Astronomy Today

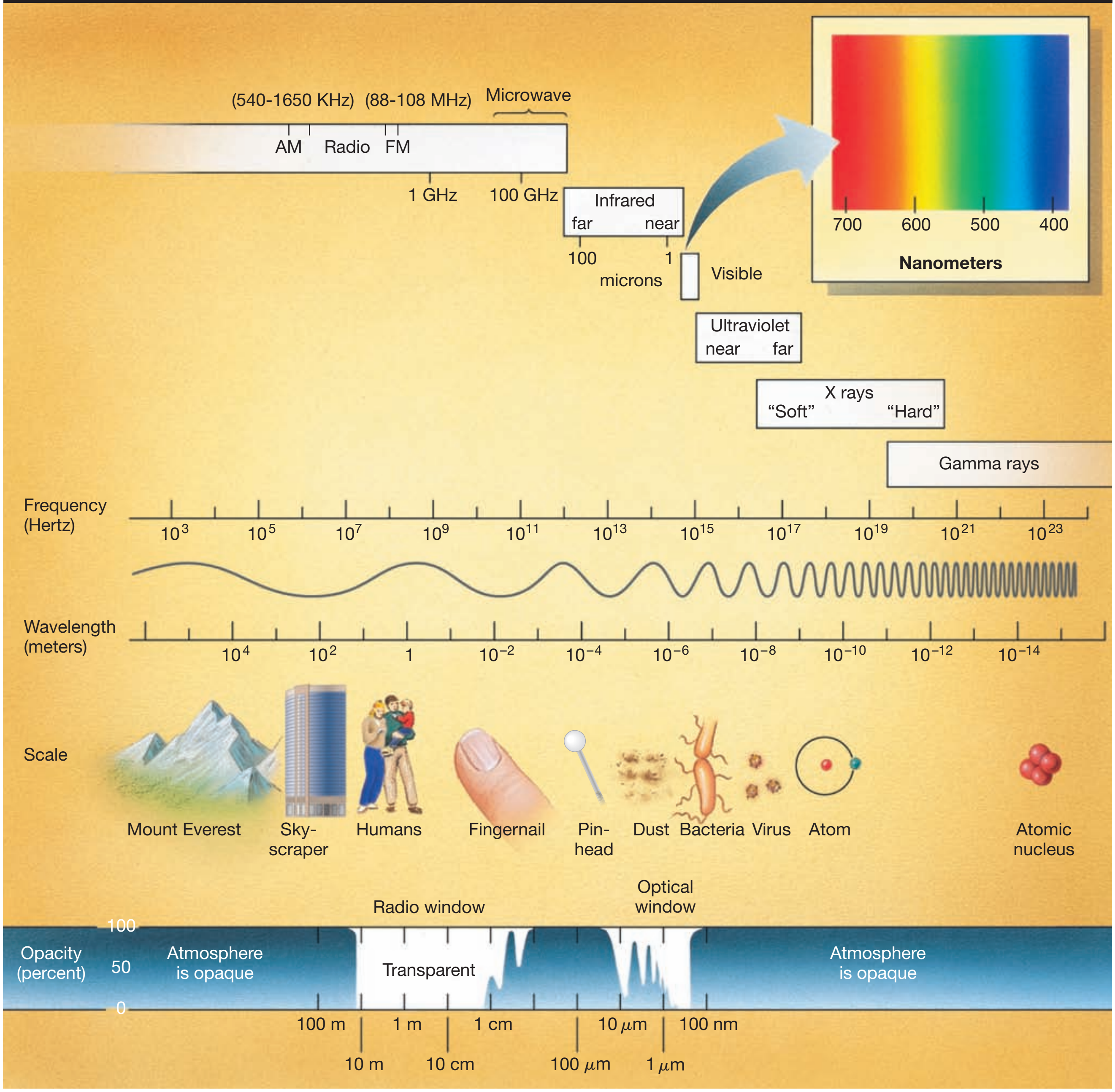
EIGHTH EDITION

Eric Chaisson • Steve McMillan

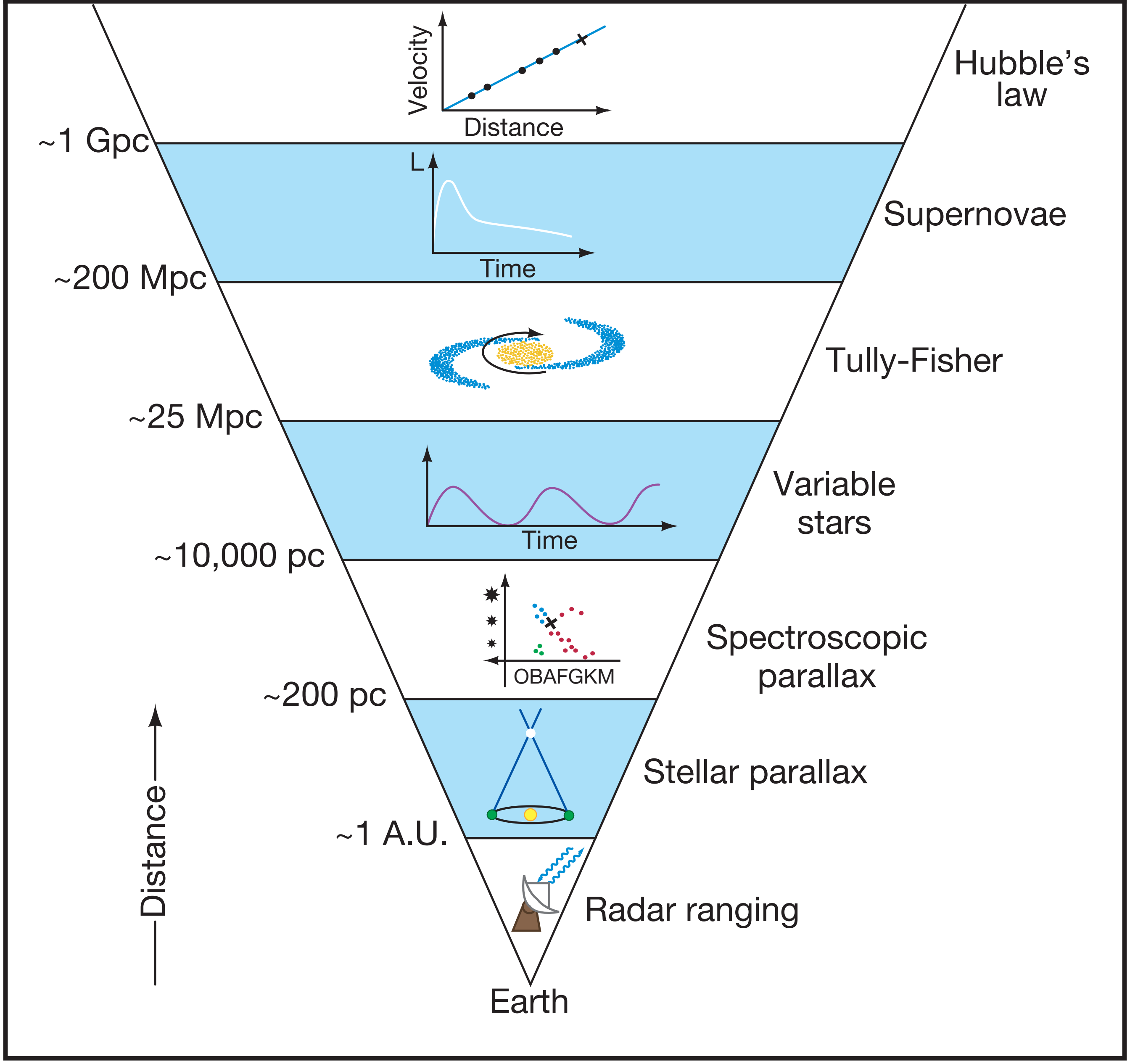
ALWAYS LEARNING

PEARSON

The Entire Electromagnetic Spectrum



The Distance Scale



Astronomy Today 8e
