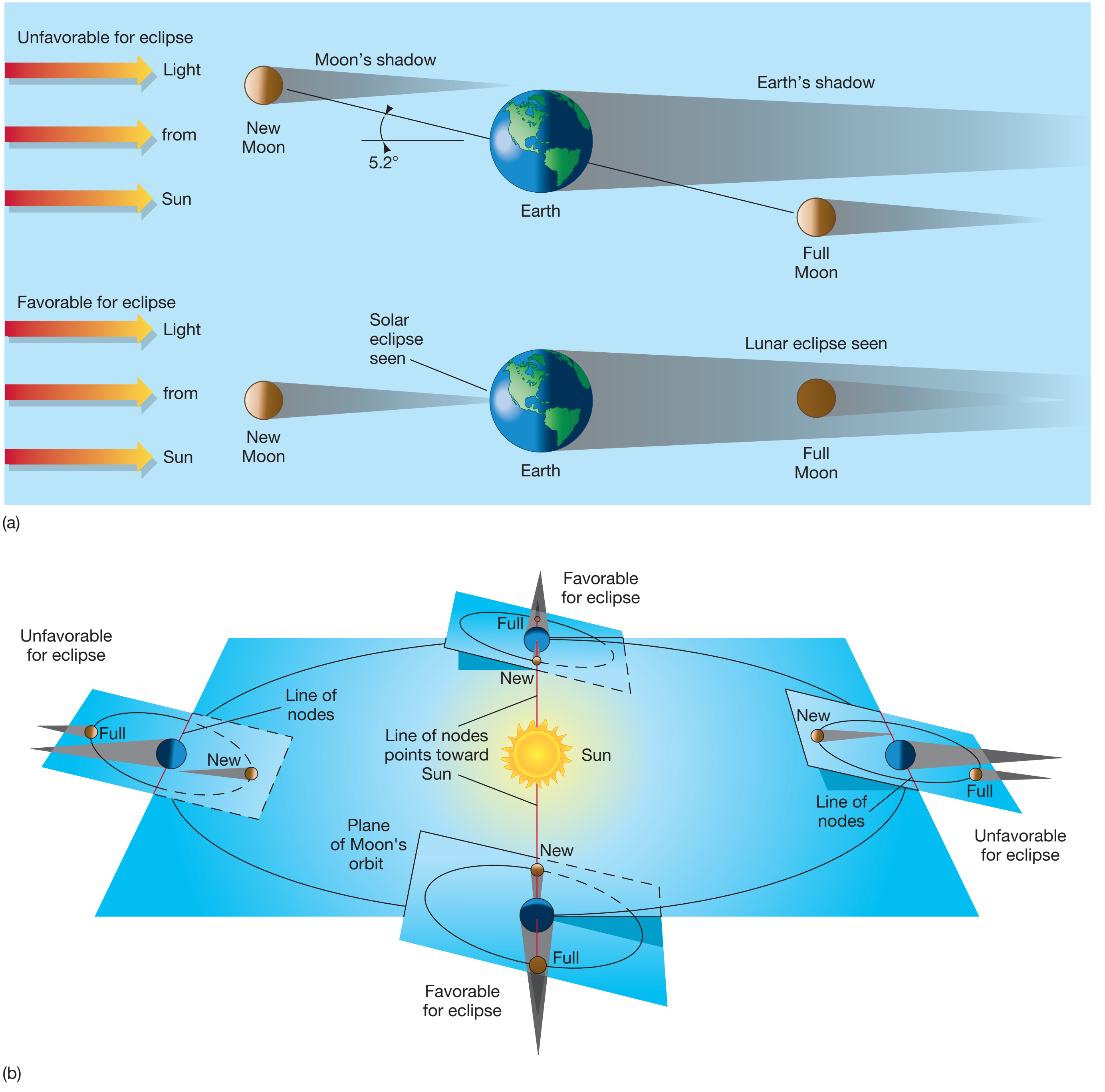
As indicated on Figure 1.26(b), the two points on the Moon's orbit where it crosses the plane of the ecliptic are known as the *nodes* of the orbit. The line joining the nodes, which is also the line of intersection of Earth's and the Moon's orbital planes, is known as the *line of nodes*. When the line of nodes is not directed toward the Sun, conditions are unfavorable for eclipses. However, when the line of nodes briefly lies along the Earth–Sun line, eclipses are possible. These two periods, known as **eclipse seasons**, are the only times at which an eclipse can occur. Notice that there is no guarantee that an eclipse *will* occur. For a solar eclipse, we must have a new Moon during an eclipse season. Similarly, a lunar eclipse can occur only at full Moon during an eclipse season.

Because we know the orbits of Earth and the Moon to great accuracy, we can predict eclipses far into the future. Figure 1.27 shows the location and duration of all total eclipses of the Sun between 2010 and 2030. Note that the eclipse tracks run from west to east—just the opposite of more familiar phenomena such as sunrise and sunset, which are seen earlier by observers located farther east. The reason is that the Moon's shadow sweeps across Earth's surface faster than our planet rotates, so the eclipse actually *overtakes* observers on the ground.

The solar eclipses that we do see highlight a remarkable cosmic coincidence. Although the Sun is many times farther away from Earth than is the Moon, it is also much larger. In fact, the ratio of distances is almost exactly the same as the ratio of sizes, so the Sun and the Moon both have roughly the *same* angular diameter—about half a degree, seen from Earth. Thus, the Moon covers the face of the Sun almost exactly. If the Moon were larger, we would never see annular eclipses, and total eclipses would be much more common. If the Moon were a little smaller, we would see only annular eclipses.

The gravitational tug of the Sun causes the Moon's orbital orientation, and hence the direction of the line of nodes, to change slowly with time. As a result, the time between one orbital configuration with the line of nodes pointing at the Sun and the next (with the Moon crossing the ecliptic in the same sense in each case) is not exactly 1 year, but instead is 346.6 days—sometimes called 1 *eclipse year*. Thus, the eclipse seasons gradually progress backward through the calendar, occurring about 19 days earlier each year. For example, in 1999 the eclipse seasons were in February and August, and on August 11 much of Europe and southern Asia was treated to the last total eclipse of the millennium (Figure 1.23). By 2002, those seasons had drifted into December and June, and eclipses actually occurred on June 10 and December 4 of that year. By studying Figure 1.27, you can follow the progression of the eclipse seasons through the calendar.

The combination of the eclipse year and the Moon's synodic period leads to an interesting long-term cycle in solar (and lunar) eclipses. A simple calculation shows that 19 eclipse years is almost exactly 223 lunar months. Thus, every 6585 solar days (actually 18 years, 11.3 days) the "same" eclipse recurs, with Earth, the Moon, and the Sun in the same relative configuration. Several such repetitions are evident in Figure 1.27—see, for example, the similarly shaped July 11, 2010, and July 22, 2028, tracks. (Note that we must

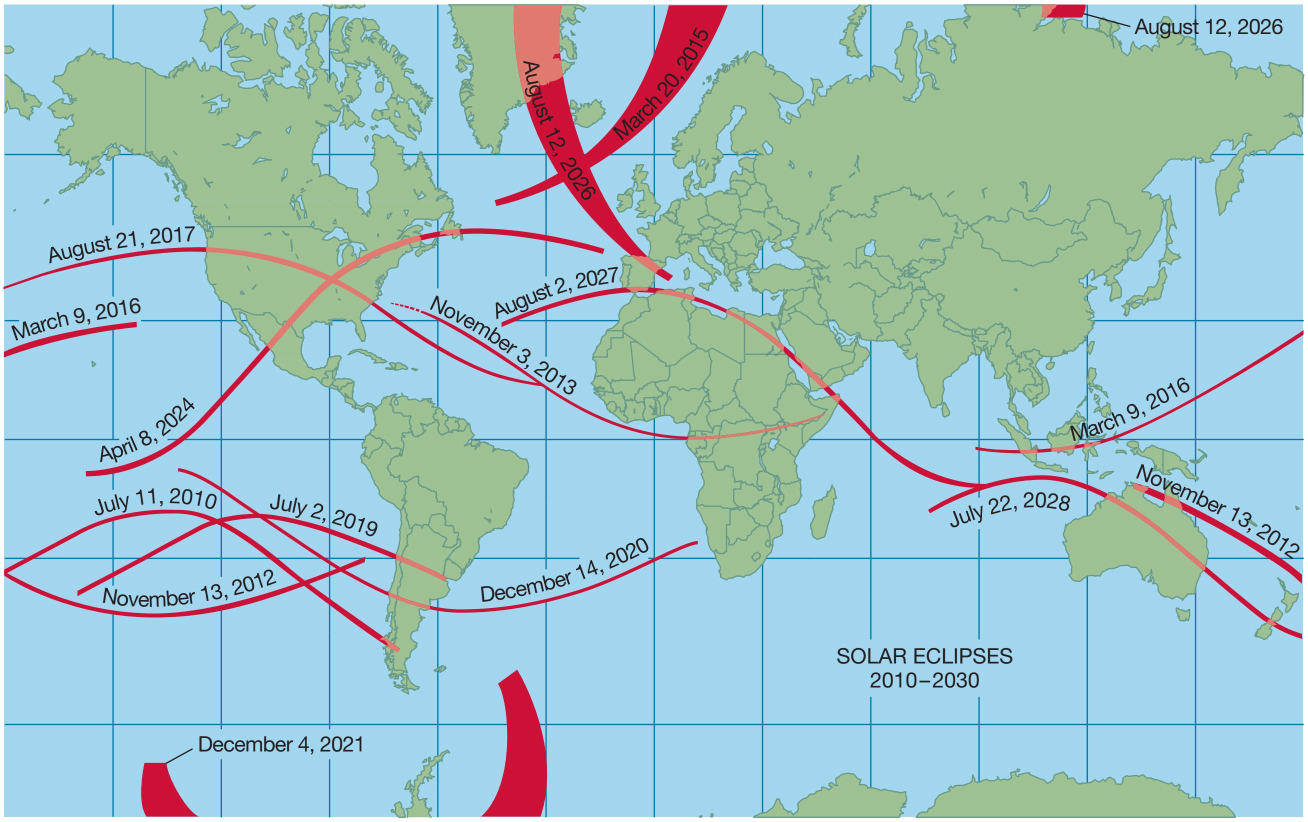


▲ **FIGURE 1.26 Eclipse Geometry** (a) An eclipse occurs when Earth, Moon, and Sun are precisely aligned. If the Moon's orbital plane lay in exactly the plane of the ecliptic, this alignment would occur once a month. However, the Moon's orbit is inclined at about 5° to the ecliptic, so not all configurations are favorable for producing an eclipse. (b) For an eclipse to occur, the line of intersection of the two planes must lie along the Earth–Sun line. Thus, eclipses can occur just at specific times of the year. Only the umbra of each shadow is shown, for clarity (see Figure 1.24).

take leap years properly into account to get the dates right!) The roughly 120° offset in longitude corresponds to Earth's rotation in 0.3 day. This recurrence is called the *Saros cycle*. Well known to ancient astronomers, it undoubtedly was the key to their "mystical" ability to predict eclipses!

CONCEPT Check

✔ What types of solar eclipses would you expect to see if Earth's distance from the Sun were to double? What if the distance became half its present value?



▲ **FIGURE 1.27 Eclipse Tracks** Regions of Earth that saw or will see total solar eclipses between the years 2010 and 2030. Each track represents the path of the Moon's umbra across Earth's surface during an eclipse. The width of the track depends upon the latitude on Earth and the distance from Earth to the Moon during the eclipse. High-latitude tracks are broader because sunlight strikes Earth's surface at an oblique angle near the poles (and also because of the projection of the map). The closer the Moon is to Earth during a total eclipse, the wider is the umbra (see Figure 1.24).

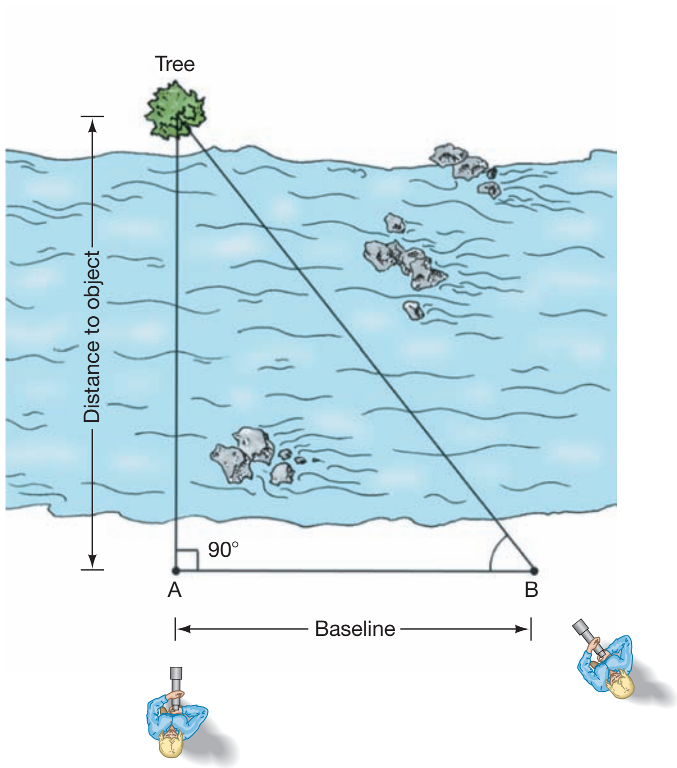
1.6 The Measurement of Distance

We have seen a little of how astronomers track and record the positions of the stars in the sky. But knowing the direction to an object is only part of the information needed to locate it in space. Before we can make a systematic study of the heavens, we must find a way of measuring *distances,* too. One distance-measurement method, called **triangulation**, is based on the principles of Euclidean geometry and finds widespread application today in both terrestrial and astronomical settings. Surveyors use these age-old geometric ideas to measure the distance to faraway objects indirectly. Triangulation forms the foundation of the family of distance-measurement techniques making up the **cosmic distance scale**.

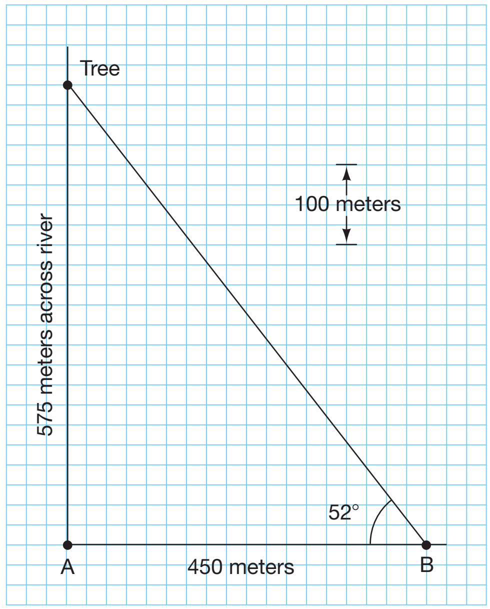
Triangulation and Parallax

Imagine trying to measure the distance to a tree on the other side of a river. The most direct method is to lay a tape across the river, but that's not the simplest way (nor, because of the current, may it even be possible). A smart surveyor would make the measurement by visualizing an *imaginary* triangle (hence *triangulation*), sighting the tree on the far side of the river from two positions on the near side, as illustrated in Figure 1.28. The simplest possible triangle is a right triangle, in which one of the angles is exactly 90°, so it is usually convenient to set up one observation position directly opposite the object, as at point A. The surveyor then moves to another observation position at point B, noting the distance covered between points A and B. This distance is called the **baseline** of the imaginary triangle. Finally, the surveyor, standing at point B, sights toward the tree and notes the angle at point B between this line of sight and the baseline. Knowing the value of one side (AB) and two angles (the right angle at point A and the angle at point B) of the right triangle, the surveyor geometrically constructs the remaining sides and angles and establishes the distance from A to the tree.

To use triangulation to measure distances, a surveyor uses *trigonometry,* the mathematics of geometrical angles and distances. However, even knowing no trigonometry at all, we can still solve the problem by graphical means, as shown in Figure 1.29. Suppose that we pace off the baseline AB, measuring it to be 450 meters, and measure the angle between the



▲ **FIGURE 1.28 Triangulation** Surveyors often use simple geometry and trigonometry to estimate the distance to a faraway object by triangulation. By measuring the angles at A and B and the length of the baseline, the distance can be calculated without the need for direct measurement.



▲ **FIGURE 1.29 Geometric Scaling** Not even trigonometry is needed to estimate distances indirectly. Scaled estimates, like this one on a piece of graph paper, often suffice.

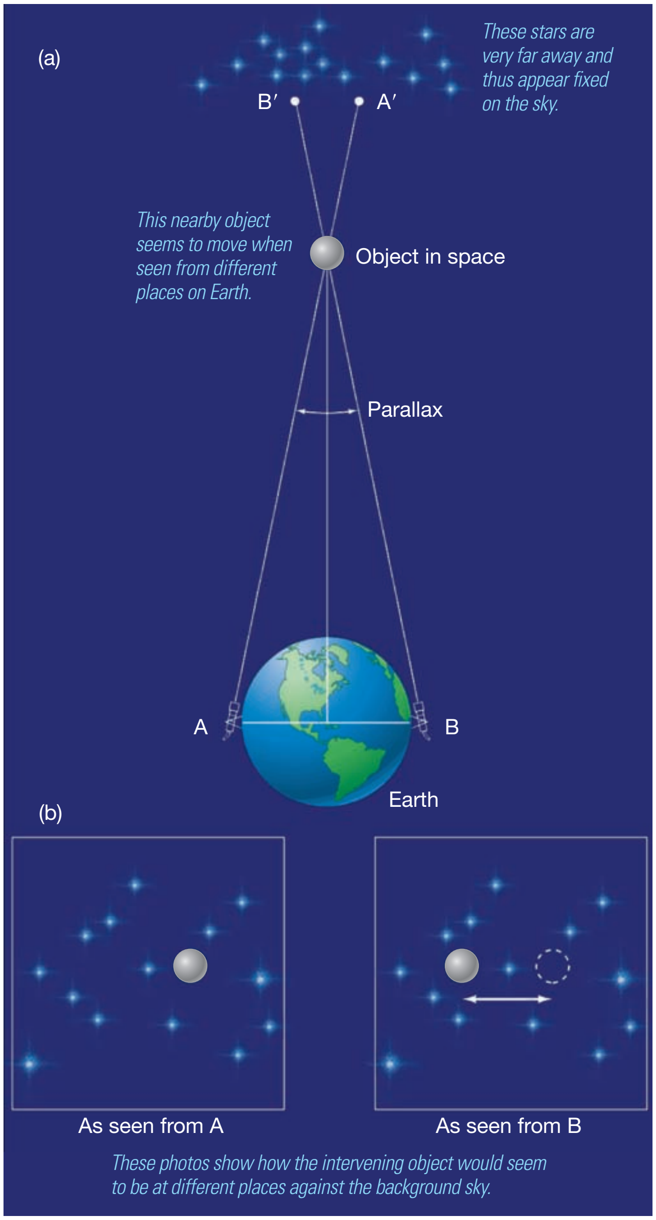
baseline and the line from B to the tree to be 52°, as illustrated in the figure. We can transfer the problem to paper by letting one box on our graph represent 25 meters on the ground. Drawing the line AB on paper and completing the other two sides of the triangle, at angles of 90° (at A) and 52° (at B), we measure the distance on paper from A to the tree to be 23 boxes—that is, 575 meters. We have solved the real problem by *modeling* it on paper. The point to remember here is this: Nothing more complex than basic geometry is needed to infer the distance, the size, and even the shape of an object that is too far away or inaccessible for direct measurement.