Global Edition

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PEARSON

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Brief Contents

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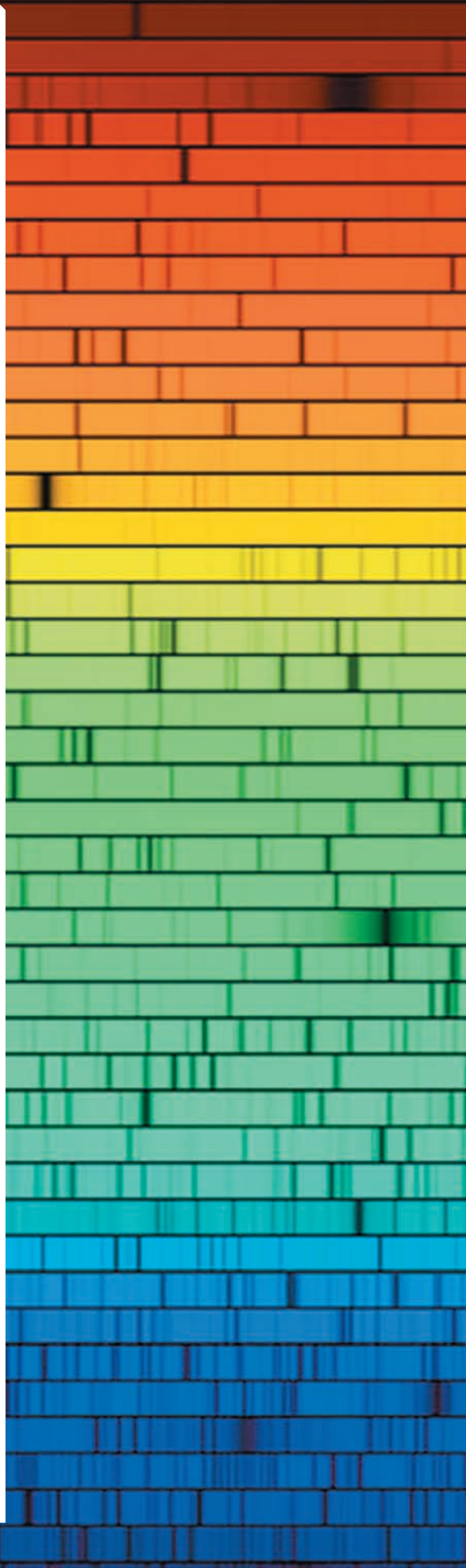

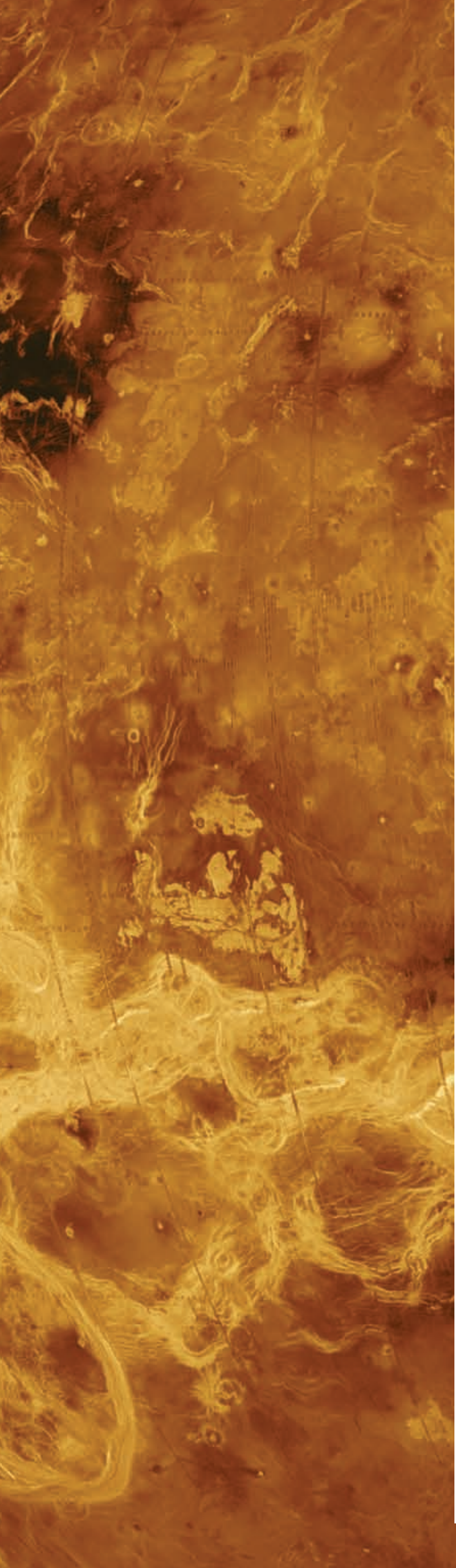

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About the Authors

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

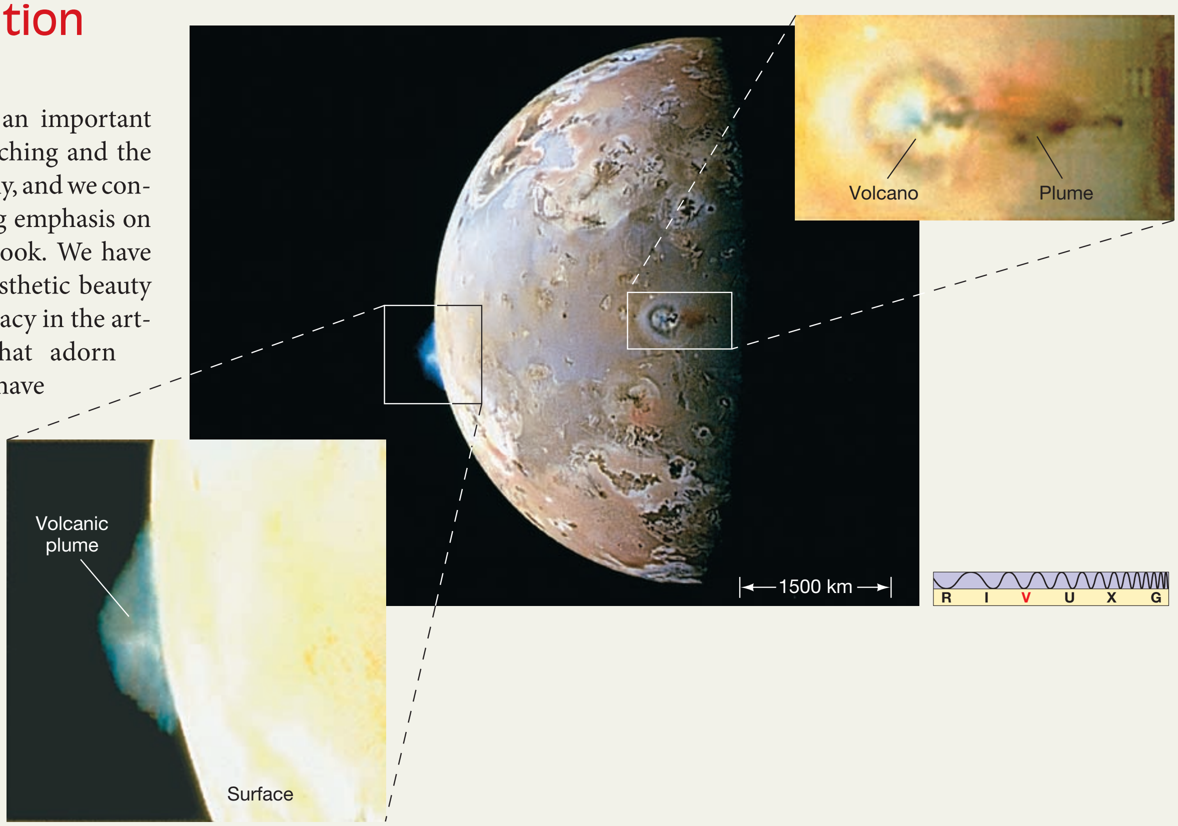
Astronomy is a rapidly evolving field and, in the three years since the publication of the seventh edition of *Astronomy Today,* has seen many new discoveries covering the entire spectrum of astronomical research. Almost every chapter in the eighth edition has been substantially updated with new information. 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.

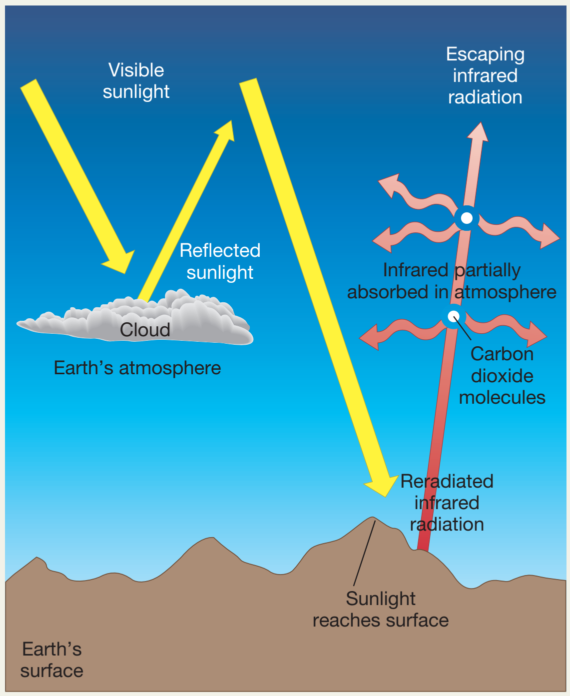
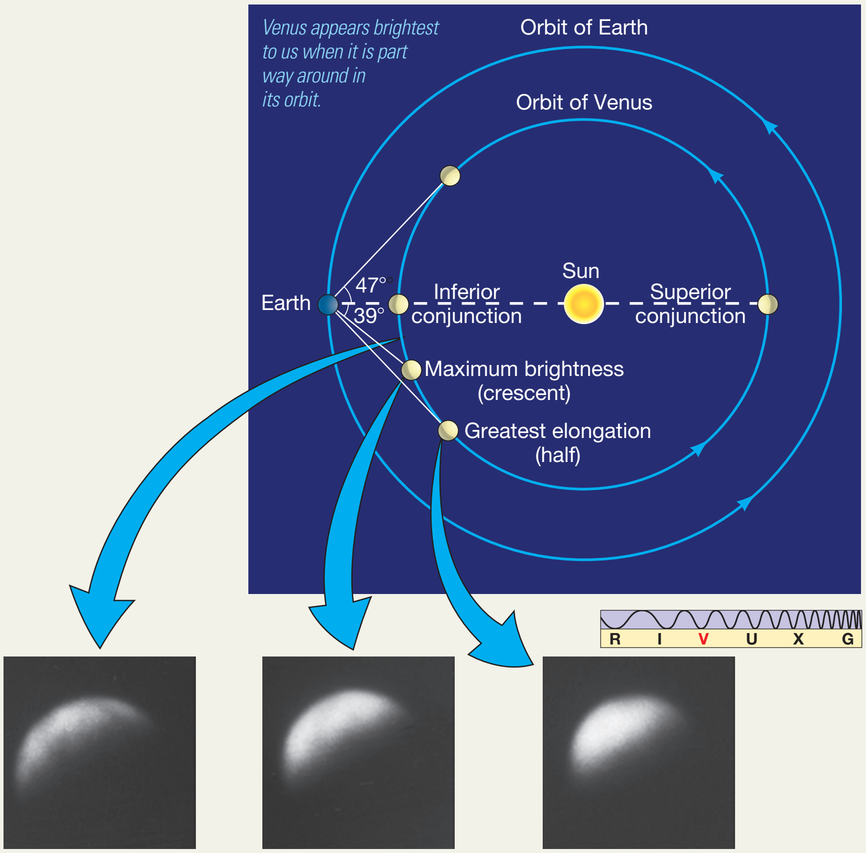