Obviously, for a fixed baseline the triangle becomes longer and narrower as the tree's distance from A increases. Narrow triangles cause problems, because it becomes hard to measure the angles at A and B with sufficient accuracy. The measurements can be made easier by "fattening" the triangle—that is, by lengthening the baseline—but there are limits on how long a baseline we can choose in astronomy. For example, consider an imaginary triangle extending from Earth to a nearby object in space, perhaps a neighboring planet. The triangle is now extremely long and narrow, even for a relatively nearby object (by cosmic standards). Figure 1.30(a) illustrates a case in which the longest baseline possible on Earth—Earth's diameter, measured from point A to point B—is used.

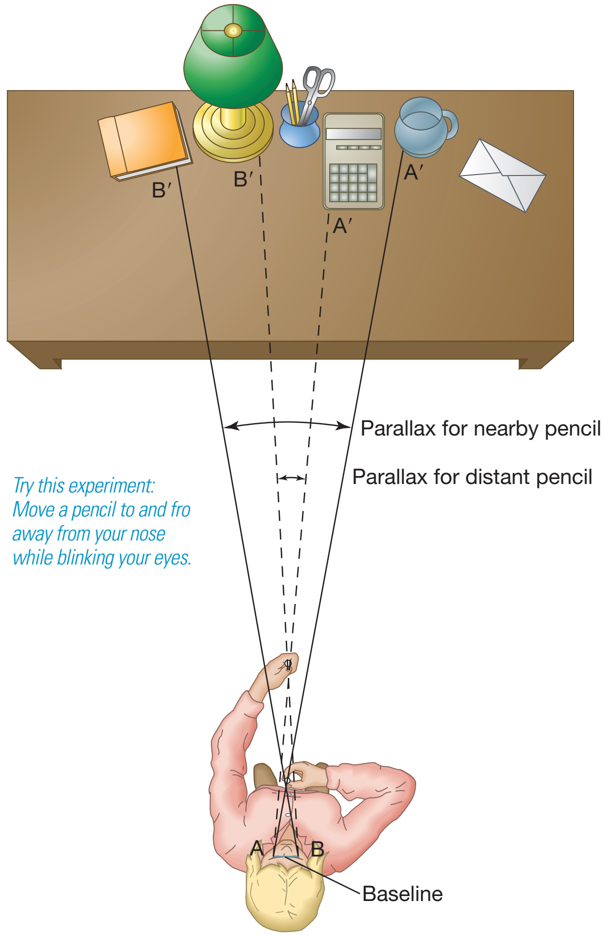
In principle, two observers could sight the planet from opposite sides of Earth, measuring the triangle's angles at A and B. However, in practice it is easier to measure the third angle of the imaginary triangle. The observers sight toward the planet, taking note of its position *relative to some distant stars* seen on the plane of the sky. The observer at point A sees the planet at apparent location A′ relative to those stars, as indicated in Figure 1.30(a). The observer at B sees the planet at point B′. If each observer takes a photograph of the appropriate region of the sky, the planet will appear at slightly different places in the two images. The planet's position is slightly displaced, or shifted, relative to the field of distant background stars, as shown in Figure 1.30(b). The background stars themselves appear undisplaced because of their much greater distance from the observer.

This apparent displacement of a foreground object relative to the background as the observer's location changes is known as **parallax**. The size of the shift in Figure 1.30(b), measured as an angle on the celestial sphere, is the third, small angle in Figure 1.30(a). In astronomical contexts, the parallax is usually very small. For example, the parallax of a point on the Moon, viewed using a baseline equal to Earth's diameter, is about 2°; the parallax of the planet Venus at closest approach (45 million kilometers), is just 1′ (see *More Precisely 1-2*).

The closer an object is to the observer, the larger is the parallax. Figure 1.31 illustrates how you can see this for yourself. Hold a pencil vertically in front of your nose and concentrate on some far-off object—a distant wall, perhaps.



▲ **FIGURE 1.30 Parallax** (a) An imaginary triangle extending from Earth to a nearby object in space. The group of stars at the top represents a background field of very distant stars. (b) Hypothetical photographs of the same star field showing the nearby object's apparent displacement, or shift, relative to the distant undisplaced stars.



▲ **FIGURE 1.31 Parallax Geometry** Parallax is inversely proportional to an object's distance. An object near your nose has a much larger parallax than an object held at arm's length.

Close one eye, and then open it while closing the other. You should see a large shift in the apparent position of the pencil projected onto the distant wall—a large parallax. In this example, one eye corresponds to point A, the other eye to point B, the distance between your eyeballs to the baseline, the pencil to the planet, and the distant wall to a remote field of stars. Now hold the pencil at arm's length, corresponding to a more distant object (but still not as far away as the even more distant stars). The apparent shift of the pencil will be less. You might even be able to verify that the apparent shift is inversely proportional to the distance to the pencil. By moving the pencil farther away, we are narrowing the triangle and decreasing the parallax (and also making accurate measurement more difficult). If you were to paste the pencil to the wall, corresponding to the case where the object of interest is as far away as the background star field, blinking would produce no apparent shift of the pencil at all.

The amount of parallax is thus inversely proportional to an object's distance. Small parallax implies large distance, and large parallax implies small distance. Knowing the amount of parallax (as an angle) and the length of the baseline, we can easily derive the distance through triangulation. *More Precisely 1-2* explores the connection between angular measure and distance in more detail, showing how we can use elementary geometry to determine both the distances and the dimensions of far away objects.

Surveyors of the land use these simple geometric techniques to map out planet Earth. As surveyors of the sky, astronomers use the same basic principles to chart the universe.

Sizing Up Planet Earth

Now that we have studied some of the tools available to astronomers, let's end the chapter with a classic example of how the scientific method, combined with the basic geometric techniques just described, enabled an early scientist to perform a calculation of truly "global" proportions.

In about 200 B.C., a Greek philosopher named Eratosthenes (276–194 B.C.) used simple geometric reasoning to calculate the size of our planet. He knew that at noon on the first day of summer observers in the city of Syene (now called Aswan) in Egypt saw the Sun pass directly overhead. This was evident from the fact that vertical objects cast no shadows and sunlight reached to the very bottoms of deep wells, as shown in the insets in Figure 1.32. However, at noon of the same day in Alexandria, a city 5000 *stadia* to the north, the Sun was seen to be displaced slightly from the vertical. (The *stadium* was a Greek unit of length, roughly equal to 0.16 km—the modern town of Aswan lies about 780 km, or 490 miles, south of Alexandria.) By measuring the length of the shadow of a vertical stick and applying elementary trigonometry, Eratosthenes determined the angular displacement of the Sun from the vertical at Alexandria to be 7.2°.

What could have caused this discrepancy between the two measurements? It was not the result of measurement error—the same results were obtained every time the observations were repeated. Instead, as illustrated in Figure 1.32, the explanation is simply that Earth's surface is not flat, but *curved*. Our planet is a sphere. Eratosthenes was not the first person to realize that Earth is spherical—the philosopher Aristotle had done that over 100 years earlier (see Section 1.2),—but he was apparently the first to build on this knowledge, combining geometry with direct measurement to infer the size of our planet. Here's how he did it.

Rays of light reaching Earth from a very distant object, such as the Sun, travel almost parallel to one another. Consequently, as shown in the figure, the angle measured at Alexandria between the Sun's rays and the vertical (i.e., the line joining Alexandria to the center of Earth) is equal to the angle between Syene and Alexandria, as seen from Earth's center. (For the sake of clarity, the angle has been exaggerated in the figure.) As discussed in *More Precisely 1-2,* the size of this angle in turn is proportional to the fraction of Earth's circumference that lies between Syene and Alexandria:

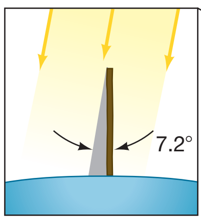
$$\frac{7.2^\circ \text{ (angle between Syene and Alexandria)}}{360^\circ \text{ (circumference of a circle)}} = \frac{5000 \text{ stadia}}{\text{Earth's circumference}}.$$

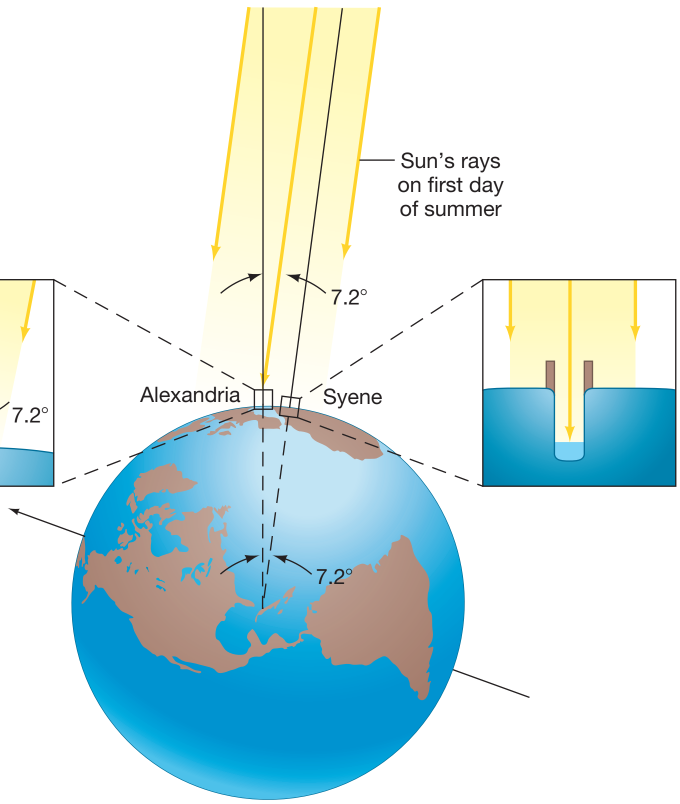
Earth's circumference is therefore 50 × 5000, or 250,000 stadia, or about 40,000 km, so Earth's radius is 250,000/2π stadia, or 6366 km. The correct values for Earth's circumference and radius, now measured accurately by orbiting spacecraft, are 40,070 km and 6378 km, respectively.

Eratosthenes' reasoning was a remarkable accomplishment. More than 20 centuries ago, he estimated the circumference of Earth to within 1 percent accuracy, using only simple geometry and basic scientific reasoning. A person making measurements on only a small portion of Earth's surface was able to compute the size of the entire planet on the basis of observation and pure logic—an early triumph of the scientific method.

CONCEPT Check

✔ Why is elementary geometry essential for measuring distances in astronomy?





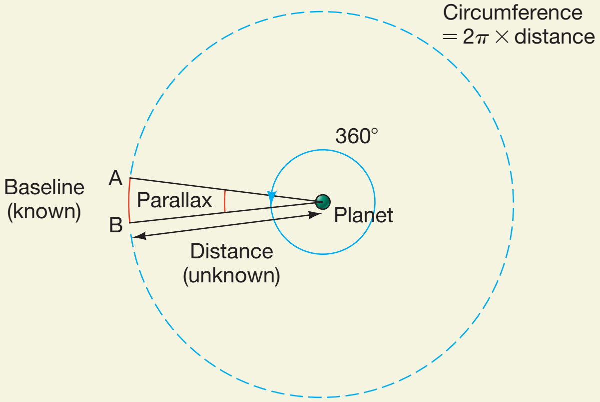
▶ **FIGURE 1.32 Measuring Earth's Radius** The Sun's rays strike different parts of Earth's surface at different angles. The Greek philosopher Eratosthenes realized that the difference was due to Earth's curvature, enabling him to determine Earth's radius by using simple geometry.

MORE PRECISELY 1-2

Measuring Distances with Geometry

Simple geometrical reasoning forms the basis for almost every statement made in this book about size and scale in the universe. In a very real sense, our modern knowledge of the cosmos depends on the elementary mathematics of ancient Greece. Let's take a moment to look in a little more detail at how astronomers use geometry to measure the distances to, and sizes of, objects near and far.

We can convert baselines and parallaxes into distances, and vice versa, by using arguments made by the Greek geometer Euclid. The first figure represents Figure 1.30(a), but we have changed the scale and added the circle centered on the target planet and passing through our baseline on Earth:



To see how the planet's parallax relates to its distance, we note that the ratio of the baseline AB to the circumference of the large circle shown in the figure must be equal to the ratio of the parallax to one full revolution, 360°. Recall that the circumference of a circle is always 2π times its radius (where π—the Greek letter "pi"—is approximately equal to 3.142). Applying this relation to the large circle in the figure, we find that

$$\frac{\text{baseline}}{2\pi \times \text{distance}} = \frac{\text{parallax}}{360°},$$

from which it follows that

$$\text{parallax} = (360°/2\pi) \times \frac{\text{baseline}}{\text{distance}}.$$

The angle $360°/2\pi \approx 57.3°$ in the preceding equation is usually called 1 *radian*.

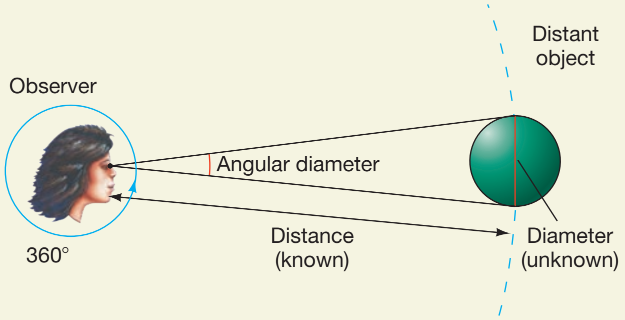
EXAMPLE 1 The planet Venus lies roughly 45,000,000 km from Earth at closest approach. Two observers 13,000 km apart (i.e., at opposite ends of Earth's diameter) looking at the planet would measure a parallax of $57.3° \times (13{,}000\text{ km}/45{,}000{,}000\text{ km}) = 0.017° = 1.0$ arc minutes, as stated in the text.

Alternatively, if we know the parallax (from direct measurement, such as the photographic technique described in Section 1.6), we can rearrange the above equation to tell us the distance to the planet:

$$\text{distance} = \text{baseline} \times \frac{57.3°}{\text{parallax}}.$$

EXAMPLE 2 Two observers 1000 km apart looking at the Moon might measure a parallax of 9.0 arc minutes—that is, 0.15°. It then follows that the distance to the Moon is $1000\text{ km} \times (57.3/0.15) \approx 380{,}000$ km. (More accurate measurements, based on laser ranging using equipment left on the lunar surface by *Apollo* astronauts, yield a mean distance of 384,000 km.)

Knowing the distance to an object, we can determine many other properties. For example, by measuring the object's *angular diameter*—the angle from one side of the object to the other as we view it in the sky—we can compute its size. The second figure illustrates the geometry involved:



Notice that this is basically the same diagram as the previous one, except that now the angle (the angular diameter) and distance are known, instead of the angle (the parallax) and baseline. Exactly the same reasoning as before then allows us to calculate the diameter. We have

$$\frac{\text{diameter}}{2\pi \times \text{distance}} = \frac{\text{angular diameter}}{360},$$

so

$$\text{diameter} = \text{distance} \times \frac{\text{angular diameter}}{57.3°}.$$

EXAMPLE 3 The Moon's angular diameter is measured to be about 31 arc minutes—a little over half a degree. From the preceding discussion, it follows that the Moon's actual diameter is $380{,}000\text{ km} \times (0.52°/57.3°) \approx 3450$ km. A more precise measurement gives 3476 km.

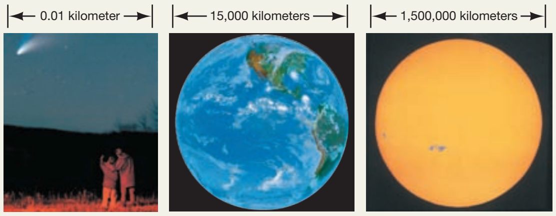
Study the foregoing reasoning carefully. We will use these simple arguments, in various forms, many times throughout this text.

The Big Question Take another look at the spectacular photo at the beginning of this chapter. Contemplate for a moment all those stars—about 100,000,000,000 in our Galaxy alone—of which our Sun is just one. We cannot help wondering: Are there planets around some of those stars, and perhaps intelligent beings on some of those planets? One of the grandest of all unsolved questions in astronomy concerns life on other worlds. No one yet knows the answer, but we will return to this fascinating topic in the last chapter.

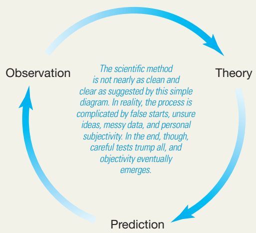
Chapter Review

SUMMARY

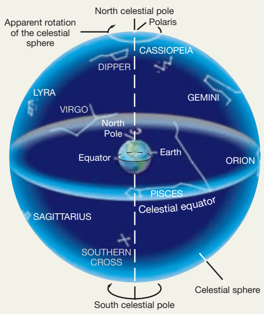
1 The **universe (p. 32)** is the totality of all space, time, matter, and energy. **Astronomy (p. 32)** is the study of the universe. In order of increasing size, the basic constituents of the cosmos are planets, stars, galaxies, galaxy clusters, and the universe itself. They differ enormously in scale—a factor of a billion billion from planet Earth to the entire observable universe.



2 The **scientific method (p. 34)** is a methodical approach employed by scientists to explore the universe around us in an objective manner. A **theory (p. 34)** is a framework of ideas and assumptions used to explain some set of observations and construct **theoretical models (p. 34)** that make predictions about the real world. These predictions in turn are amenable to further observational testing. In this way, the theory expands and science advances.

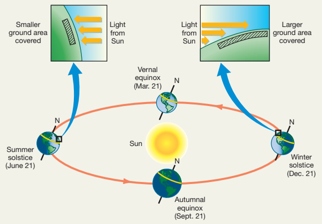


3 Early observers grouped the thousands of stars visible to the naked eye into patterns called **constellations (p. 36),** which they imagined were attached to a vast **celestial sphere (p. 38)** centered on Earth. Constellations have no physical significance, but are still used to label regions of the sky. The points where Earth's axis of rotation intersects the celestial sphere are called the north and south **celestial poles (p. 38)**. The line where Earth's equatorial plane cuts the celestial sphere is the **celestial equator (p. 39)**.

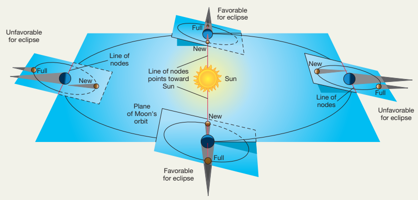


4 The nightly motion of the stars across the sky is the result of Earth's **rotation (p. 38)** on its axis. The time from one noon to the next is called a **solar day (p. 39)**. The time between successive risings of any given star is 1 **sidereal day (p. 39)**. Because of Earth's **revolution (p. 40)** around the Sun, we see different stars at night at different times of the year, and the Sun appears to move relative to the stars. The Sun's apparent yearly path around the celestial sphere (or the plane of Earth's orbit around the Sun) is called the **ecliptic (p. 40)**.

5 We experience **seasons (p. 42)** because Earth's rotation axis is inclined to the ecliptic plane. At the **summer solstice (p. 41)**, the Sun is highest in the sky and the length of the day is greatest. At the **winter solstice (p. 42)**, the Sun is lowest and the day is shortest. At the **vernal (p. 43)** and **autumnal equinoxes (p. 43)**, Earth's axis of rotation is perpendicular to the line joining Earth to the Sun, so day and night are of equal length. Because of **precession (p. 43)**, the slow "wobble" of Earth's axis due to the influence of the Moon, the orientation of Earth's axis changes slowly over time. As a result, the particular constellations visible during any given season change over the course of thousands of years.

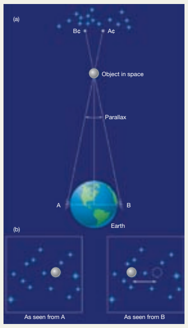


6 The Moon emits no light of its own, but instead shines by reflected sunlight. As the Moon orbits Earth, we see **lunar phases (p. 44)** as the amount of the Moon's sunlit face visible to us varies. A **lunar eclipse (p. 45)** occurs when the Moon enters Earth's shadow.



A **solar eclipse (p. 46)** occurs when the Moon passes between Earth and the Sun. An eclipse may be **total (p. 47)** if the body in question (Moon or Sun) is completely obscured, or **partial (p. 47)** if only a portion of the surface is affected. If the Moon happens to be too far from Earth for its disk to completely hide the Sun, an **annular eclipse (p. 47)** occurs. Because the Moon's orbit around Earth is slightly inclined with respect to the ecliptic, solar and lunar eclipses are relatively rare events.

7 Astronomers use **triangulation (p. 50)** to measure the distances to planets and stars, forming the foundation of the **cosmic distance scale (p. 50)**, the family of distance-measurement techniques used to chart the universe. **Parallax (p. 51)** is the apparent motion of a foreground object relative to a distant background as the observer's position changes. The larger the **baseline (p. 50)**—the distance between the two observation points—the greater is the parallax. The same basic geometric reasoning is used to determine the sizes of objects whose distances are known.



Problems labeled **POS** explore the process of science. **VIS** problems focus on reading and interpreting visual information. **LO** connects to the introduction's numbered Learning Outcomes.

Review and Discussion

1. **LO1** Compare the size of Earth with that of the Sun, the Milky Way Galaxy, and the entire universe.
2. What is the difference between the northern and the southern night sky?
3. **LO2 POS** What is the scientific method, and how does science differ from religion?
4. **LO3** What is a constellation? Why are constellations useful for mapping the sky?
5. How does the Sun rise and set in the North and South Pole?
6. **LO4** How and why does a day measured with respect to the Sun differ from a day measured with respect to the stars?
7. Why do we see different stars at different times of the year?
8. **LO5** Why are there seasons on Earth?
9. What is precession, and what causes it?
10. What causes phases of the Moon?
11. **LO6** What causes a lunar eclipse? A solar eclipse? Why aren't there lunar and solar eclipses every month?
12. **POS** Do you think an observer on another planet in the solar system might see eclipses? Why or why not?
13. What is parallax? Give an everyday example.
14. Explain why the triangulation method forms the foundation of the family of distance-measurement techniques, making up the cosmic distance scale.
15. **LO7** What two pieces of information are needed to determine the diameter of a faraway object?

Conceptual Self-Test: Multiple Choice

1. If Earth rotated twice as fast as it currently does, but its motion around the Sun stayed the same, then **(a)** the night would be twice as long; **(b)** the night would be half as long; **(c)** the year would be half as long; **(d)** the length of the day would be unchanged.
2. Suppose Sun takes 6 hours to move from the eastern horizon to being directly overhead. Assuming that the angle covered is 90 degrees, the Sun moves across the sky at a rate of **(a)** 15 degrees/hour; **(b)** 10 degrees/hour; **(c)** 30 degrees/hour.
3. **VIS** According to Figure 1.15 ("The Zodiac"), in January the Sun is in the constellation **(a)** Cancer; **(b)** Gemini; **(c)** Leo; **(d)** Aquarius.
4. If Earth orbited the Sun in 9 months instead of 12, then, compared with a sidereal day, a solar day would be **(a)** longer; **(b)** shorter; **(c)** unchanged.
5. When a thin crescent of the Moon is visible just before sunrise, the Moon is in its **(a)** waxing phase; **(b)** new phase; **(c)** waning phase; **(d)** quarter phase.
6. If the Moon's orbit were a little larger, solar eclipses would be **(a)** more likely to be annular; **(b)** more likely to be total; **(c)** more frequent; **(d)** unchanged in appearance.
7. The constellations are not used for **(a)** navigating the night; **(b)** demarcating regions of the sky; **(c)** classifying the stars.
8. **VIS** In Figure 1.28 ("Triangulation"), using a longer baseline would result in **(a)** a less accurate distance to the tree; **(b)** a more accurate distance to the tree; **(c)** a smaller angle at point B; **(d)** a greater distance across the river.
9. **VIS** In Figure 1.32 ("Parallax"), a smaller Earth would result in **(a)** a smaller parallax angle; **(b)** a shorter distance measured to the object; **(c)** a larger apparent displacement; **(d)** stars appearing closer together.
10. Today, distances to stars are measured by **(a)** bouncing radar signals; **(b)** reflected laser beams; **(c)** travel time by spacecraft; **(d)** geometry.

Problems

The number of dots preceding each Problem indicates its approximate level of difficulty.

1. • How long does it take for light emitted by **(a)** aircraft at a height of 10 km; **(b)** a satellite at distance of 36000 km; **(c)** Moon at 384,000 km; and **(d)** the Sun at a distance of 150,000,000 km to reach Earth's surface?
2. • **(a)** Write the following numbers in scientific notation (see Appendix 1 if you are unfamiliar with this notation): 1000; 0.000001; 1001; 1,000,000,000,000,000; 123,000; 0.000456. **(b)** Write the following numbers in "normal" numerical form: 3.16×10^7; 2.998×10^5; 6.67×10^{-11}; 2×10^0. **(c)** Calculate: $(2 \times 10^3) + 10^{-2}$; $(1.99 \times 10^{30})/(5.98 \times 10^{24})$; $(3.16 \times 10^7) \times (2.998 \times 10^5)$.
3. • The vernal equinox is now just entering the constellation Aquarius (see Figure 1.15). In what constellation will it lie in A.D. 10,000?
4. • Relative to the stars, through how many degrees, arc minutes, or arc seconds does the Moon move in **(a)** 1 hour of time; **(b)** 1 minute; **(c)** 1 second? How long does it take for the Moon to move a distance equal to its own diameter?
5. • At what distance is an object if its parallax, as measured from either end of a 1000-km baseline, is **(a)** 1°; **(b)** 1′; **(c)** 1″?
6. • Given that the angular size of Venus is 55″ when the planet is 45,000,000 km from Earth, calculate Venus's diameter (in kilometers).
7. • The Moon lies 384,000 km from Earth, and the Sun lies 150,000,000 km away. If both have the same angular size as seen from Earth, how many times larger than the Moon is the Sun?
8. • Estimate the angular diameter of your thumb, held at arm's length.

Activities

Collaborative

1. Measure the nightly and monthly motion of the Moon. On a clear night, sketch a 10°-wide patch of the sky containing the Moon, with the Moon initially toward the wet side of the patch. (See Individual Activity 2 below for how to estimate angles on the sky.) Repeat the observation of the same collection of stars every hour over the course of a night. You will see that the Moon's position relative to the stars changes noticeably even in a few hours. What is the Moon's angular speed (in degrees per hour)? Now observe the Moon at the *same* time each night over the course of a month. Sketch its appearance and note its position on the sky each night. Can you interpret its changing phase in terms of the relative positions of Earth, the Sun, and the Moon? (See Figure 1.20.)

Individual

1. Find the star Polaris, also known as the North Star, in the evening sky. Identify any separate pattern of stars in the same general vicinity of the sky. Wait several hours, at least until after midnight, and then locate Polaris again. Has Polaris moved? What has happened to the nearby pattern of stars? Why?
2. Hold your little finger out at arm's length. Can you cover the disk of the Moon? The Moon projects an angular size of 30′ (half a degree); your finger should more than cover it. You can use this fact to make some basic sky measurements. As a simple rule, your little finger at arm's length is about 1° across, your middle three fingers are about 4° across, and your clenched fist is about 10° across. If the constellation Orion is visible, use this information to estimate the angular size of Orion's belt and the angular distance between Betelgeuse and Rigel. Compare your findings with Figure 1.8(a).

2

The Copernican Revolution

THE BIRTH OF MODERN SCIENCE

Living in the Space Age, we have become accustomed to the modern view of our place in the universe. Images of our planet taken from space leave little doubt that Earth is round, and no one seriously questions the idea that we orbit the Sun. Yet there was a time, not so long ago, when some of our ancestors maintained that Earth was flat and lay at the center of all things.

Our view of the universe—and of ourselves—has undergone a radical transformation since those early days. Earth has become a planet like many others, and humankind has been torn from its throne at the center of the cosmos and relegated to a rather unremarkable position on the periphery of the Milky Way Galaxy. But we have been amply compensated for our loss of prominence: We have gained a wealth of scientific knowledge in the process. The story of how all this came about is the story of the rise of the scientific method and the genesis of modern astronomy.

The Big Picture Exploration is at the heart of the modern scientific method used by all scientists around the world. Ideas must be tested against what is observed in nature, and those ideas that fail the test are discarded. In this way, astronomers progressively generate, not "truth," but better and better approximations of reality.

LEFT: In this colorized piece of historical artwork, a young Nicholas Copernicus is observing a lunar eclipse in Rome in the year 1500. He is not actually using a telescope, which would not be invented for another century; rather, he is looking along a transit device that improved naked-eye estimates of angular sizes. Perhaps more than anyone else, this Polish astronomer began the revolution that overthrew more than a thousand years of philosophical thinking that claimed Earth to be the immovable center of all things. (S. Terry; engraving from the 1875 edition of *Vies des Savants Illustres*)

Learning Outcomes

Studying this chapter will enable you to

1. Describe how some ancient civilizations attempted to explain the heavens in terms of Earth-centered models of the universe.
2. Explain how the observed motions of the planets led to our modern view of a Sun-centered solar system.
3. Describe the major contributions of Galileo and Kepler to our understanding of the solar system.
4. State Kepler's laws of planetary motion.
5. Explain how astronomers have measured the true size of the solar system.
6. State Newton's laws of motion and universal gravitation and explain how they account for Kepler's laws.
7. Explain how the law of gravitation enables us to measure the masses of astronomical bodies.

2.1 Ancient Astronomy

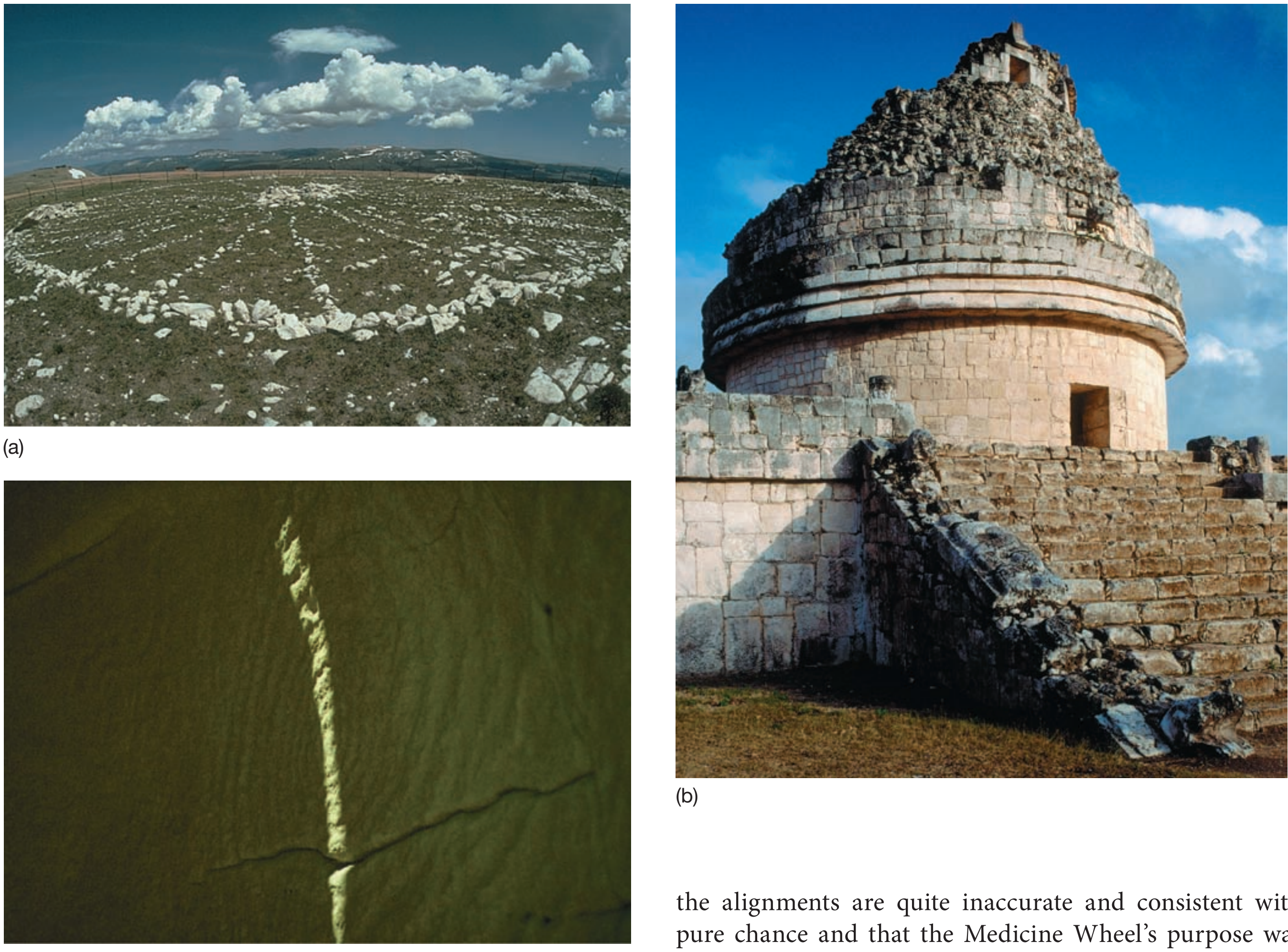
Many ancient cultures took a keen interest in the changing nighttime sky. The records and artifacts that have survived until the present make that abundantly clear. But unlike today, the major driving force behind the development of astronomy in those early societies was probably neither scientific nor religious. Instead, it was decidedly practical and down to earth. Seafarers needed to navigate their vessels, and farmers had to know when to plant their crops. In a real sense, then, human survival depended on knowledge of the heavens. The ability to predict accurately the arrival of the seasons, as well as other astronomical events, was undoubtedly a highly prized, perhaps jealously guarded, skill.

In Chapter 1, we saw that the human mind's ability to perceive patterns in the stars led to the "invention" of constellations as a convenient means of labeling regions of the celestial sphere. ∞ (Sec. 1.3) The realization that these patterns returned to the night sky at the same time each year met the need for a practical means of tracking the seasons. Widely separated cultures all over the world built elaborate structures to serve, at least in part, as primitive calendars. Often the keepers of the secrets of the sky enshrined their knowledge in myth and ritual, and these astronomical sites were also used for religious ceremonies.

Perhaps the best-known such site is *Stonehenge*, located on Salisbury Plain in England, and shown in Figure 2.1. This ancient stone circle, which today is one of the most popular tourist attractions in Britain, dates from the Stone Age. Researchers think it was an early astronomical observatory of sorts—not in the modern sense of the term (a place for making new observations and discoveries pertaining to the heavens)—but rather a kind of three-dimensional calendar or almanac, enabling its builders and their descendants to identify important dates by means of specific celestial events. Its construction apparently spanned a period of about 17 centuries, beginning around 2800 B.C. Additions and modifications continued to about 1100 B.C., indicating its ongoing importance to the Stone Age and, later, Bronze Age people who built, maintained, and used Stonehenge. The largest stones shown in Figure 2.1 weigh up to 50 tons and were transported from quarries many miles away.

Many of the stones are aligned so that they point toward important astronomical events. For example, the line joining the center of the inner circle to the so-called heel stone, set off some distance from the rest of the structure, points in the direction of the rising Sun on the summer solstice. Other alignments are related to the rising and setting of the Sun and the Moon at other times of the year. The accurate alignments (within a degree or so) of the stones of Stonehenge were first noted in the 18th century, but it was only relatively recently—in the second half of the 20th century, in fact—that the scientific community began to credit Stone Age technology with the ability to carry out such a precise feat of engineering. Although some of Stonehenge's purposes remain uncertain and controversial, the site's function as an astronomical almanac seems well established. Although Stonehenge is the most impressive and the best preserved, other stone circles, found all over Europe, are thought to have performed similar functions.

◀ **FIGURE 2.1 Stonehenge** This remarkable site in the south of England was probably constructed as a primitive calendar or almanac. The inset shows sunrise at Stonehenge at the summer solstice. As seen from the center of the stone circle, the Sun rose directly over the "heel stone" on the longest day of the year. *(S. Pitamitz/Superstock; inset D. Nunuk/All Canada Photos/Superstock)*



(a)

(b)

(c)

▲ **FIGURE 2.2 Observatories in the Americas** (a) The Big Horn Medicine Wheel in Wyoming, built by the Plains Indians, has spokes and other features that roughly align with risings and settings of the Sun and other stars. (b) The Caracol temple in Mexico, built by the Mayan civilization, has some windows that seem to align with astronomical events, suggesting that at least part of Caracol's function may have kept track of the seasons and the heavens. (c) This thin streak of light and shadow, created by the Sun's rays playing off the cliffs in Chaco Canyon of America's Southwest, aligns exactly with a carved rock pattern at noon on the summer solstice—almost certainly an intentional sign for astronomical or agricultural purposes. *(G. Gerster; H. Lapahie Jr; F1online Digitale Bildagentur)*

Many North American cultures were interested in the heavens. The Big Horn Medicine Wheel in Wyoming (Figure 2.2a) is similar to Stonehenge in design—and, perhaps, intent—although it is somewhat simpler in execution. Some researchers have identified alignments between the Medicine Wheel's spokes and the rising and setting Sun at solstices and equinoxes, and with some bright stars, suggesting that its builders—the Plains Indians—had much more than a passing familiarity with the changing nighttime sky. Other experts disagree, however, arguing that the alignments are quite inaccurate and consistent with pure chance and that the Medicine Wheel's purpose was more likely symbolic, rather than practical. A similar controversy swirls around the Caracol temple (Figure 2.2b) in the famous Mayan city of Chitzen Itza, built around A.D. 1000 on Mexico's Yucatán peninsula. Was it an observatory, as some suggest, perhaps tied to human sacrifices when Venus appeared in the morning or evening sky? Or are the claimed alignments of its windows just wishful thinking and the temple's purpose simply religious, rather than astronomical?