Figure Annotations (REVISED) The eighth edition incorporates the research-proven technique of strategically placing annotations (which always appear in blue type) within key pieces of art, fostering students' ability to read and interpret complex figures, focus on the most relevant information, and integrate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

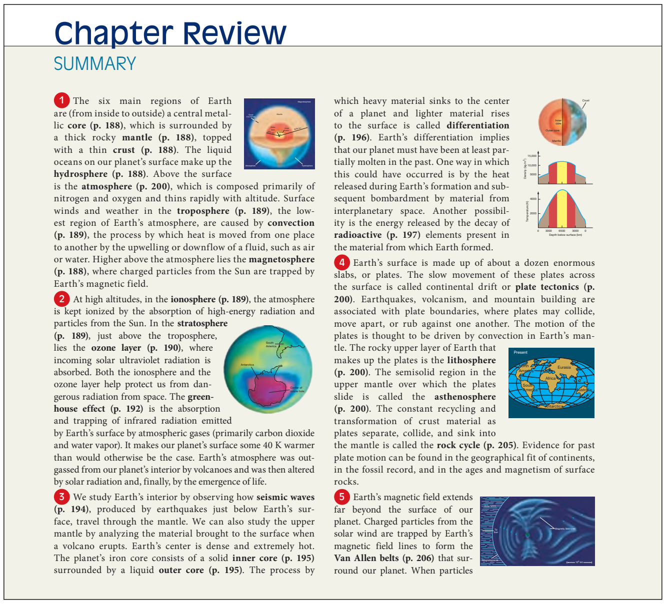
Discovery Boxes Exploring a wide variety of interesting supplementary topics, Discovery boxes provide the reader with insight into how scientific knowledge evolves and emphasizes the process of science.

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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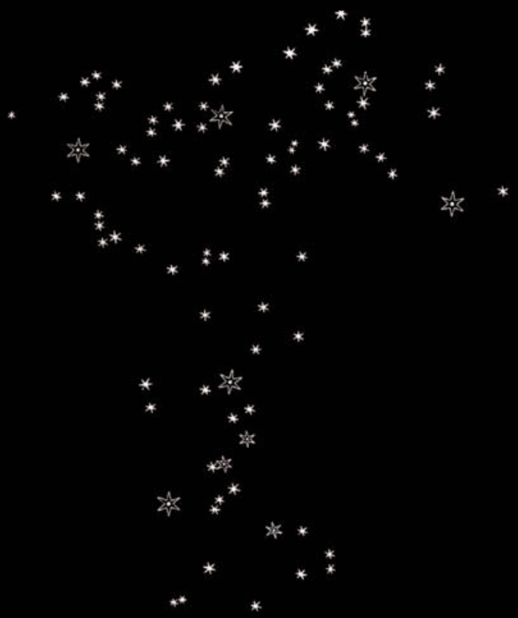
Astronomy Today 8e

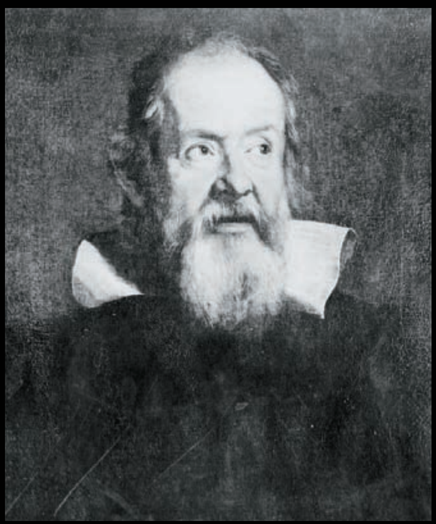
Galileo's sketch of Saturn

PART ONE

Astronomy and the Universe



Galileo's sketch of Orion



Galileo Galilei

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'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)*

Charting the Heavens

1

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.

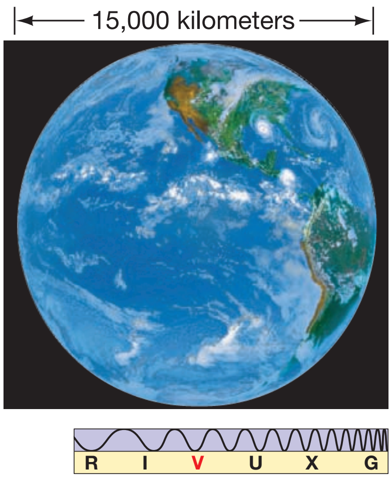
1.1 Our Place in Space

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 1.1 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)*



▲ **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)*

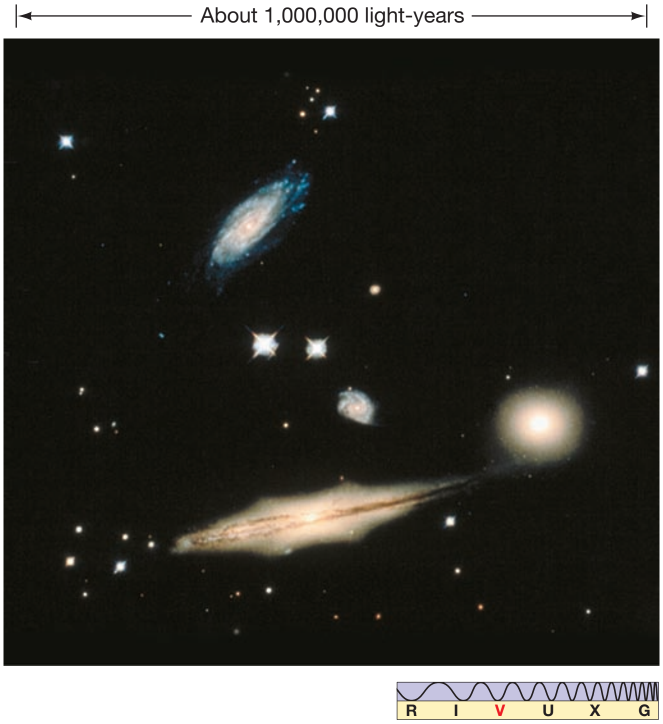
▲ **FIGURE 1.3 The Sun** The Sun is a star, a very hot ball of gas composed mainly of hydrogen and helium. Much bigger than Earth—more than 100 times larger in diameter—the Sun is held together by its own gravity. The dark blemishes are sunspots (see Chapter 16). *(AURA)*

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



▲ **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)*

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.

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.