Experts do seem to agree—for now, at least—that the Sun Dagger (Figure 2.2c), in Chaco Canyon, New Mexico, is a genuine astronomical calendar. It is constructed so that the sliver of light passes precisely through the center of the carved stone spiral at noon on the summer solstice. Numerous similar sites have been found throughout the American Southwest.

The ancient Chinese also observed the heavens. Their astrology attached particular importance to "omens" such as comets and "guest stars"—stars that appeared suddenly in the sky and then slowly faded away—and they kept careful and extensive records of such events. Twentieth-century astronomers still turn to the Chinese records to obtain observational data recorded during the Dark Ages (roughly from the 5th to the 10th century A.D.), when turmoil in Europe

▲ **FIGURE 2.3 Persian Astronomers at Work** During the Dark Ages, much scientific information was preserved and new discoveries were made by astronomers in the Islamic world, as depicted in this illustration from a 16th-century manuscript. *(Bridgeman Art Library)*

largely halted the progress of Western science. Perhaps the best-known guest star was one that appeared in A.D. 1054 and was visible in the daytime sky for many months. We now know that the event was actually a *supernova:* the explosion of a giant star, which scattered most of its mass into space (see Chapter 21). It left behind a remnant that is still detectable today, nine centuries later. The Chinese data are a prime source of historical information for supernova research.

A vital link between the astronomy of ancient Greece and that of medieval Europe was provided by astronomers in the Muslim world (see Figure 2.3). For six centuries, from the depths of the Dark Ages to the beginning of the Renaissance, Islamic astronomy flourished and grew, preserving and augmenting the knowledge of the Greeks. Its influence on modern astronomy is subtle, but widespread. Many of the mathematical techniques involved in trigonometry were developed by Islamic astronomers in response to practical problems, such as determining the precise dates of holy days or the direction of Mecca from any given location on Earth. Astronomical terms such as *zenith* and *azimuth* and the names of many stars—for example, Rigel, Betelgeuse, and Vega—all bear witness to this extended period of Muslim scholarship.

Astronomy is not the property of any one culture, civilization, or era. The same ideas, the same tools, and even the same misconceptions have been invented and reinvented by human societies all over the world in response to the same basic driving forces. Astronomy came into being because people knew that there was a practical benefit in being able to predict the positions of the stars, but its roots go much deeper than that. The need to understand where we came from and how we fit into the cosmos is an integral part of human nature.

2.2 The Geocentric Universe

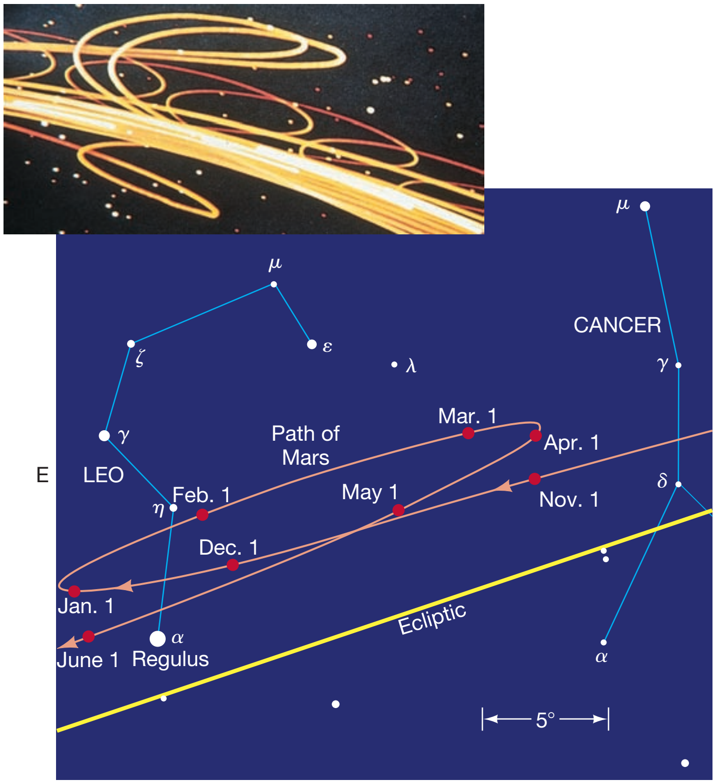
The Greeks of antiquity, and undoubtedly civilizations before them, built models of the universe. The study of the workings of the universe on the largest scales is called *cosmology*. Today, cosmology entails looking at the universe on scales so large that even entire galaxies can be regarded as mere points of light scattered throughout space. To the Greeks, however, the universe was basically the *solar system*—the Sun, Earth, and Moon, and the planets known at that time. The stars beyond were surely part of the universe, but they were considered to be fixed, unchanging beacons on the celestial sphere. The Greeks did not consider the Sun, the Moon, and the planets to be part of this mammoth celestial dome, however. Those objects had patterns of behavior that set them apart.

Observations of the Planets

Greek astronomers observed that over the course of a night, the stars slid smoothly across the sky. Over the course of a month, the Moon moved smoothly and steadily along its path on the sky relative to the stars, passing through its familiar cycle of phases. Over the course of a year, the Sun progressed along the ecliptic at an almost constant rate, varying little in brightness from day to day. In short, the behavior of both Sun and Moon seemed fairly simple and orderly. But ancient astronomers were also aware of five other bodies in the sky—the planets Mercury, Venus, Mars, Jupiter, and Saturn—whose behavior was not so easy to grasp. Their motions ultimately led to the downfall of an entire theory of the solar system and to a fundamental change in humankind's view of the universe.

To the naked eye (or even through a telescope), planets do not behave in as regular and predictable a fashion as the Sun, Moon, and stars. They vary in brightness, and they don't maintain a fixed position in the sky. Unlike the Sun and Moon, the planets seem to wander around the celestial

Motions of the planets relative to the stars produce continuous streaks on a planetarium "sky."



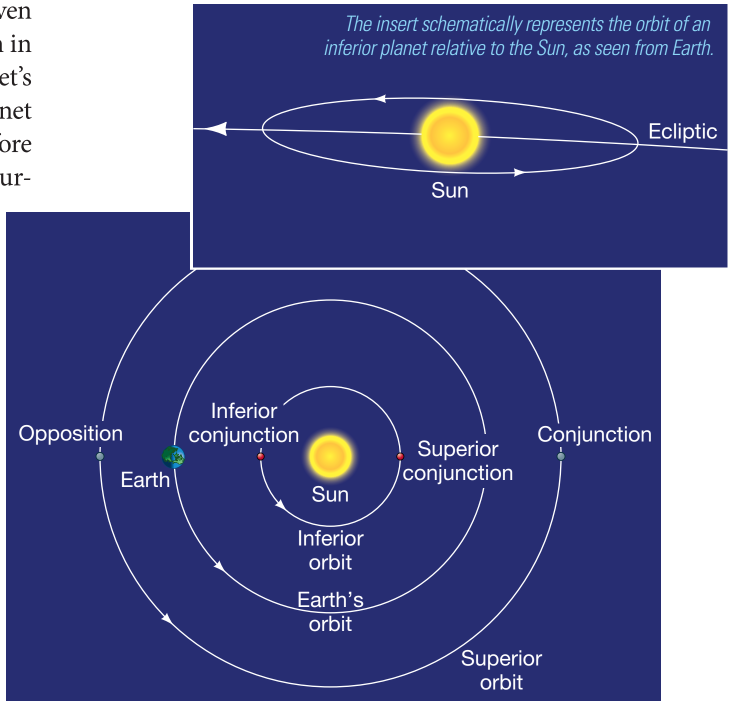
Observed planet motions can be complicated because each planet travels with a different speed around the Sun.

◀ **FIGURE 2.4 Planetary Motion** Most of the time, planets move from west to east relative to the background stars. Occasionally—roughly once per year—they change direction and temporarily undergo retrograde motion (east to west) before looping back. The main illustration shows an actual retrograde loop in the motion of the planet Mars. The inset depicts the movements of several planets over the course of several years, as reproduced on the inside dome of a planetarium. *(Boston Museum of Science)*

sphere—indeed, the word *planet* derives from the Greek word *planetes*, meaning "wanderer." Planets never stray far from the ecliptic and generally traverse the celestial sphere from west to east, like the Sun. However, they seem to speed up and slow down during their journeys, and at times they even appear to loop back and forth relative to the stars, as shown in Figure 2.4. In other words, there are periods when a planet's eastward motion (relative to the stars) stops, and the planet appears to move westward in the sky for a month or two before reversing direction again and continuing on its eastward journey. Motion in the eastward sense is usually referred to as *direct*, or *prograde*, motion; the backward (westward) loops are known as **retrograde motion**.

Ancient astronomers knew well that the periods of retrograde motion were closely correlated with other planetary properties, such as apparent brightness and position in the sky. Figure 2.5 (a modern view of the solar system, note!) shows three schematic planetary orbits and defines some time-honored astronomical terminology describing a planet's location relative to Earth and the Sun. Mercury and Venus are referred to as *inferior* ("lower") *planets* because their orbits lie between Earth and the Sun. Mars, Jupiter, and Saturn, whose orbits lie outside Earth's, are known as *superior* ("higher") *planets*. For early astronomers, the key observations of planetary orbits were the following:

- An inferior planet never strays too far from the Sun, as seen from Earth. As illustrated in the inset to Figure 2.5, because its path on the celestial sphere is close to the ecliptic, an inferior planet makes two *conjunctions* (or close approaches) with the Sun during each orbit. (It doesn't actually come close to the Sun, of course. Conjunction is simply the occasion when the planet and the Sun are in the same direction in the sky.) At *inferior conjunction*, the planet is closest to Earth and moves past the Sun from east to west—that is, in the retrograde



▶ **FIGURE 2.5 Inferior and Superior Orbits** Diagram of Earth's orbit and two other possible planetary orbits. An "inferior" orbit lies between Earth's orbit and the Sun. Mercury and Venus move in such orbits. A "superior" orbit (such as the orbit of Mars, Jupiter, or Saturn) lies outside that of Earth. The points noted on the orbits indicate times when a planet appears to come close to the Sun (conjunction) or is diametrically opposite the Sun on the celestial sphere (opposition).

sense. At *superior conjunction*, the planet is farthest from Earth and passes the Sun in the opposite (prograde) direction.

- Seen from Earth, the superior planets are not "tied" to the Sun as the inferior planets are. The superior planets make one prograde conjunction with the Sun during each trip around the celestial sphere. However, they exhibit retrograde motion (Figure 2.4) when they are at *opposition*, diametrically opposite the Sun on the celestial sphere.
- The superior planets are brightest at opposition, during retrograde motion. By contrast, the inferior planets are brightest a few weeks before and after inferior conjunction.

The challenge facing astronomers—then as now—was to find a solar system model that could explain all the existing observations and that could also make testable and reliable predictions of future planetary motions. ∞ (Sec. 1.2)

Ancient astronomers correctly reasoned that the changing brightness of a planet in the night sky is related to the planet's distance from Earth. Like the Moon, the planets produce no light of their own. Instead, they shine by reflected sunlight and, generally speaking, appear brightest when closest to us. Looking at Figure 2.5, you may already be able to discern the basic reasons for some of the planetary properties just listed; we'll return to the "modern" explanation in the next section. However, as we now discuss, the ancients took a very different path in their attempts to explain planetary motion.

A Theoretical Model

The earliest models of the solar system followed the teachings of the Greek philosopher Aristotle (384–322 B.C.) and were **geocentric**, meaning that Earth lay at the center of the universe and all other bodies moved around it. ∞ (Sec. 1.3) The celestial sphere, shown in Figures 1.11 and 1.16, illustrates the basic geocentric view. These models employed what Aristotle, and Plato before him, had taught was the perfect form: the circle. The simplest possible description—uniform motion around a circle with Earth at its center—provided a fairly good approximation to the orbits of the Sun and the Moon, but it could not account for the observed variations in planetary brightness or the retrograde motion of the planets. A more complex model was needed to describe these heavenly "wanderers."

In the first step toward this new model, each planet was taken to move uniformly around a small circle, called an **epicycle**, whose *center* moved uniformly around Earth on a second and larger circle, known as a **deferent** (Figure 2.6). The motion was now composed of two separate circular orbits, creating the possibility that, at some times, the planet's apparent motion could be retrograde. Also, the distance from the planet to Earth would vary, accounting for changes

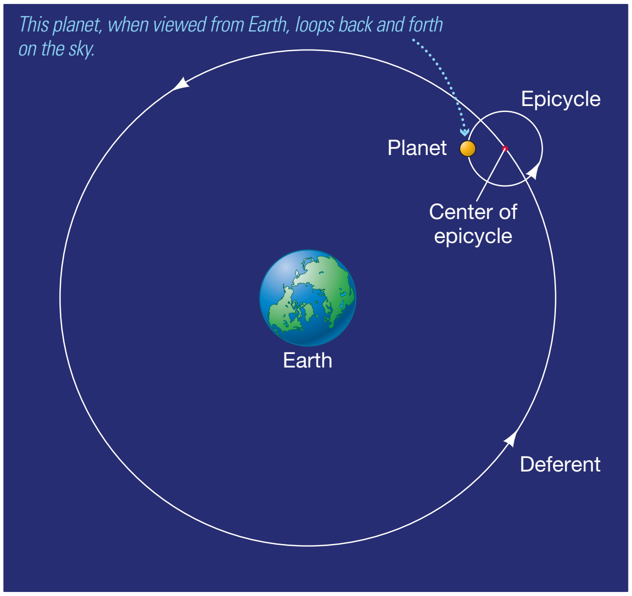
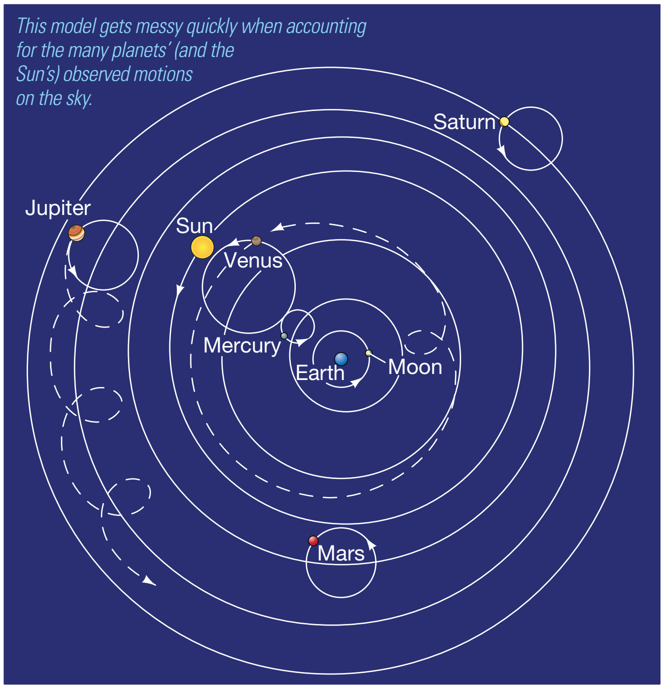


FIGURE 2.6 Geocentric Model In the geocentric model of the solar system, the observed motions of the planets made it impossible to assume that they moved on simple circular paths around Earth. Instead, each planet was thought to follow a small circular orbit (the epicycle) about an imaginary point that itself traveled in a large, circular orbit (the deferent) about Earth.

in brightness. By tinkering with the relative sizes of the epicycle and deferent, with the planet's speed on the epicycle, and with the epicycle's speed along the deferent, early astronomers were able to bring this "epicyclic" motion into fairly good agreement with the observed paths of the planets in the sky. Moreover, the model had good predictive power, at least to the accuracy of observations at the time.

However, as the number and the quality of observations increased, it became clear that the simple epicyclic model was not perfect. Small corrections had to be introduced to bring it into line with new observations. The center of the deferents had to be shifted slightly from Earth's center, and the motion of the epicycles had to be imagined uniform with respect to yet another point in space, not Earth. Furthermore, in order to explain the motions of the inferior planets, the model simply had to assume that the deferents of Mercury and Venus were, for some (unknown) reason, tied to that of the Sun. Similar assumptions also applied to the superior planets, to ensure that their retrograde motion occurred at opposition.

Around A.D. 140, a Greek astronomer named Ptolemy constructed perhaps the most complete geocentric model of all time. Illustrated in simplified form in Figure 2.7, it explained remarkably well the observed paths of the five planets then known, as well as the paths of the Sun and the Moon. However, to achieve its explanatory and predictive power, the full **Ptolemaic model** required a series of no fewer than 80 distinct circles. To account for the paths of the



▲ **FIGURE 2.7 Ptolemaic Model** The basic features, drawn roughly to scale, of Ptolemy's geocentric model of the inner solar system, a model that enjoyed widespread popularity prior to the Renaissance. Only the five planets visible to the naked eye and hence known to the ancients—Mercury, Venus, Mars, Jupiter, and Saturn—are shown. To avoid confusion, partial paths (dashed) of only two planets—Venus and Jupiter—are drawn here.

Sun, Moon, and all eight planets (and their moons) that we know today would require a vastly more complicated set. Nevertheless, Ptolemy's comprehensive text on the topic, *Syntaxis* (better known today by its Arabic name, *Almagest*, "the greatest"), provided the intellectual framework for all discussion of the universe for well over a thousand years.

Evaluating the Geocentric Model

Today, our scientific training leads us to seek simplicity, because, in the physical sciences, simplicity has so often proved to be an indicator of truth. We would regard the intricacy of a model as complicated as the Ptolemaic system as a clear sign of a fundamentally flawed theory. ∞ (Sec. 1.2) Why was the Ptolemaic model so complex? With the benefit of hindsight, we now recognize that its major error lay in its assumption of a geocentric universe. This misconception was compounded by the insistence on uniform circular motion, whose basis was largely philosophical, rather than scientific, in nature.

Actually, history records that some ancient Greek astronomers reasoned differently about the motions of heavenly bodies. Foremost among them was Aristarchus of Samos (310–230 B.C.), who proposed that all the planets, including Earth, revolve around the Sun and, furthermore, that Earth rotates on its axis once each day. This combined revolution and rotation, he argued, would create an *apparent* motion of the sky—a simple idea that is familiar to anyone who has ridden on a merry-go-round and watched the landscape appear to move past in the opposite direction. However, Aristarchus's description of the heavens, though essentially correct, did not gain widespread acceptance during his lifetime. Aristotle's influence was too strong, his followers too numerous, and his writings too comprehensive. The geocentric model went largely unchallenged until the 16th century A.D.

The Aristotelian school did present some simple and (at the time) compelling arguments in favor of their views. First, of course, Earth doesn't *feel* as if it's moving—and if it were moving, wouldn't there be a strong wind as the planet revolves at high speed around the Sun? Also, considering that the vantage point from which we view the stars changes over the course of a year, why don't we see stellar parallax? ∞ (Sec. 1.4)

Nowadays we might dismiss the first points as merely naive, but the last is a valid argument and the reasoning essentially sound. Indeed, we now know that there *is* stellar parallax as Earth orbits the Sun. However, because the stars are so distant, it amounts to less than 1 arc second (1′), even for the closest stars. Early astronomers simply would not have noticed it. (In fact, stellar parallax was conclusively measured only in the middle of the 19th century.)

We will encounter many other instances in astronomy wherein correct reasoning led to the wrong conclusions because it relied on inadequate data. Even when the scientific method is properly applied and theoretical predictions are tested against reality, a theory can be only as good as the observations on which it is based. ∞ (Sec. 1.2)

2.3 The Heliocentric Model of the Solar System

The Ptolemaic picture of the universe survived, more or less intact, for almost 14 centuries, until a 16th-century Polish cleric, Nicolaus Copernicus (Figure 2.8), rediscovered Aristarchus's **heliocentric** (Sun-centered) model and showed how, in its harmony and organization, it provided a more natural explanation of the observed facts than did the tangled geocentric cosmology. Copernicus asserted that Earth spins on its axis and, like the other planets, orbits the Sun. Only the Moon, he said, orbits Earth. As we will see, not only does this model explain the observed daily and seasonal changes in the heavens, but it also naturally accounts for retrograde motion and variations in brightness of the planets. ∞ (Sec. 1.4)

The critical realization that Earth is not at the center of the universe is now known as the **Copernican revolution**. The seven crucial statements that form its foundation are summarized in *Discovery 2-1*.

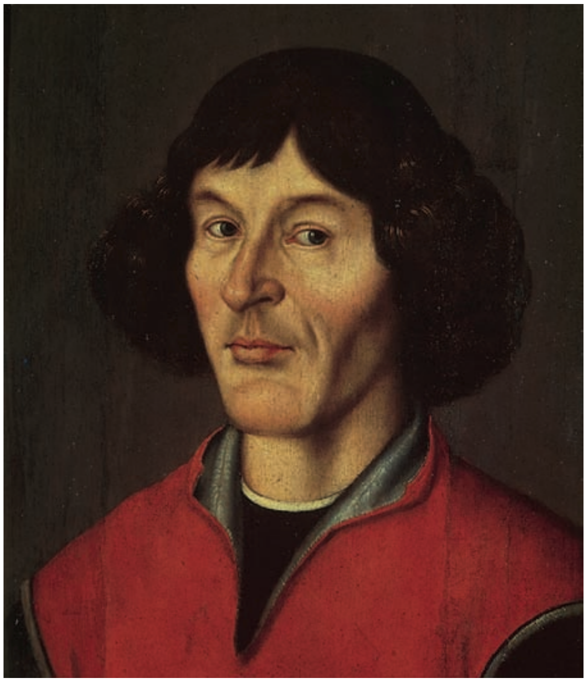
DISCOVERY 2-1

Foundations of the Copernican Revolution

The following seven points are essentially Copernicus's own words, with the italicized material providing additional explanation:

1. The celestial spheres do not have just one common center. *Specifically, Earth is not at the center of everything.*
2. The center of Earth is not the center of the universe, but is instead only the center of gravity and of the lunar orbit.
3. All the spheres revolve around the Sun. *By spheres, Copernicus meant the planets.*
4. The ratio of Earth's distance from the Sun to the height of the firmament is so much smaller than the ratio of Earth's radius to the distance to the Sun that the distance to the Sun is imperceptible compared with the height of the firmament. *By firmament, Copernicus meant the distant stars. The point he was making is that the stars are very much farther away than the Sun.*
5. The motions appearing in the firmament are not its motions, but those of Earth. Earth performs a daily rotation around its fixed poles, while the firmament remains immobile as the highest heaven. *Because the stars are so far away, any apparent motion we see in them is the result of Earth's rotation.*
6. The motions of the Sun are not its motions, but the motion of Earth. *Similarly, the Sun's apparent daily and yearly motion are actually due to the various motions of Earth.*
7. What appears to us as retrograde and forward motion of the planets is not their own, but that of Earth. *The heliocentric picture provides a natural explanation for retrograde planetary motion, again as a consequence of Earth's motion.*

Figure 2.9 shows how the Copernican view explains the varying brightness of a planet (in this case, Mars), its observed looping motions, and the fact that the retrograde motion of a superior planet occurs at opposition. If we suppose that Earth moves faster than Mars, then every so often Earth "overtakes" that planet. Mars will then appear to move backward in the sky, in much the same way as a car we overtake on the highway seems to slip backward relative to us. Replace Mars by Earth and Earth by Venus, and you should also be able to extend the explanation to the inferior planets. (To complete the story with a full explanation of their apparent brightnesses, however, you'll have to wait until Section 9.1!) Notice that, in the Copernican picture, the planet's looping motions are only apparent. In the Ptolemaic view, they are real.



▲ **FIGURE 2.8 Nicolaus Copernicus (1473–1543).** *(E. Lessing/Art Resource, NY)*

Copernicus's major motivation for introducing the heliocentric model was simplicity. Even so, he was still influenced by Greek thinking and clung to the idea of circles to model the planets' motions. To bring his theory into agreement with observations of the night sky, he was forced to retain the idea of epicyclic motion, although with the deferent centered on the Sun rather than on Earth and with smaller epicycles than in the Ptolemaic picture. Thus, he retained unnecessary complexity and actually gained little in predictive power over the geocentric model. The heliocentric model did rectify some small discrepancies and inconsistencies in the Ptolemaic system, but for Copernicus, the primary attraction of heliocentricity was its simplicity—its being "more pleasing to the mind." His theory was more something he *felt* than he could *prove*. To the present day, scientists still are guided by simplicity, symmetry, and beauty in modeling all aspects of the universe.

Despite the support of some observational data, neither his fellow scholars nor the general public easily accepted Copernicus's model. For the learned, heliocentricity went against the grain of much previous thinking and violated many of the religious teachings of the time, largely because it relegated Earth to a noncentral and undistinguished place within the solar system and the universe. And Copernicus's work had little impact on the general populace of his time, at least in part because it was published in Latin (the standard language of academic discourse at the time), which most people could not read. Only long after Copernicus's death, when others—notably Galileo Galilei—popularized his ideas, did the Roman Catholic Church take them seriously enough to

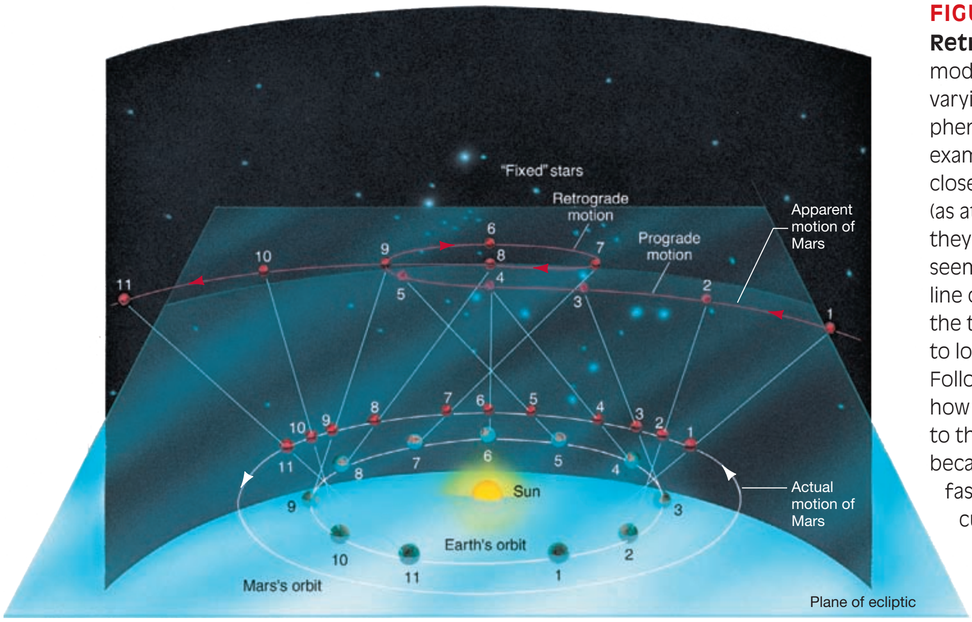


FIGURE 2.9
Retrograde Motion The Copernican model of the solar system explains both the varying brightnesses of the planets and the phenomenon of retrograde motion. Here, for example, when Earth and Mars are relatively close to one another in their respective orbits (as at position 6), Mars seems brighter. When they are farther apart (as at position 1), Mars seems dimmer. Also, because the (light blue) line of sight from Earth to Mars changes as the two planets orbit the Sun, Mars appears to loop back and forth in retrograde motion. Follow the lines in numerical order, and note how the line of sight moves backward relative to the stars between locations 5 and 7. That's because Earth, on the inside track, moves faster in its orbit than does Mars. The white curves are actual planetary orbits; the red curve is Mars's motion as seen from Earth.

bother banning them. Copernicus's writings on the heliocentric universe were placed on the Church's *Index of Prohibited Books* in 1616, 73 years after they were first published. They remained there until the end of the 18th century.

CONCEPT Check

✔ How do the geocentric and heliocentric models of the solar system differ in their explanations of planetary retrograde motion?

2.4 The Birth of Modern Astronomy

In the century following the death of Copernicus and the publication of his theory of the solar system, two scientists—Galileo Galilei and Johannes Kepler—made indelible imprints on the study of astronomy. Contemporaries, they were aware of each other's work and corresponded from time to time about their theories. Each achieved fame for his discoveries and made great strides in popularizing the Copernican viewpoint, yet in their approaches to astronomy they were as different as night and day.

Galileo's Historic Observations

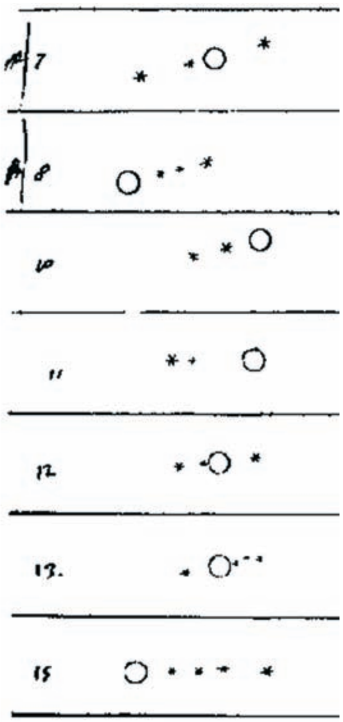
Galileo Galilei (Figure 2.10) was an Italian mathematician and philosopher. By his willingness to perform experiments to test his ideas—a rather radical approach in those days—and by embracing the brand-new technology of the telescope, he revolutionized the way in which science was done, so much so that he is now widely regarded as the father of experimental science.

▲ **FIGURE 2.10** **Galileo Galilei (1564–1642).** *(Art Resource, NY)*

The telescope was invented in Holland in the early 17th century. Hearing of the invention (but without having seen one), Galileo built a telescope for himself in 1609 and aimed it at the sky. What he saw conflicted greatly with the philosophy of Aristotle and provided much new data to support the ideas of Copernicus.*

Using his telescope, Galileo discovered that the Moon had mountains, valleys, and craters—terrain in many ways

**In fact, Galileo had already abandoned Aristotle in favor of Copernicus, although he had not published his opinions at the time he began his telescopic observations.*



The asterisks show the positions of the moons, now called Io, Europa, Ganymede, and Callisto, around Jupiter (open circle).

▲ **FIGURE 2.11 Galilean Moons** The four Galilean moons of Jupiter, as sketched by Galileo in his notebook on 7 nights between January 7 and 15, 1610. More of Galileo's remarkable sketches of Saturn, star clusters, and the Orion constellation can be seen on the first page of Part 1. (*From* Sidereus Nuncius)

reminiscent of that on Earth. Looking at the Sun (something that should *never* be done directly and that may have eventually blinded Galileo), he found imperfections—dark blemishes now known as *sunspots*. These observations ran directly counter to the orthodox wisdom of the day. By noting the changing appearance of sunspots from day to day, Galileo inferred that the Sun *rotates*, approximately once per month, around an axis roughly perpendicular to the ecliptic plane.

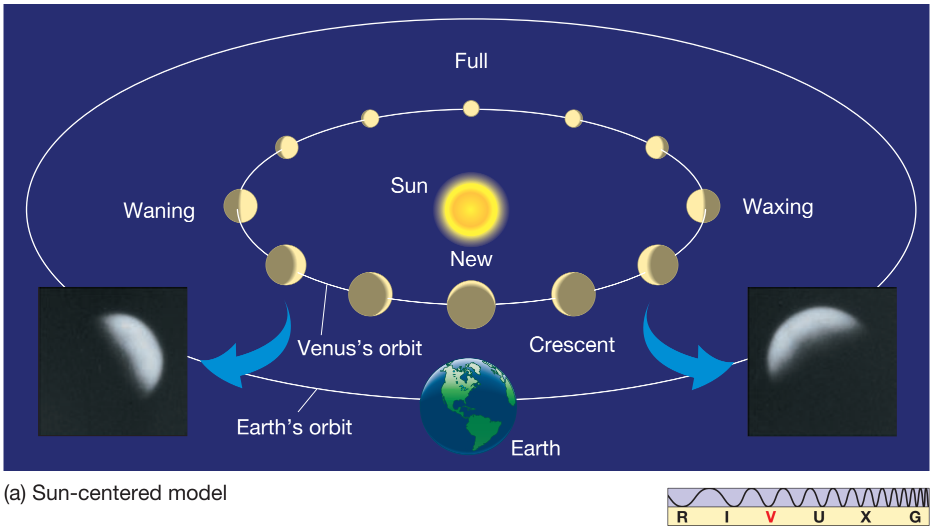
Galileo also saw four small points of light, invisible to the naked eye, orbiting the planet Jupiter and realized that they were moons. Figure 2.11 shows some sketches of these moons, taken from Galileo's notes. To Galileo, the fact that another planet had moons provided the strongest support for the Copernican model. Clearly, Earth was not the center of all things. He also found that Venus varied in apparent size and showed a complete cycle of phases, like those of our Moon (Figure 2.12), findings that could be explained only by the planet's motion around the Sun. These observations were more strong evidence that Earth is not the center of all things and that at least one planet orbited the Sun. For more of Galileo's sketches, with comparisons to modern photographs, see the Part 1 Opener on p. 28.

In 1610, Galileo published a book called *Sidereus Nuncius* (*The Starry Messenger*), detailing his observational findings and his controversial conclusions supporting the Copernican theory. In reporting and interpreting the wondrous observations made with his new telescope, Galileo was directly challenging both the scientific orthodoxy and the religious dogma of his day. He was (literally) playing with fire—he must certainly have been aware that only a few years earlier, in 1600, the astronomer Giordano Bruno had been burned at the stake in Rome, in part for his heretical teaching that Earth orbited the Sun. However, by all accounts, Galileo delighted in publicly ridiculing and irritating his Aristotelian colleagues. In 1616 his ideas were judged heretical, Copernicus's works were banned by the Roman Catholic Church, and Galileo was instructed to abandon his astronomical pursuits.

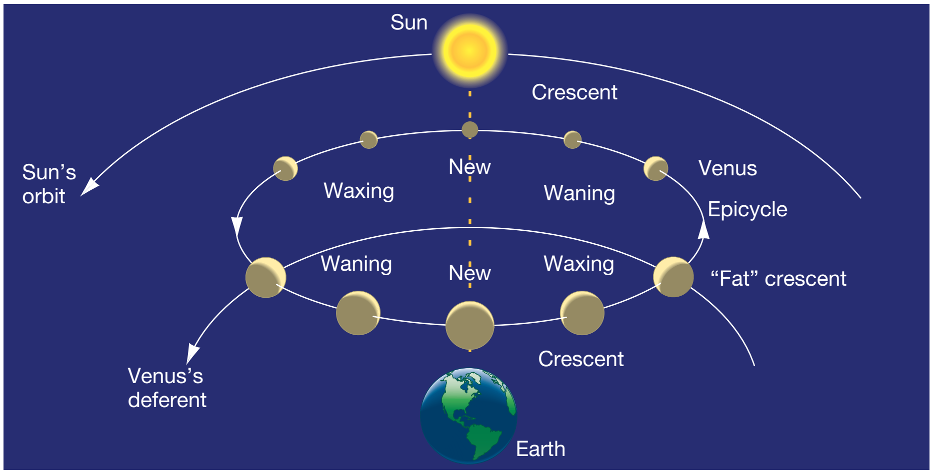
But Galileo would not desist. In 1632 he raised the stakes by publishing *Dialogue Concerning the Two Chief World Systems*, which compared the Ptolemaic and Copernican models. The book presented a discussion among three people, one of them a dull-witted Aristotelian whose views (which were in fact the stated opinions of the then Pope, Urban VIII) time and again were roundly defeated by the arguments of one of his two companions, an articulate proponent of the heliocentric system. To make the book accessible to a wide popular audience, Galileo wrote it in Italian rather than Latin. These actions brought Galileo into direct conflict with the authority of the Church. Eventually, the Inquisition forced him, under threat of torture, to retract his claim that Earth orbits the Sun, and he was placed under house arrest in 1633. He remained imprisoned for the rest of his life. Not until 1992 did the Church publicly forgive Galileo's "crimes." But the damage to the orthodox view of the universe was done, and the Copernican genie was out of the bottle once and for all.

Ascendancy of the Copernican System

Although Renaissance scholars were correct, they could not *prove* that our planetary system is centered on the Sun or even that Earth moves through space. The observational consequences of Earth's orbital motion were just too small for the technology of the day to detect. Direct evidence of Earth's motion was obtained only in 1728, when English astronomer James Bradley discovered the **aberration of starlight**—a slight (roughly 20″) shift in the observed direction to a star, caused by Earth's motion perpendicular to the line of sight, much as rain drops falling vertically leave slanted tracks on the passenger window of a moving car or train. Bradley's observation was the first proof that Earth revolves around the Sun; subsequent observations of many stars in many different directions have repeatedly confirmed the effect. Additional proof of Earth's orbital motion came in 1838, with the first unambiguous determination of stellar parallax (see Figure 1.30) by German astronomer Friedrich Bessel. ∞ (Sec. 1.6)



(a) Sun-centered model



(b) Ptolemy's model

FIGURE 2.12
Venus Phases Both the Ptolemaic and the Copernican models of the solar system predict that Venus should show phases as it moves in its orbit. (a) In the Copernican picture, when Venus is directly between Earth and the Sun, its unlit side faces us and the planet is invisible to us. As Venus moves in its orbit, progressively more of its illuminated face is visible from Earth. Note the connection between the orbital phase and the apparent size of the planet: Venus seems much larger in its crescent phase than when it is full because it is much closer to us during its crescent phase. This is the behavior actually observed. The insets at bottom left and right are actual photographs of Venus taken at two of its crescent phases. *(Courtesy N. Mex. St. Univ.)* (b) The Ptolemaic model (see also Figure 2.7) is unable to account for these observations. In particular, the full phase of the planet cannot be explained. Seen from Earth, Venus reaches only a "fat crescent", yet never a full phase, then begins to wane as it nears the Sun. (Both these views are from a sideways perspective; from overhead, both orbits are very nearly circular, as shown in Figure 2.18.)

Following those early measurements, support for the heliocentric solar system has grown steadily, as astronomers have subjected the theory to more and more sophisticated observational tests, culminating in the interplanetary expeditions of our unmanned space probes of the 1960s, 1970s, and 1980s. Today, the evidence is overwhelming. The development and eventual acceptance of the heliocentric model were milestones in human thinking. This removal of Earth from any position of great cosmic significance is generally known, even today, as the *Copernican principle*. It has become a cornerstone of modern astrophysics.