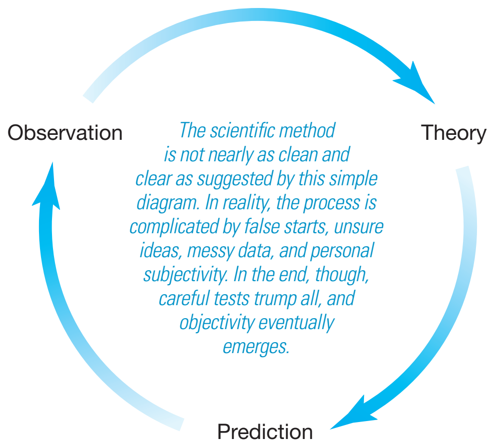
1.2 Scientific Theory and the Scientific Method

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.

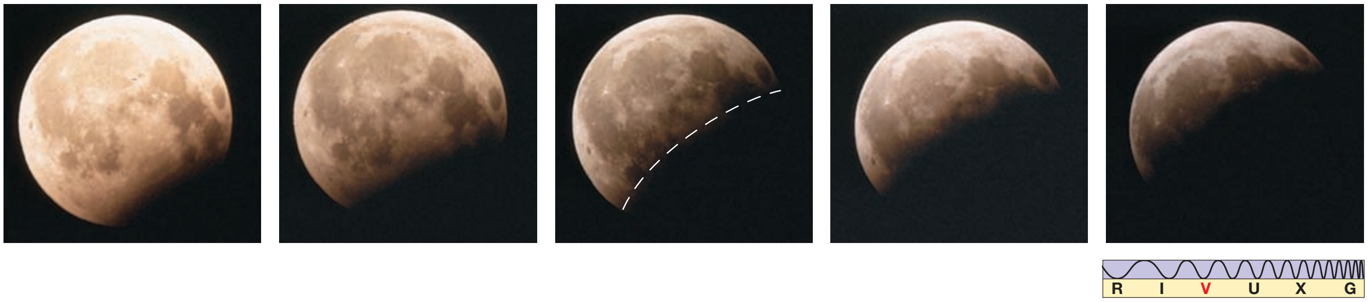
The notion that theories must be tested and may be proven wrong sometimes leads people to dismiss their importance. We have all heard the expression, "Of course, it's only a theory," used to deride or dismiss an idea that someone finds unacceptable. Don't be fooled! Gravity (see Section 2.7) is "only" 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

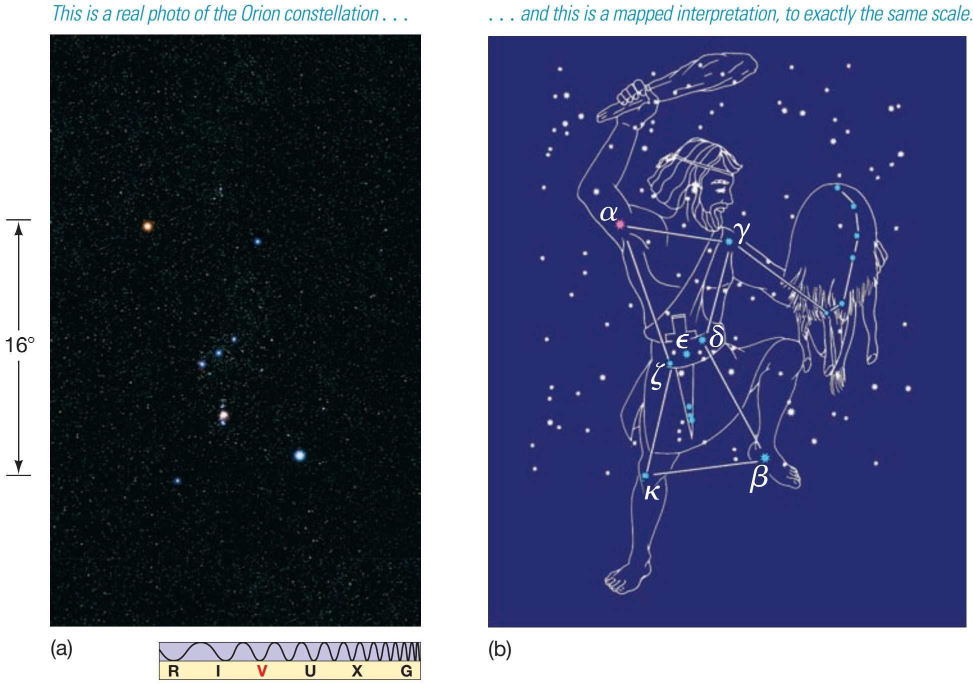
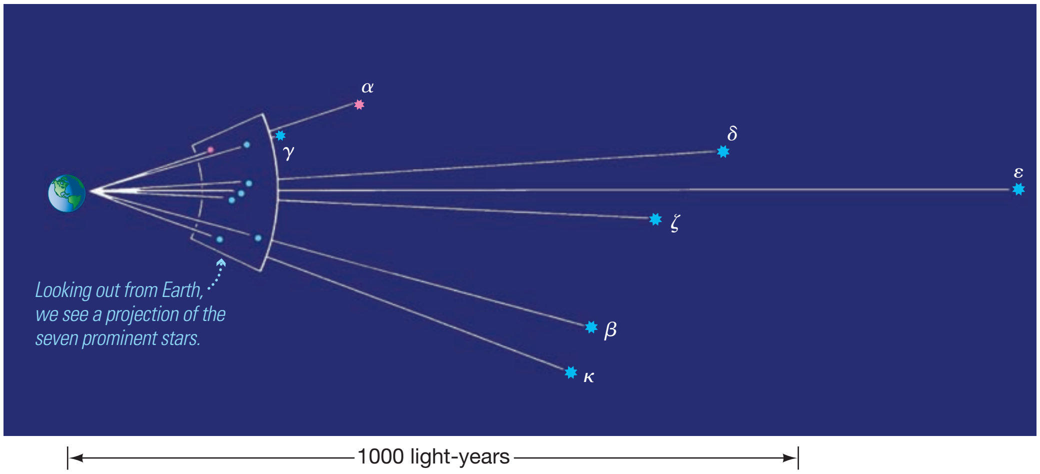


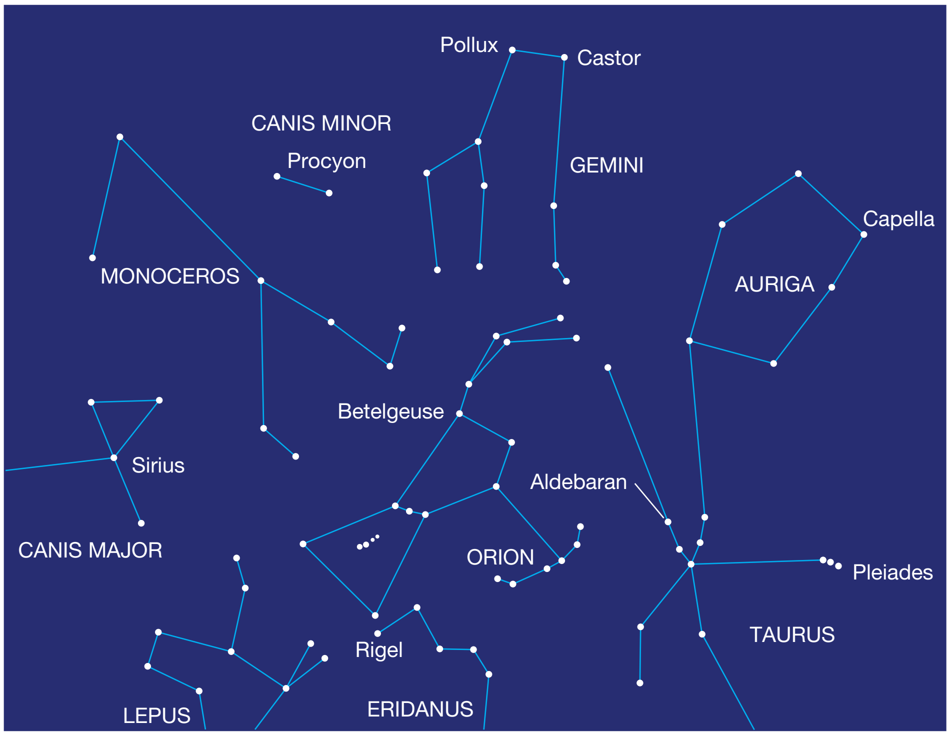
FIGURE 1.8 Constellation Orion (a) A photograph of the group of bright stars that make up the constellation Orion. (See the preface, p. 21, for an explanation of the icon at the bottom, which simply indicates that this image was made in visible light.) (b) The stars are connected to show the pattern 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).*

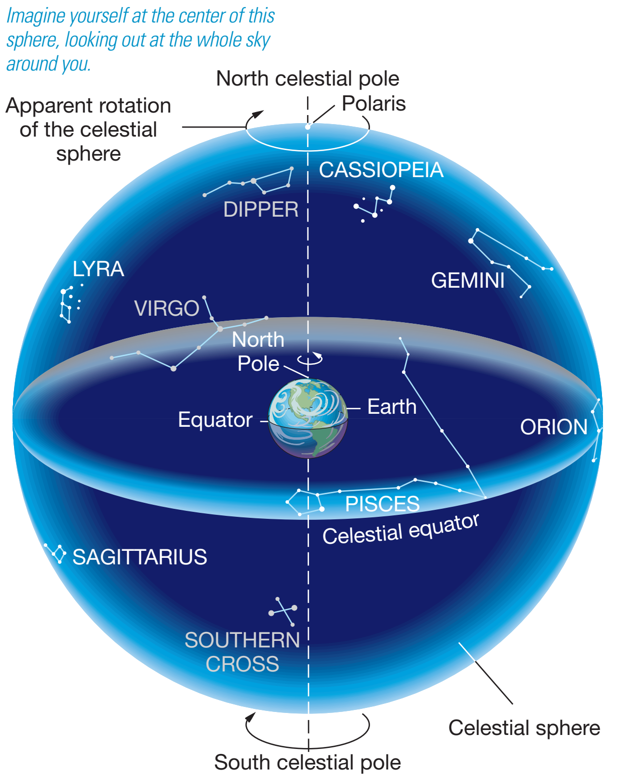


FIGURE 1.11 Celestial Sphere Planet Earth sits fixed at the hub of the celestial sphere. This is one of the simplest possible models of the universe, but it doesn't agree with the facts that astronomers now know about the universe.

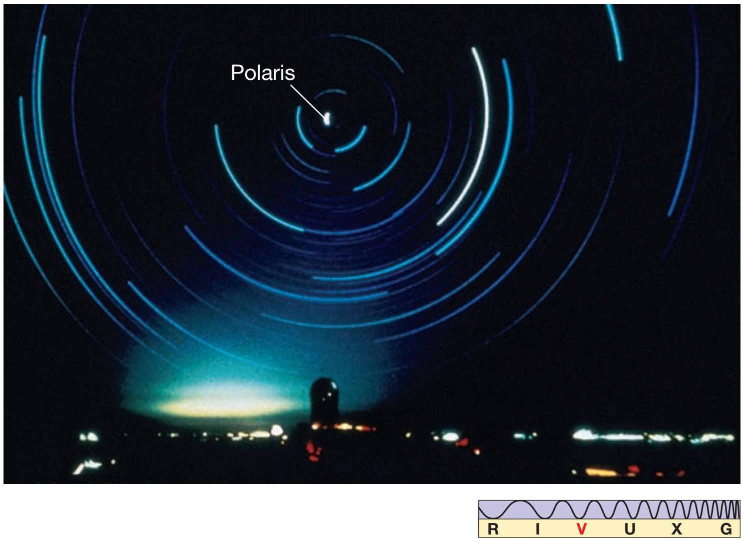


FIGURE 1.12 Northern Sky This time-lapse photograph of the northern sky shows how each star traces out a curved trail across the night sky. The concentric circles are centered near the North Star, Polaris. *(AURA)*

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

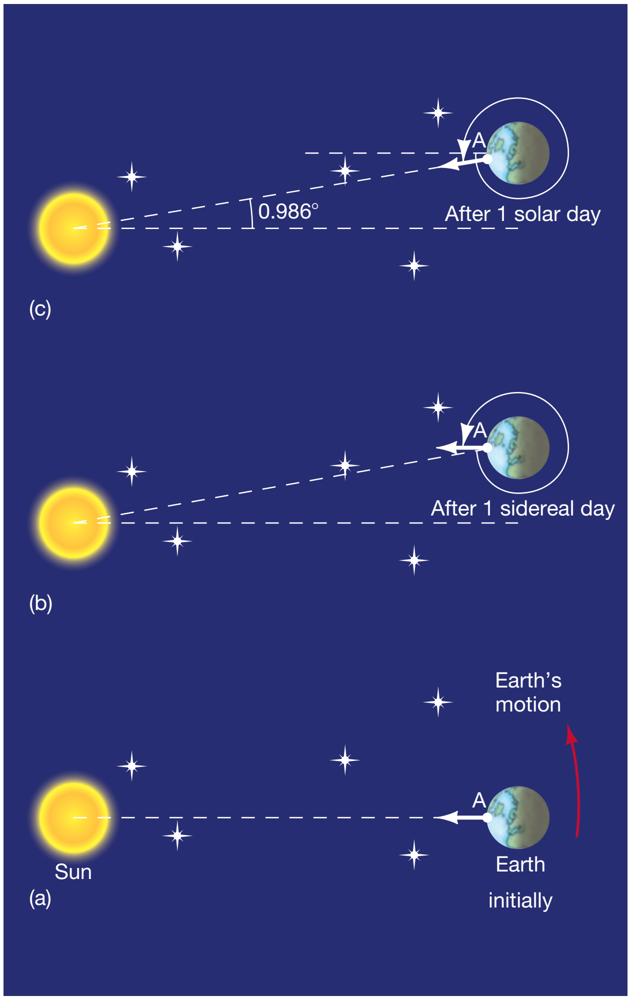
Day-to-Day Changes

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^h56^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