The Copernican revolution is a prime example of how the scientific method, though affected at any given time by the subjective whims, human biases, and even sheer luck of researchers, does ultimately lead to a definite degree of objectivity. ∞ (Sec. 1.2) Over time, many groups of scientists checking, confirming, and refining experimental tests can neutralize the subjective attitudes of individuals. Usually, one generation of scientists can bring sufficient objectivity to bear on a problem, although some especially revolutionary concepts are so swamped by tradition, religion, and politics that more time is necessary. In the case of heliocentricity, objective confirmation was not obtained until about three centuries after Copernicus published his work and more than 2000 years after Aristarchus had proposed the concept. Nonetheless, objectivity *did in fact* eventually prevail, and our knowledge of the universe has expanded immeasurably as a result.

PROCESS OF SCIENCE Check

✔ In terms of the Scientific Method presented in Chapter 1, what were the principal advantages of the heliocentric theory over the geocentric model?

2.5 The Laws of Planetary Motion

At about the same time as Galileo was becoming famous—or notorious—for his pioneering telescopic observations and outspoken promotion of the Copernican system, Johannes Kepler (Figure 2.13), a German mathematician and astronomer, was developing the laws of planetary motion that now bear his name. Galileo was in many ways the first "modern" observer. He used emerging technology, in the form of the telescope, to achieve new insights into the universe. In contrast, Kepler was a pure theorist. His groundbreaking work that so clarified our knowledge of planetary motion was based almost entirely on the observations of others, principally an extensive collection of data compiled by Tycho Brahe (1546–1601), Kepler's employer and arguably one of the greatest observational astronomers that has ever lived.

Brahe's Complex Data

Tycho, as he is often called, was both an eccentric aristocrat and a skillful observer. Born in Denmark, he was educated at some of the best universities in Europe, where he studied astrology, alchemy, and medicine. Most of his observations, which predated the invention of the telescope by several decades, were made at his own observatory, named *Uraniborg*, in Denmark (Figure 2.14). There, using instruments of his own design, Tycho maintained meticulous and accurate records of the stars, planets, and other noteworthy celestial events, including a comet and a supernova (see Chapter 21), the appearance of which helped convince him that the Aristotelian view of the universe could not be correct.

In 1597, having fallen out of favor with the Danish court, Tycho moved to Prague as Imperial Mathematician of the Holy Roman Empire. Prague happens to be fairly close to Graz, in Austria, where Kepler lived and worked. Kepler joined Tycho in Prague in 1600 and was put to work trying to find a theory that could explain Brahe's planetary data. When Tycho died a year later, Kepler inherited not only his position, but also his most priceless possession: the accumulated observations of the planets, spanning several decades. These observations, though made with the naked eye, were nevertheless of very high quality. In most cases, his measured positions of stars and planets were accurate to within about 1′. Kepler set to work seeking a unifying principle to explain in detail the motions of the planets, without the need for epicycles. The effort was to occupy much of the remaining 29 years of his life.

▲ **FIGURE 2.14 Tycho Brahe** The astronomer in his observatory Uraniborg, on the island of Hveen in Denmark. Brahe's observations of the positions of stars and planets on the sky were the most accurate and complete set of naked-eye measurements ever made. *(Newberry Library/Superstock)*

▲ **FIGURE 2.13 Johannes Kepler (1571–1630)**. *(E. Lessing/Art Resource, NY)*

Kepler had already accepted the heliocentric picture of the solar system. His goal was to find a simple and elegant description of planetary motion within the Copernican framework that fit Brahe's complex mass of detailed observations. In the end, he found it necessary to abandon Copernicus's simple idea of circular planetary orbits. However, even greater simplicity emerged as a result. After long years of studying Brahe's planetary data, and after many false starts and blind alleys, Kepler developed the laws that now bear his name.

Kepler determined the shape of each planet's orbit by triangulation—not from different points on Earth, but from different points on Earth's orbit, using observations made at many different times of the year. ∞ (Sec. 1.6) By using a portion of Earth's orbit as a baseline for his triangle, Kepler was able to measure the relative sizes of the other planetary orbits. Noting where the planets were on successive nights, he found the speeds at which the planets move. We do not know how many geometric shapes Kepler tried for the orbits before he hit upon the correct one. His difficult task was made even more complicated because he had to determine Earth's own orbit, too. Nevertheless, he eventually succeeded in summarizing the motions of all the known planets, including Earth, in just three laws: the **laws of planetary motion**.

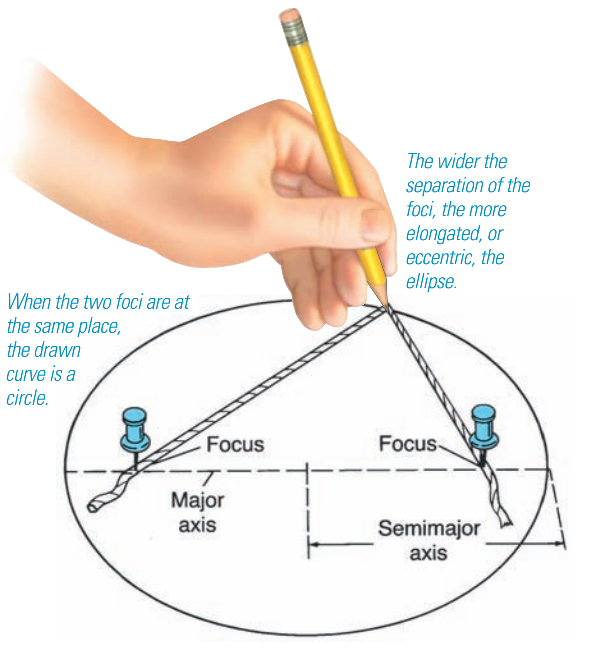


FIGURE 2.15 Ellipse An ellipse can be drawn with the aid of a string, a pencil, and two thumbtacks.

Kepler's Simple Laws

Kepler's first law of planetary motion has to do with the *shapes* of the planetary orbits:

> The orbital paths of the planets are elliptical (*not* circular), with the Sun at one focus.

An **ellipse** is simply a flattened circle. Figure 2.15 illustrates a means of constructing an ellipse with a piece of string and two thumbtacks. Each point at which the string is pinned is called a **focus** (plural: *foci*) of the ellipse. The long axis of the ellipse, containing the two foci, is known as the *major axis*. Half the length of this long axis is referred to as the **semimajor axis**, a measure of the ellipse's size. A circle is a special case in which the two foci happen to coincide; its semimajor axis is simply its radius.

The **eccentricity** of an ellipse is simply a measure of how flattened it is. Technically, eccentricity is defined as the ratio of the distance between the foci to the length of the major axis, but the most important thing to remember here is that an eccentricity of zero corresponds to no flattening—a perfect circle—whereas an eccentricity of one means that the circle has been squashed all the way down to a straight line. Note that, while the Sun resides at one focus of the elliptical orbit, the other focus is empty and has no particular physical significance. (However, we can still figure out where it is, because the two foci are symmetrically placed about the center, along the major axis.)

The length of the semimajor axis and the eccentricity are all we need to describe the size and shape of a planet's orbital path (see *More Precisely 2-1*). In fact, no planet's elliptical orbit is nearly as elongated as the one shown in Figure 2.15. With one exception (the orbit of Mercury), planetary orbits in our solar system have such small eccentricities that our eyes would have trouble distinguishing them from true circles. Only because the orbits are so nearly circular were the Ptolemaic and Copernican models able to come as close as they did to describing reality.

Kepler's substitution of elliptical for circular orbits was no small advance. It amounted to abandoning an aesthetic bias—the Aristotelian belief in the perfection of the circle—that had governed astronomy since Greek antiquity. Even Galileo Galilei, not known for his conservatism in scholarly matters, clung to the idea of circular motion and never accepted the notion that the planets move in elliptical paths.

The second law, illustrated in Figure 2.16, addresses the *speed* at which a planet traverses different parts of its orbit:

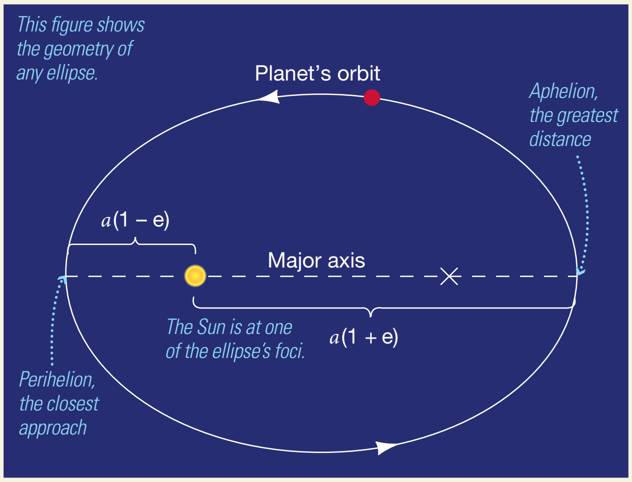
> An imaginary line connecting the Sun to any planet sweeps out equal areas of the ellipse in equal intervals of time.

While orbiting the Sun, a planet traces the arcs labeled A, B, and C in the figure in equal times. Notice, however, that the

MORE PRECISELY 2-1

Some Properties of Planetary Orbits

Two numbers—*semimajor axis* and *eccentricity*—are all that are needed to describe the size and shape of a planet's orbital path. From them, we can derive many other useful quantities. Two of the most important are the planet's *perihelion* (its point of closest approach to the Sun) and its *aphelion* (point of greatest distance from the Sun). From the definitions presented in the text, it follows that if the planet's orbit has semimajor axis a and eccentricity e, the planet's perihelion is at a distance $a(1 - e)$ from the Sun, while its aphelion is at $a(1 + e)$. These points and distances are illustrated in the following figure:



EXAMPLE 1 We can locate the other focus of the ellipse in the diagram and hence determine the eccentricity from the definition in the text quite simply. The second focus is placed symmetrically along the major axis, at the point marked with an "X." With a ruler, measure (1) the length of the major axis and (2) the distance between the two foci. Dividing the second distance by the first, you should find an eccentricity of 3.4 cm/6.8 cm = 0.5. Alternatively, we could use the formula given for the perihelion. Measure the perihelion distance to be $a(1 - e)$ = 1.7 cm. Dividing this by a = 3.4 cm, we obtain $1 - e = 0.5$, so once again, $e = 0.5$.

EXAMPLE 2 A (hypothetical) planet with a semimajor axis of 400 million km and an eccentricity of 0.5 (i.e., with an orbit as shown in the diagram) would range between 400 × (1 − 0.5) = 200 million km and 400 × (1 + 0.5) = 600 million km from the Sun over the course of one complete orbit. With $e = 0.9$, the range in distances would be 40 to 760 million km, and so on.

No planet has an orbital eccentricity as large as 0.5—the planet with the most eccentric orbit is Mercury, with $e = 0.206$ (see Table 2.1). However, many meteoroids and all comets (see Chapter 14) have eccentricities considerably greater than that. In fact, most comets visible from Earth have eccentricities very close to $e = 1$. Their highly elongated orbits approach within a few astronomical units of the Sun at perihelion, yet these tiny frozen worlds spend most of their time far beyond the orbit of Pluto.

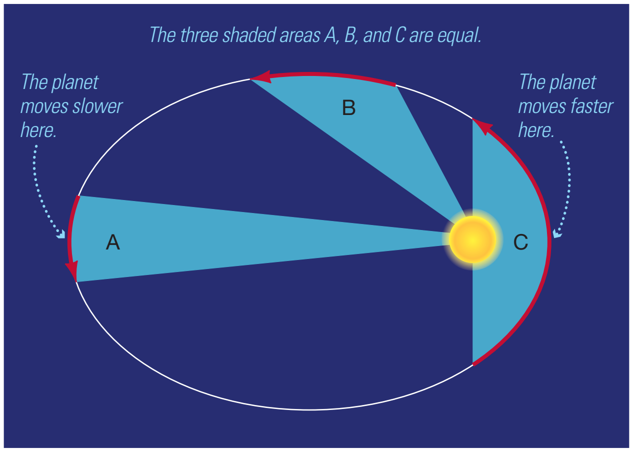


FIGURE 2.16 Kepler's Second Law A line joining a planet to the Sun sweeps out equal areas in equal intervals of time. The three shaded areas A, B, and C are equal. Any object traveling along the elliptical path would take the same amount of time to cover the distance indicated by the three red arrows. Planets move faster when closer to the Sun.

distance traveled by the planet along arc C is greater than the distance traveled along arc A or arc B. Because the time is the same and the distance is different, the speed must vary. When a planet is close to the Sun, as in sector C, it moves much faster than when farther away, as in sector A.

By taking into account the relative speeds and positions of the planets in their elliptical orbits about the Sun, Kepler's first two laws explained the variations in planetary brightness and some observed peculiar nonuniform motions that could not be accommodated within the assumption of circular motion, even with the inclusion of epicycles. Gone at last were the circles within circles that rolled across the sky. Kepler's modification of the Copernican theory to allow the possibility of elliptical orbits both greatly simplified the model of the solar system and at the same time provided much greater predictive accuracy than had previously been possible. Note, too, that these laws are not restricted to planets. They apply to *any* orbiting object. Spy satellites, for example, move very rapidly as they swoop close to Earth's surface, not because they are

TABLE 2.1 Some Solar System Dimensions

Planet	Orbital Semimajor Axis, a (AU)	Orbital Period, P (years)	Orbital Eccentricity, e	P^2/a^3
Mercury	0.387	0.241	0.206	1.002
Venus	0.723	0.615	0.007	1.001
Earth	1.000	1.000	0.017	1.000
Mars	1.524	1.881	0.093	1.000
Jupiter	5.203	11.86	0.048	0.999
Saturn	9.537	29.42	0.054	0.998
Uranus	19.19	83.75	0.047	0.993
Neptune	30.07	163.7	0.009	0.986

propelled with powerful onboard rockets, but because their highly eccentric orbits are governed by Kepler's laws.

Kepler published his first two laws in 1609, stating that he had proved them only for the orbit of Mars. Ten years later, he extended them to all the then-known planets (Mercury, Venus, Earth, Mars, Jupiter, and Saturn) and added a third law relating the size of a planet's orbit to its sidereal orbital **period**—the time needed for the planet to complete one circuit around the Sun:

> The square of a planet's orbital period is proportional to the cube of its semimajor axis.

This law becomes particularly simple when we choose the (Earth sidereal) year as our unit of time and the *astronomical unit* as our unit of length. One **astronomical unit** (AU) is the semimajor axis of Earth's orbit around the Sun—essentially the average distance between Earth and the Sun. Like the light-year, the astronomical unit is custom-made for the vast distances encountered in astronomy. Using these units for time and distance, we can rewrite Kepler's third law for any planet as

$$P^2 \text{ (in Earth years)} = a^3 \text{ (in astronomical units)},$$

where P is the planet's sidereal orbital period and a is the length of its semimajor axis. The law implies that a planet's "year" P increases more rapidly than does the size of its orbit, a. For example, Earth, with an orbital semimajor axis of 1 AU, has an orbital period of 1 Earth year. The planet Venus, orbiting at a distance of roughly 0.7 AU, takes only 0.6 Earth year—about 225 days—to complete one circuit. By contrast, Saturn, almost 10 AU from the Sun, takes considerably more than 10 Earth years—in fact, nearly 30 years—to orbit the Sun just once.

Table 2.1 presents basic data describing the orbits of the eight planets now known. Renaissance astronomers knew these properties for the innermost six planets and used them to construct the currently accepted heliocentric model of the solar system. The second column presents each planet's orbital semimajor axis, measured in astronomical units; the third column gives the orbital period, in Earth years. The fourth column lists the planets' orbital eccentricities. For purposes of verifying Kepler's third law, the fifth column lists the ratio P^2/a^3. As we have just seen, the third law implies that this number should always be unity in the units used in the table.

The main points to be grasped from Table 2.1 are these: (1) With the exception of Mercury, the planets' orbits are nearly circular (i.e., their eccentricities are close to zero) and (2) the farther a planet is from the Sun, the greater is its orbital period, in agreement with Kepler's third law to within the accuracy of the numbers in the table. (The small, but significant, deviations of P^2/a^3 from unity in the cases of Uranus and Neptune are caused by the gravitational attraction between those two planets; see Chapter 13.) Most important, note that Kepler's laws are obeyed by *all* the known planets, *not just by the six on which he based his conclusions.*

The laws developed by Kepler were far more than mere fits to existing data. They also made definite, testable predictions about the future locations of the planets. Those predictions have been borne out to high accuracy every time they have been tested by observation—the hallmark of any credible scientific theory. ∞ (Sec. 1.2)

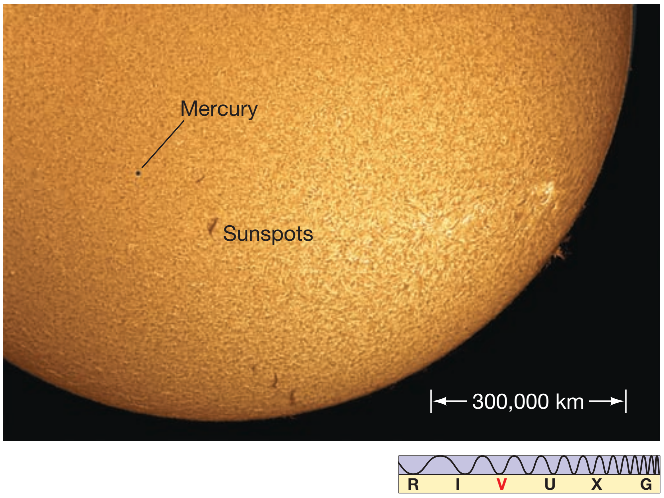
CONCEPT Check

✔ Why is it significant that Kepler's laws also apply to Uranus and Neptune?

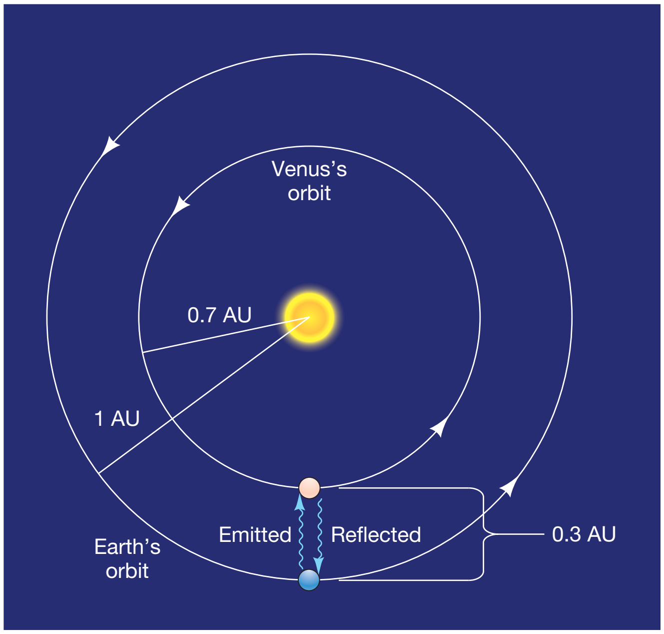
2.6 The Dimensions of the Solar System

Kepler's laws allow us to construct a scale model of the solar system, with the correct shapes and *relative* sizes of all the planetary orbits, but they do not tell us the *actual* size of any orbit. We can express the distance to each planet only in terms of the distance from Earth to the Sun. Why is this? Because Kepler's triangulation measurements all used a portion of Earth's orbit as a baseline, distances could be expressed only relative to the size of that orbit, which was itself not determined by the method. Thus, our model of the solar system would be like a road map of the United States showing the *relative* positions of cities and towns, but lacking the all-important scale marker indicating distances in kilometers or miles. For example, we would know that Kansas City is about three times more distant from New York than it is from Chicago, but we would not know the actual mileage between any two points on the map.