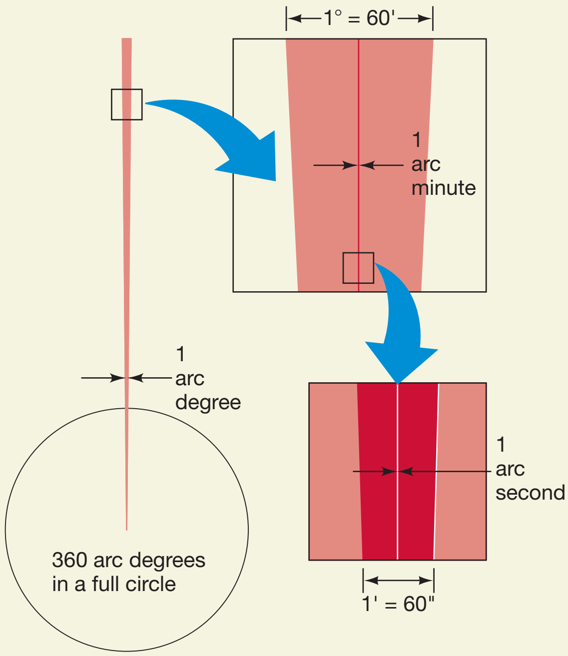
Angular Measure

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.



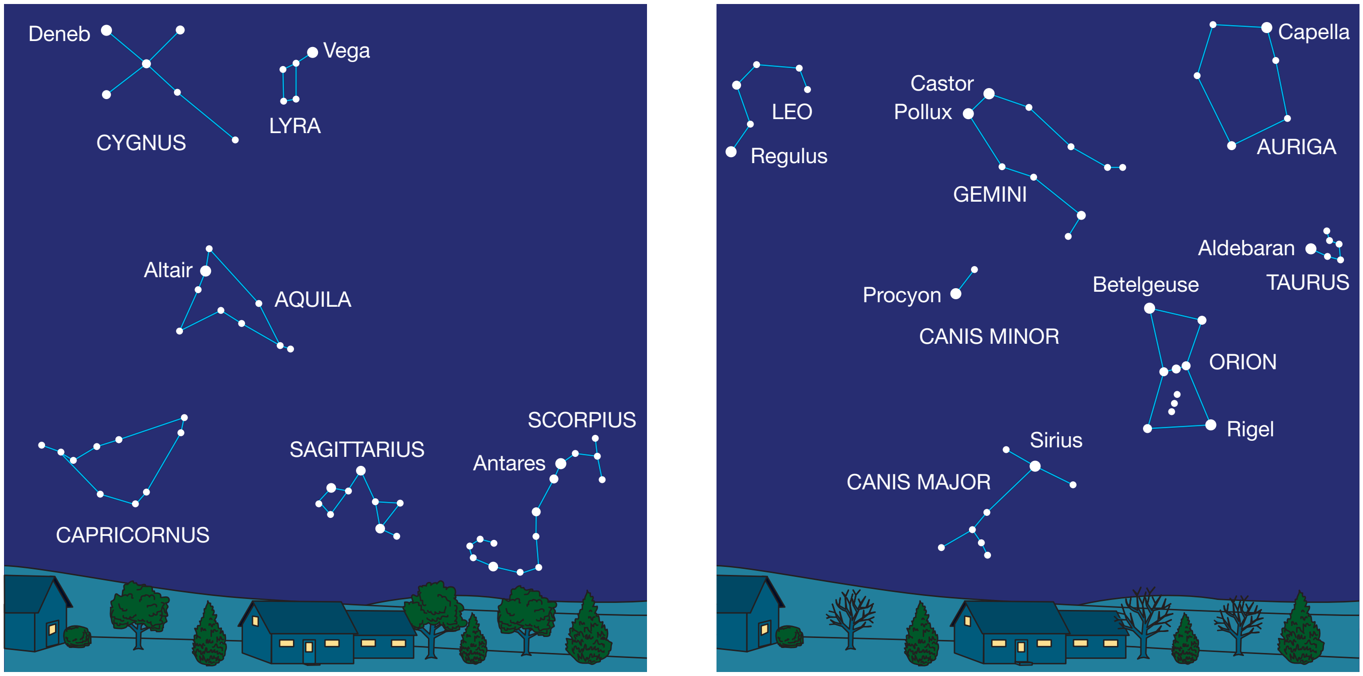
The angular size of an object depends both on its actual size and on its distance from us. For example, the Moon at its present distance from Earth has an angular diameter of 0.5°, or 30′. If the Moon were twice as far away, it would appear half as big—15′ across—even though its actual size would be 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.