If we could somehow determine the value of the astronomical unit—in kilometers, say—we would be able to add the vital scale marker to our map of the solar system and compute the precise distances between the Sun and each of



▲ **FIGURE 2.17 Solar Transit** The transit of Mercury across the face of the Sun. Such transits happen only about once per decade because Mercury's orbit does not quite coincide with the plane of the ecliptic. Transits of Venus are even rarer, occurring only about twice per century. The most recent took place in 2006. *(P. Jones)*



▲ **FIGURE 2.18 Astronomical Unit** The wavy blue lines represent the paths along which radar signals are transmitted toward Venus and received back at Earth when Venus is at its minimum distance from Earth. Because the radius of Earth's orbit is 1 AU and that of Venus is about 0.7 AU, the one-way distance covered by the signal is 0.3 AU. Thus, we can calibrate the astronomical unit in kilometers.

the planets. We might propose using triangulation to measure the distance from Earth to the Sun directly. However, we would find it impossible to measure the Sun's parallax using Earth's diameter as a baseline. The Sun is too bright, too big, and too fuzzy for us to distinguish any apparent displacement relative to a field of distant stars. To measure the Sun's distance from Earth, we must resort to some other method.

Before the middle of the 20th century, the most accurate measurements of the astronomical unit were made by using triangulation on the planets Mercury and Venus during their rare *transits* of the Sun—that is, during the brief periods when those planets passed directly between the Sun and Earth (as shown for the case of Mercury in Figure 2.17). Because the time at which a transit occurs can be measured with great precision, astronomers can use this information to make accurate measurements of a planet's position in the sky. They can then employ simple geometry to compute the distance to the planet by combining observations made from different locations on Earth, as discussed earlier in Chapter 1. ∞ (Sec. 1.6) For example, the parallax of Venus at closest approach to Earth, as seen from two diametrically opposite points on Earth (separated by about 13,000 km), is about 1′ (1/60°)—at the limit of naked-eye capabilities, but easily measurable telescopically. Using the second formula presented in *More Precisely 1-2*, we find that this parallax represents a distance of 13,000 km × 57.3°/(1/60°), or approximately 45,000,000 km.

Knowing the distance to Venus, we can compute the magnitude of the astronomical unit. Figure 2.18 is an idealized diagram of the Sun–Earth–Venus orbital geometry. The planetary orbits are drawn as circles here, but in reality they are slight ellipses. This is a subtle difference, and we can correct for it using detailed knowledge of orbital motions. Assuming for the sake of simplicity that the orbits are perfect circles, we see from the figure that the distance from Earth to Venus at closest approach is approximately 0.3 AU. Knowing that 0.3 AU is 45,000,000 km makes determining 1 AU straightforward—the answer is 45,000,000/0.3, or 150,000,000 km.

The modern method for deriving the absolute scale (that is, the scale expressed in kilometers, rather than just relative to Earth's orbit) of the solar system uses radar rather than triangulation. The word **radar** is an acronym for **ra**dio **d**etection **a**nd **r**anging. In this technique, radio waves are transmitted toward an astronomical body, such as a planet. (We cannot use radar ranging to measure the distance to the Sun directly, because radio signals are absorbed at the solar surface and are not reflected to Earth.) The returning echo indicates the body's direction and range, or distance, in absolute terms—that is, in kilometers rather than in astronomical units. Multiplying the 300-second round-trip travel time of the radar signal (the time elapsed between transmission of the signal and reception of the echo) by the speed of light (300,000 km/s, which is also the speed of radio waves), we obtain twice the distance to the target planet.

Venus, whose orbit periodically brings it closest to Earth, is the most common target for radar ranging. The round-trip travel time (for example, at closest approach, as indicated by the wavy lines in Figure 2.18) can be measured with high precision—in fact, well enough to determine the planet's distance to an accuracy of about 1 km. In this way, the astronomical unit is now known to be 149,597,870 km. We will use the rounded-off value of 1.5×10^8 km in this text.

Having determined the value of the astronomical unit, we can reexpress the sizes of the other planetary orbits in terms of more familiar units, such as miles or kilometers. The entire scale of the solar system can then be calibrated to high precision.

CONCEPT Check

✔ Why don't Kepler's laws tell us the value of the astronomical unit?

2.7 Newton's Laws

Kepler's three laws, which so simplified the solar system, were discovered *empirically*. In other words, they resulted solely from the analysis of observational data and were not derived from any theory or mathematical model. Indeed, Kepler did not have any appreciation of the physics underlying his laws. Nor did Copernicus understand *why* his heliocentric model of the solar system worked. Even Galileo, often called the father of modern physics, failed to understand why the planets orbit the Sun (although Galileo's work laid vital groundwork for Newton's theories).

What prevents the planets from flying off into space or from falling into the Sun? What causes them to revolve about the Sun, apparently endlessly? To be sure, the motions of the planets obey Kepler's three laws, but only by considering something more fundamental than those laws can we really understand planetary motion. The heliocentric system was secured when, in the 17th century, the British mathematician Isaac Newton (Figure 2.19) developed a deeper understanding of the way *all* objects move and interact with one another.

The Laws of Motion

Isaac Newton was born in Lincolnshire, England, on Christmas Day in 1642, the year Galileo died. Newton studied at Trinity College of Cambridge University, but when the bubonic plague reached Cambridge in 1665, he returned to the relative safety of his home for 2 years. During that time he made probably the most famous of his discoveries, the law of gravity (although it is but one of the many major scientific advances for which Newton was responsible). However, either because he regarded the theory as incomplete or possibly because he was afraid that he would be attacked or plagiarized by his colleagues, he did not tell anyone of his monumental achievement for almost 20 years. It was not until 1684, when Newton was discussing the leading astronomical problem of the day—*Why* do the planets move according to Kepler's laws?—with Edmund Halley (of Halley's comet fame) that he astounded his companion by revealing that he had solved the problem in its entirety nearly two decades before!

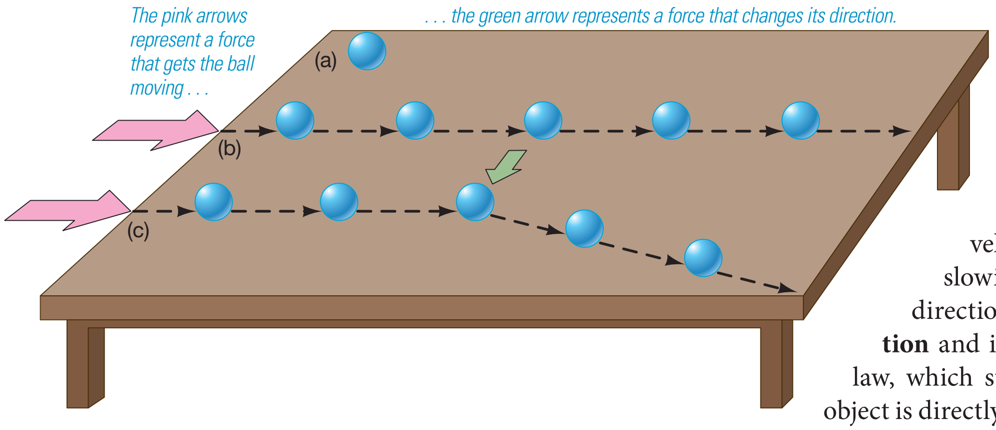
▲ **FIGURE 2.19** **Isaac Newton (1642–1727).** *(S. Terry)*

Prompted by Halley, Newton published his theories in perhaps the most influential physics book ever written: *Philosophiae Naturalis Principia Mathematica* (*The Mathematical Principles of Natural Philosophy*—what we would today call "science"), usually known simply as Newton's *Principia*. The ideas expressed in that work form the basis for what is now known as **Newtonian mechanics.** Three basic laws of motion, the law of gravity, and a little calculus (which Newton also developed) are sufficient to explain and quantify virtually all the complex dynamic behavior we see on Earth and throughout the universe.

Figure 2.20 illustrates Newton's first law of motion:

> Every body continues in a state of rest or in a state of uniform motion in a straight line, unless it is compelled to change that state by a force acting on it.

The first law simply states that a moving object will move forever in a straight line, unless some external **force**—a push or a pull—changes its speed or direction of motion. For example, the object might glance off a brick wall or be hit with a baseball bat; in either case, a force changes the original motion of the object. Another example of a force, well known to most of us, is **weight**—the force (commonly



▲ **FIGURE 2.20 Newton's First Law** An object at rest will remain at rest (a) until some force acts on it. When a force (represented by the red arrow) does act (b), the object will remain in that state of uniform motion until another force acts on it. When a second force (green arrow) acts in a direction different from the first force (c), the object changes its direction of motion.

measured in pounds in the United States) with which gravity pulls you toward Earth's center.

The tendency of an object to keep moving at the same speed and in the same direction unless acted upon by a force is known as **inertia**. Newton's first law implies that it requires no force to maintain motion in a straight line with constant speed. This contrasts sharply with the view of Aristotle, who maintained (incorrectly) that the natural state of an object was to be *at rest*—most probably an opinion based on Aristotle's observations of the effect of friction. In our discussion, we will neglect friction—the force that slows balls rolling along the ground, blocks sliding across tabletops, and baseballs moving through the air. In any case, it is not an issue for the planets because there is no appreciable friction in outer space—there is no air or any other matter to impede a planet's motion. The fallacy in Aristotle's argument was first realized and exposed by Galileo, who conceived of the notion of inertia long before Newton formalized it into a law.

A familiar measure of an object's inertia is its **mass**—loosely speaking, the total amount of matter the object contains. The greater an object's mass, the more inertia it has, and the greater is the force needed to change its state of motion.

Newton's first law describes motion in a straight line with constant speed—that is, motion with constant **velocity**. An object's velocity includes both its speed (in miles per hour or meters per second, say) *and* its direction in space (up, down, northwest, and so on). In everyday speech, we tend to use the terms "speed" and "velocity" more or less interchangeably, but we must realize that they are actually different quantities and that Newton's laws are always stated in terms of the latter. As a specific illustration of the difference, consider a rock tied to a string, moving at a constant rate in a circle as you whirl it around your head. The rock's *speed* is constant, but its *direction* of motion, and hence its velocity, is continually changing. Thus, according to Newton's first law, a force must be acting. That force is the tension you feel in the string. In a moment, we'll see reasoning similar to this applied to the problem of planetary motion.

The rate of change of the velocity of an object—speeding up, slowing down, or simply changing direction—is called the object's **acceleration** and is the subject of Newton's second law, which states that the acceleration of an object is directly proportional to the applied force and inversely proportional to its mass:

> When a force F acts on a body of mass m, it produces in it an acceleration a equal to the force divided by the mass. Thus, $a = F/m$, or $F = ma$.

Hence, the greater the force acting on the object or the smaller the mass of the object, the greater is the acceleration of the object. If two objects are pulled with the same force, the more massive one will accelerate less; if two identical objects are pulled with different forces, the one acted on by the greater force will accelerate more.

Acceleration is the rate of change of velocity, so its units are velocity units per unit of time, such as meters per second *per second* (usually written as m/s^2). In honor of Newton, the SI unit of force is named after him. By definition, 1 newton (N) is the force required to cause a mass of 1 kilogram to accelerate at a rate of 1 meter per second every second (1 m/s^2). One newton is approximately 0.22 pound.

At Earth's surface, the force of gravity produces a downward acceleration of approximately 9.8 m/s^2 on *all* bodies, regardless of mass. According to Newton's second law, this means that your weight (in newtons) is directly proportional to your mass (in kilograms). We will return to this very important point later.

Finally, Newton's third law simply tells us that forces cannot occur in isolation:

> To every action, there is an equal and opposite reaction.

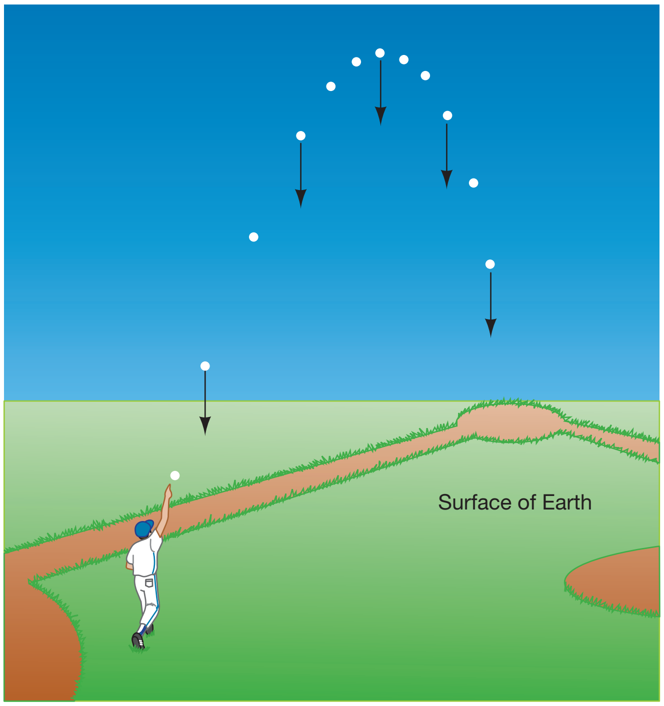
In other words, if body A exerts a force on body B, then body B necessarily exerts a force on body A that is equal in magnitude, but oppositely directed. For example, when a baseball player hits a home run, Newton's third law says that the bat and the ball exert equal and opposite forces on one another during the instant they are in contact. According to the second law, the ball subsequently moves away much faster than the bat because the *mass* of the ball is much less than the combined mass of the bat plus batter (whose body absorbs much of the reaction force), so the ball's *acceleration* is much greater.

Only in extreme circumstances—when speeds approach the speed of light—do Newton's laws break down, and this fact was not realized until the 20th century, when Albert Einstein's theories of relativity once again revolutionized our view of the universe (see Chapter 22). Most of the time, however, Newtonian mechanics provides an excellent description of the motions of planets, stars, and galaxies through the cosmos.

Gravity

Forces may act *instantaneously* or *continuously*. The force from the baseball bat that hits the home run can reasonably be thought of as being instantaneous. A good example of a continuous force is the one that prevents the baseball from zooming off into space—**gravity**, the phenomenon that started Newton on the path to the discovery of his laws. Newton hypothesized that any object having mass always exerts an attractive **gravitational force** on all other massive objects. The more massive an object, the stronger is its gravitational pull.

Consider a baseball thrown upward from Earth's surface, as illustrated in Figure 2.21. In accordance with Newton's first law, the downward force of Earth's gravity continuously modifies the baseball's velocity, slowing the initial upward motion and eventually causing the ball to fall back to the ground. Of course, the baseball, having some mass of its own, also exerts a gravitational pull on Earth. By Newton's third law, this force is equal and opposite to the weight of the ball (the force with which Earth attracts it). But, by Newton's second law, Earth has a much greater effect on the light baseball than the baseball has on the much more massive Earth. The ball and Earth act upon each other with the same gravitational force, but Earth's acceleration is much smaller.



▲ **FIGURE 2.21 Gravity** A ball thrown up from the surface of a massive object, such as a planet, is pulled continuously downward (arrows) by the gravity of that planet—and, conversely, the gravity of the ball continuously pulls the planet (although very, very little).

Now consider the trajectory of the same baseball batted from the surface of the Moon. The pull of gravity is about one-sixth as great on the Moon as on Earth, so the baseball's velocity changes more slowly—a typical home run in a ballpark on Earth would travel nearly half a mile on the Moon. Less massive than Earth, the Moon has less gravitational influence on the baseball. The magnitude of the gravitational force, then, depends on the *masses* of the attracting bodies. In fact, the force is *directly proportional* to the product of the two masses.

Studying the motions of the planets uncovers a second aspect of the gravitational force. At locations equidistant from the Sun's center, the gravitational force has the same strength and is always directed toward the Sun. Furthermore, detailed calculation of the planets' accelerations as they orbit the Sun reveals that the strength of the Sun's gravitational pull decreases in proportion to the *square* of the distance from the Sun. The force of gravity is said to obey an **inverse-square law**. As shown in Figure 2.22, inverse-square forces decrease rapidly with distance from their source. For example, tripling the distance makes the force $3^2 = 9$ times weaker, whereas multiplying the distance by five results in a force that is $5^2 = 25$ times weaker. Despite this rapid decrease, the force never quite reaches zero. The gravitational pull of an object having some mass can never be completely extinguished.

We can combine the preceding statements about mass and distance to form a law of gravity that dictates the way in which *all* massive objects (i.e., objects having some mass) attract one another:

> Every particle of matter in the universe attracts every other particle with a force that is directly proportional to the product of the masses of the particles and inversely proportional to the square of the distance between their centers.

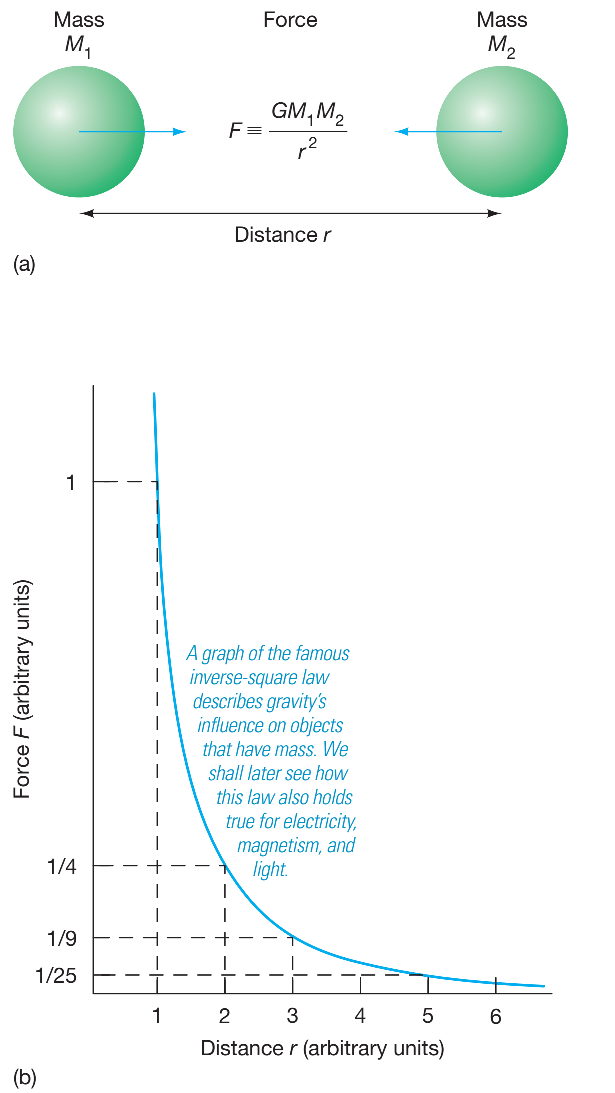
As a proportionality, the law of gravity may be written as

$$\text{gravitational force} \propto \frac{\text{mass of object 1} \times \text{mass of object 2}}{\text{distance}^2}$$

(The symbol $\propto$ here means "is proportional to.") The rule for computing the force F between two bodies of masses m_1 and m_2, separated by a distance r, is usually written more compactly as

$$F = \frac{Gm_1m_2}{r^2}.$$

The quantity G is known as the *gravitational constant*, or, often, simply as Newton's constant. It is one of the fundamental constants of the universe. The value of G has been measured in extremely delicate laboratory experiments as 6.67×10^{-11} newton meter^2/kilogram^2 ($N \cdot m^2/kg^2$).



▲ **FIGURE 2.22 Gravitational Force** (a) The gravitational force between two bodies is proportional to the mass of each and is inversely proportional to the square of the distance between them. (b) Inverse-square forces rapidly weaken with distance from their source, never quite reaching zero, no matter how far away.

2.8 Newtonian Mechanics

Newton's three laws of motion and the law of gravitation provide a solid theoretical foundation upon which we can base a deeper understanding of planetary orbits, the laws of planetary motion, and many other important aspects of orbital motion. With the development of Newtonian mechanics, the transition from geocentric lore to heliocentric fact was complete.

Planetary Motion

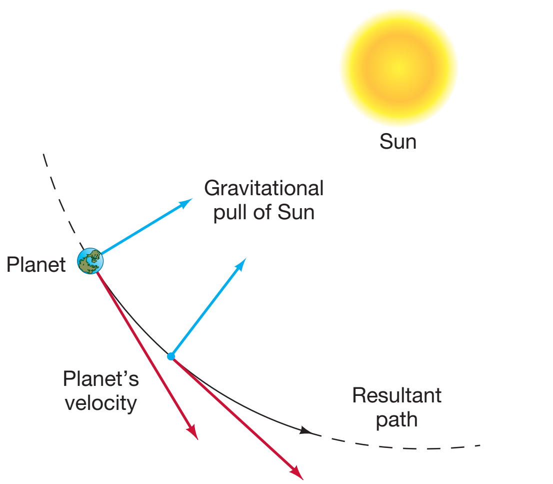
The mutual gravitational attraction between the Sun and the planets, as expressed by Newton's law of gravity, is responsible for the observed planetary orbits. As depicted in Figure 2.23, this gravitational force continuously pulls each planet toward the Sun, deflecting its forward motion into a curved orbital path. Because the Sun is much more massive than any of the planets, it dominates the interaction. We might say that the Sun "controls" the planets, not the other way around.

The Sun–planet interaction sketched here is analogous to our earlier example of the rock whirling on a string. The Sun's gravitational pull is your hand and the string, and the planet is the rock at the end of that string. The tension in the string provides the force necessary for the rock to move in a circular path. If you were suddenly to release the string—which would be like eliminating the Sun's gravity—the rock would fly away along a tangent to the circle, in accordance with Newton's first law.

In the solar system, at this very moment, Earth is moving under the combined influence of gravity and inertia. The net result is a stable orbit, despite our continuous rapid motion through space. (In fact, Earth orbits the Sun at a speed of about 30 km/s, or approximately 70,000 mph. You can verify this for yourself by calculating how fast Earth must move to complete a circle of radius 1 AU—and hence of circumference 2π AU, or 940 million km—in 1 year, or 3.2×10^7 seconds. The answer is 9.4×10^8 km / 3.2×10^7 s, or 29.4 km/s.) *More Precisely 2-2* describes how astronomers can use Newtonian mechanics and the law of gravity to quantify planetary motion and measure the masses of Earth, the Sun, and many other astronomical objects by studying the orbits of objects near them.

Kepler's Laws Reconsidered

Newton's laws of motion and law of universal gravitation provide a theoretical explanation for Kepler's empirical laws of planetary motion. Kepler's three laws follow directly from

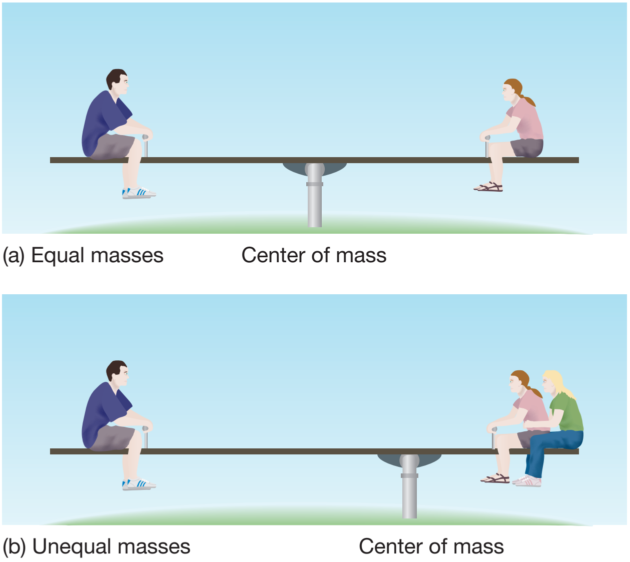


▲ **FIGURE 2.23 Solar Gravity** The Sun's inward pull of gravity on a planet competes with the planet's tendency to continue moving in a straight line. These two effects combine, causing the planet to move smoothly along an intermediate path, which continuously "falls around" the Sun. This unending tug-of-war between the Sun's gravity and the planet's inertia results in a stable orbit.

Newtonian mechanics, as solutions of the equations describing the motion of a body moving in response to an inverse-square force. However, just as Kepler modified the Copernican model by introducing ellipses rather than circles, so, too, did Newton make corrections to Kepler's first and third laws. It turns out that a planet does not orbit the exact center of the Sun. Instead, both the planet and the Sun orbit their common **center of mass**—the "average" position of all the matter making up the two bodies (Figure 2.24). Because the Sun and the planet are acted upon by equal and opposite gravitational forces (by Newton's third law), the Sun must also move (by Newton's first law), driven by the gravitational influence of the planet. The Sun, however, is so much more massive than any planet that the center of mass of the planet–Sun system is very close to the center of the Sun, which is why Kepler's laws are so accurate. Thus, Kepler's first law becomes

> The orbit of a planet around the Sun is an ellipse, with the *center of mass of the planet–Sun system* at one focus.

As shown in Figure 2.24, the center of mass of two objects of comparable mass does not lie within either object. For identical masses orbiting one another (Figure 2.25a), the orbits are identical ellipses, with a common focus located midway between the two objects. For unequal masses (as in Figure 2.25b), the elliptical orbits still share a focus, and both have the same eccentricity, but the more massive object moves more slowly and on a tighter orbit. (Note that Kepler's second law, as stated earlier, continues to apply without modification to each orbit separately, but the *rates* at which the two orbits sweep out areas are different.)



▲ **FIGURE 2.24 Center of Mass** (a) The center of mass of two bodies of equal mass lies midway between them. (b) As the mass of one body increases, the center of mass moves toward it. Experienced seesawers know that when both sides are balanced, the center of mass is at the pivot point.

The change to Kepler's third law is also small in the case of a planet orbiting the Sun, but very important in other circumstances, such as the orbital motion of two stars that are gravitationally bound to each other. Following through the mathematics of Newton's theory, we find that the true relationship between the semimajor axis a (measured in astronomical units) of the planet's orbit relative to the Sun and its orbital period P (in Earth years) is

$$P^2\,(\text{in Earth years}) = \frac{a^3\,(\text{in astronomical units})}{M_{\text{total}}\,(\text{in solar units})},$$

where M_{total} is the *combined* mass of the two objects. Notice that Newton's restatement of Kepler's third law preserves the proportionality between P^2 and a^3, but now the proportionality includes M_{total}, so it is *not* quite the same for all the

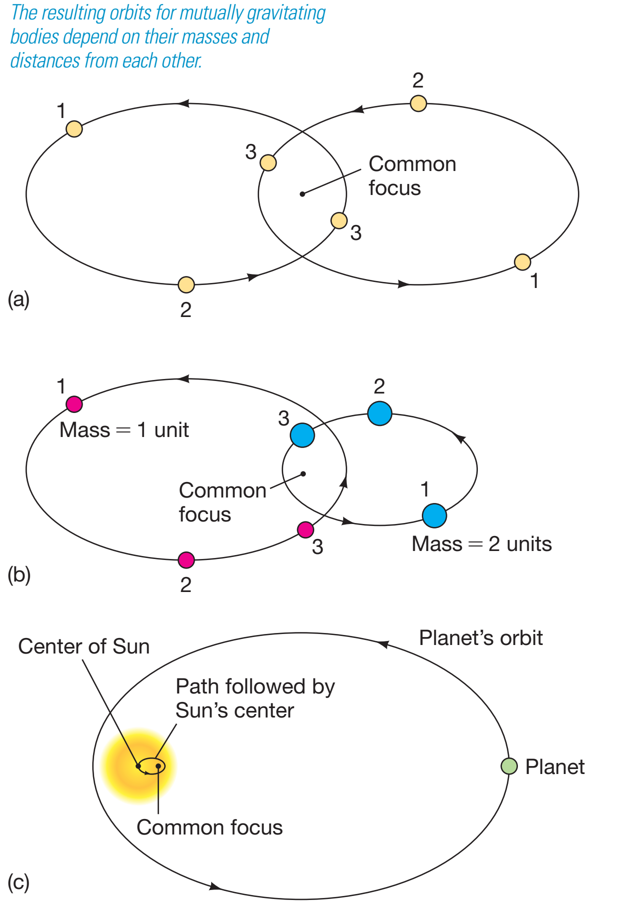


FIGURE 2.25 Orbits (a) The orbits of two bodies (stars, for example) with equal masses, under the influence of their mutual gravity, are identical ellipses with a common focus. The pairs of numbers (e.g., the two 2s in each orbit) indicate the positions of the two bodies at three different times. (Note that a line joining the bodies at any give time always passes through the common focus.) (b) The orbits of two bodies, one twice as massive as the other, are again elliptical and with the same eccentricity, but according to Newton's laws, the more massive body moves more slowly and in a smaller orbit. (c) In the case of an extremely small planet orbiting the massive Sun, the common focus of the two orbits could be inside the Sun.

MORE PRECISELY 2-2

Weighing the Sun

We can use Newtonian mechanics to calculate some useful formulae relating the properties of planetary orbits to the mass of the Sun. Again for simplicity, let's assume that the orbits are circular (not a bad approximation in most cases, and Newton's laws easily extend to cover the more general case of eccentric orbits). Consider a planet of mass m moving at speed v in an orbit of radius r around the Sun, of mass M. Even though the planet's *speed* is constant, the *direction* of its motion is not, so the planet's velocity is changing—it is accelerating. In fact, the planet's acceleration is

$$a = \frac{v^2}{r},$$

so, by Newton's second law, the force required to keep the planet in orbit is

$$F = ma = \frac{mv^2}{r}.$$

Setting this equation equal to the gravitational force due to the Sun, we obtain

$$\frac{mv^2}{r} = \frac{GmM}{r^2},$$

so the speed of the planet in the circular orbit is

$$v = \sqrt{\frac{GM}{r}}.$$

Now let's turn the problem around. Because we have measured G in the laboratory on Earth, and because we know the length of a year and the size of the astronomical unit, we can use Newtonian mechanics to *weigh* the Sun—that is, find its mass by measuring its gravitational influence on another body (in this case, Earth). Rearranging the last equation to read

$$M = \frac{rv^2}{G}$$

and substituting the known values of $v = 30$ km/s, $r = 1$ AU $= 1.5 \times 10^{11}$ m, and $G = 6.7 \times 10^{-11}$ Nm^2/kg^2, we calculate the mass of the Sun to be 2.0×10^{30} kg—an enormous mass by terrestrial standards.

EXAMPLE Similarly, knowing the distance from Earth to the Moon ($r = 384{,}000$ km) and the length of the (sidereal) month ($P = 27.3$ days), we can calculate the Moon's orbital speed to be $v = 2\pi r/P = 1.02$ km/s, and hence, using the preceding formula, measure Earth's mass to be 6.0×10^{24} kg.

In fact, this is basically how *all* masses are measured in astronomy. Because we can't just go out and attach a scale to an astronomical object when we need to know its mass, we must look for its gravitational influence on something else. This principle applies to planets, stars, galaxies, and even clusters of galaxies—very different objects, but all subject to the same physical laws.

planets. The Sun's mass is so great, however, that the differences in M_{total} among the various combinations of the Sun and the other planets are almost unnoticeable, so Kepler's third law, as originally stated, is a very good approximation. This modified form of Kepler's third law is true in all circumstances, inside or outside the solar system.

PROCESS OF SCIENCE Check

✔ In what ways did Newtonian mechanics supersede Kepler's laws as a model of the solar system?

Escaping Forever

The law of gravity that describes the orbits of planets around the Sun applies equally well to natural moons and artificial satellites orbiting any planet. All our Earth-orbiting, human-made satellites move along paths governed by a combination of the inward pull of Earth's gravity and the forward motion gained during the rocket launch. If the rocket initially imparts enough speed to the satellite, it can go into orbit. Satellites not given enough speed at launch, by accident or design (e.g., intercontinental ballistic missiles), fail to achieve orbit and fall back to Earth (see Figure 2.26).

Some space vehicles, such as the robot probes that visit other planets, attain enough speed to escape our planet's gravity and move away from Earth forever. This speed, known as the **escape speed**, is about 41% greater (actually, $\sqrt{2} = 1.414\ldots$ times greater) than the speed of an object traveling in a circular orbit at any given radius.* At less than the escape speed, the old adage "What goes up must come down" (or at least stay in orbit) still applies. At more than the escape speed, however, a spacecraft will leave Earth for good. Planets, stars, galaxies—all gravitating bodies—have escape speeds. No matter how massive the body, gravity decreases with distance. As a result, the escape speed diminishes with increasing separation. The farther we go from Earth (or any gravitating body), the easier it becomes to escape.

The speed of a satellite in a circular orbit just above Earth's atmosphere is 7.9 km/s (roughly 18,000 mph). The satellite would have to travel at 11.2 km/s (about 25,000 mph) to escape from Earth altogether. If an object exceeds the escape speed, its motion is said to be **unbound**, and the orbit is no longer

**In terms of the formula presented in* More Precisely 2-2, *the escape speed is given by* $v_{\text{escape}} = \sqrt{2\,GM/r}$.

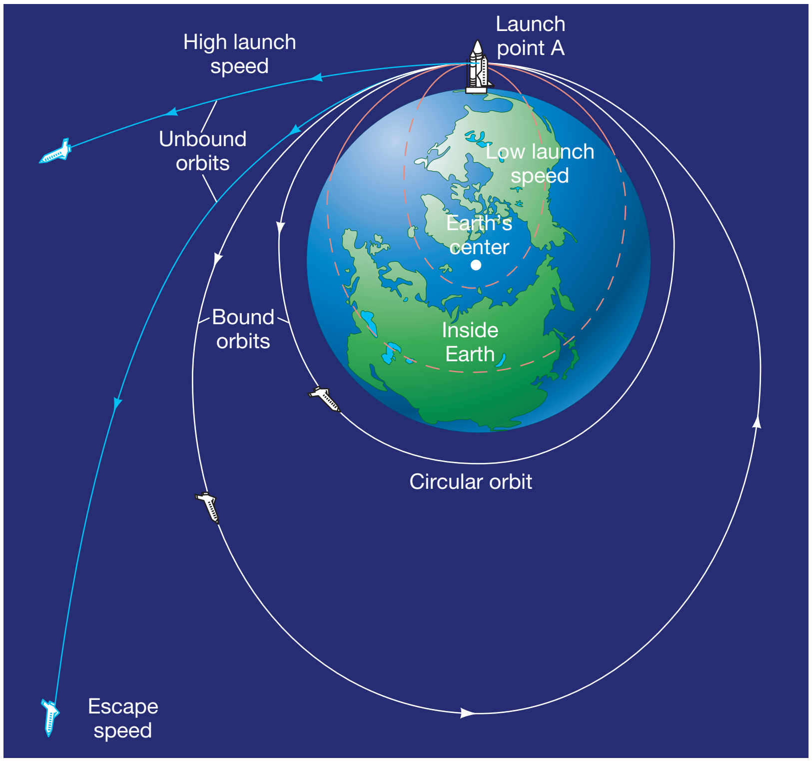


FIGURE 2.26 Escape Speed The effect of launch speed on the trajectory of a satellite. With too low a speed at point A, the satellite will simply fall back to Earth. Given enough speed, however, the satellite will go into orbit—it "falls around Earth." As the initial speed at point A is increased, the orbit will become more and more elongated. When the initial speed exceeds the escape speed, the satellite will become unbound from Earth and will escape along a hyperbolic trajectory.

an ellipse. In fact, the path of the spacecraft relative to Earth is a related geometric figure called a *hyperbola*. If we simply change the word *ellipse* to *hyperbola*, the modified version of Kepler's first law still applies, as does Kepler's second law. (Kepler's third law does not extend to unbound orbits because it doesn't make sense to talk about a period in those cases.)

The Circle of Scientific Progress

The progression from the complex Ptolemaic model of the universe to the elegant simplicity of Newton's laws is a case study in the scientific method. ∞ (Sec. 1.2) Copernicus made a radical conceptual leap away from the Ptolemaic view, gaining much in insight but little in predictive power. Kepler made critical changes to the Copernican picture and gained both accuracy and predictive power but still fell short of a true physical explanation of planetary motion within the solar system, or of orbital motion in general. Eventually, Newton showed how all known planetary motion could be explained in detail by the application of four, simple, fundamental laws—the three laws of motion and the law of gravity. The process was slow, with many starts and stops and a few wrong turns, but it worked!

In a sense, then, the development of Newton's laws and their application to planetary motion represented the end of the first "loop" around the schematic diagram presented in Figure 1.6. The long-standing practical and conceptual questions raised by ancient observations of retrograde motion were finally resolved, and new predictions, themselves amenable to observational testing, became possible. And the laws are still being tested today. Every time a comet appears in the night sky right on schedule, or a spacecraft reaches the end of a billion-kilometer journey within meters of its target and seconds of the predicted arrival time, our confidence in Newtonian mechanics is further strengthened. But unlike the essentially descriptive models of Ptolemy, Copernicus, and Kepler, Newtonian mechanics is not limited to the motions of planets, or even to events occurring within our own solar system. They apply to moons, comets, spacecraft, stars, and even the most distant galaxies, extending the range of our scientific inquiries across the observable universe—as well as apples falling to the ground.

CONCEPT Check

✔ Explain, in terms of Newton's laws of motion and gravity, why planets orbit the Sun.

The Big Question The concept of gravity is well developed, thanks to Isaac Newton's efforts in the 17th century; it works well for small masses and small velocities, thus for almost every application on or near Earth. But, as we shall see later in this book, in the 20th century Albert Einstein overthrew the idea of gravity with a better one—relativity theory, which deals with fast-moving, often massive objects in curved space. Even so, now in the 21st century, relativity is coming up short, especially when studying exotic objects such as black holes. Who will take the next great leap in understanding and what will the new concept be? No one knows the answers, but this is the way the scientific method works, by constantly refining our ideas about the nature of the universe.