(a) Southern horizon, summer

(b) Southern horizon, winter

▲ **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

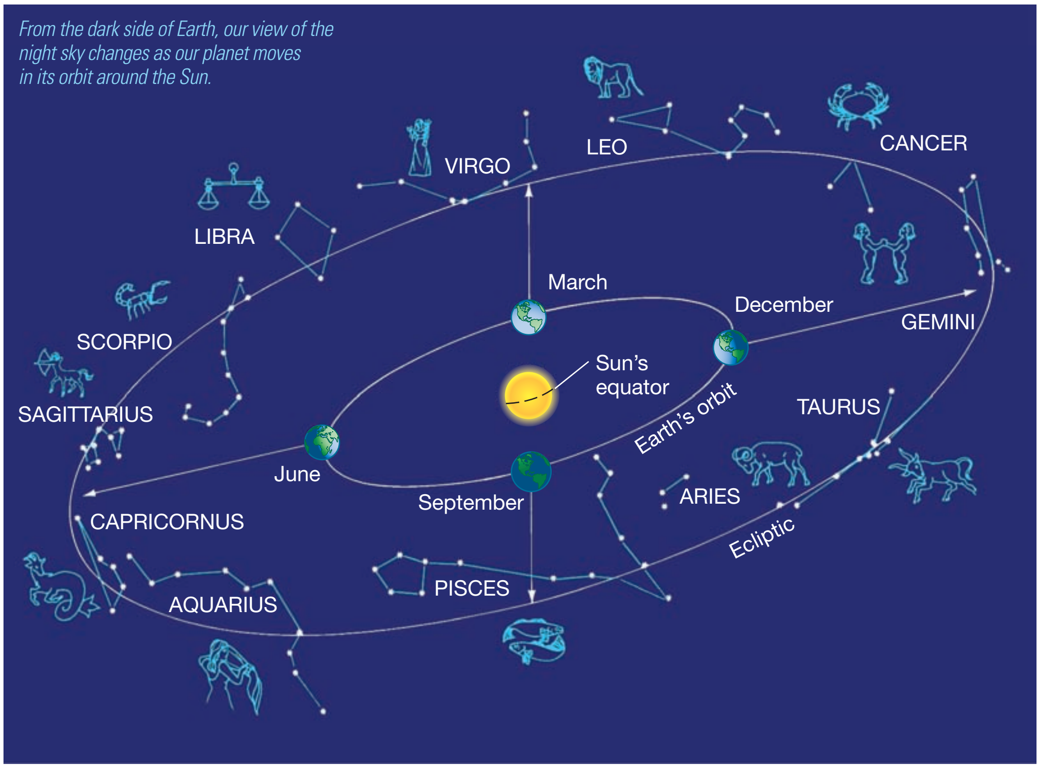
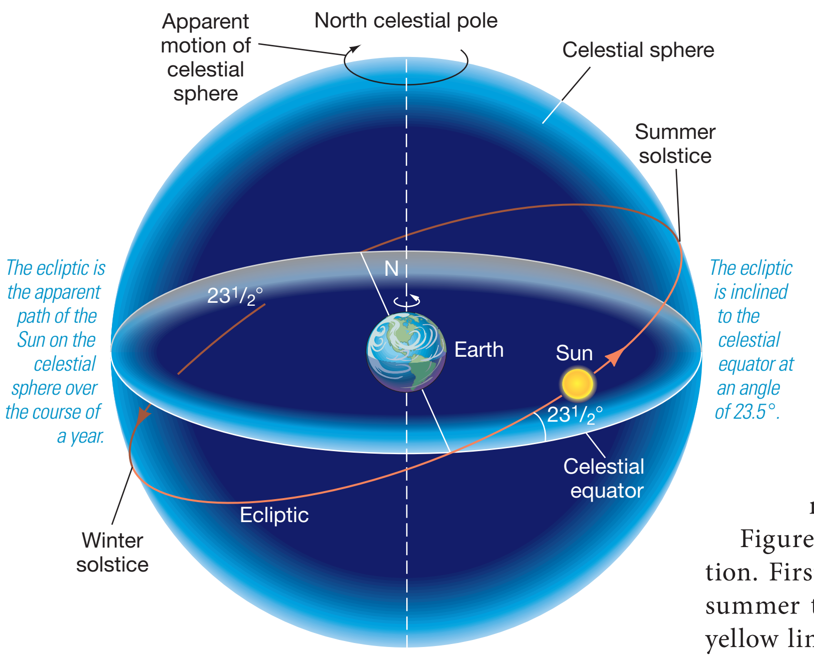


FIGURE 1.15
The Zodiac The night side of Earth faces a different set of constellations at different times of the year. The 12 constellations named here make up the astrological zodiac. The arrows indicate the most prominent zodiacal constellations in the night sky at various times of the year. For example, 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.

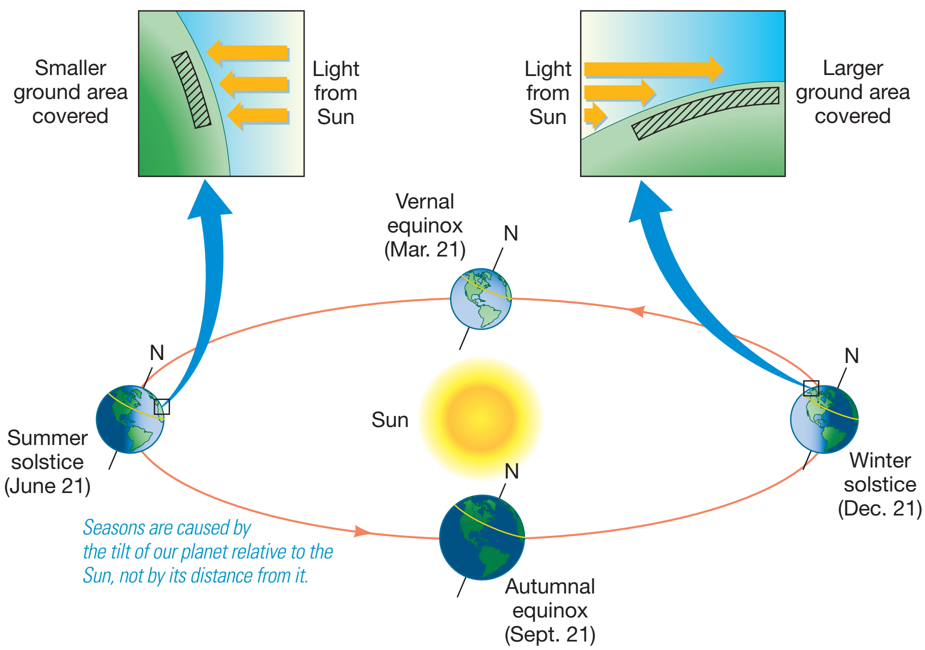
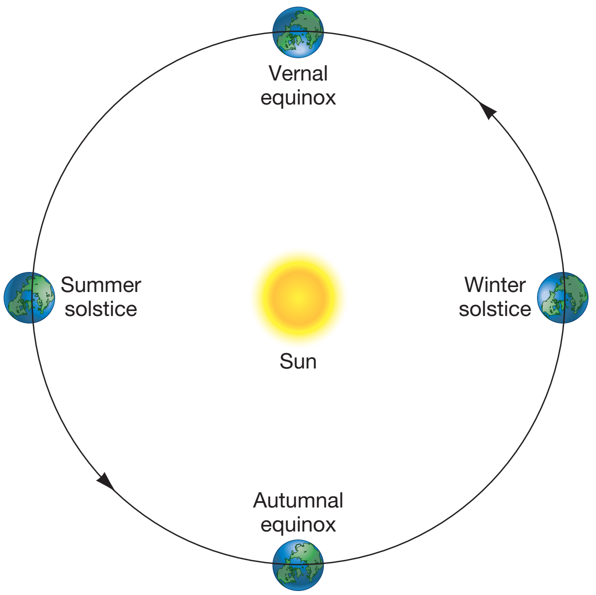


FIGURE 1.17 Seasons Earth's seasons result from the inclination of our planet's rotation axis with respect to its orbit plane. The summer solstice corresponds to the point on Earth's orbit where our planet's North Pole points most nearly toward the Sun. The opposite is true of the winter solstice. The 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?

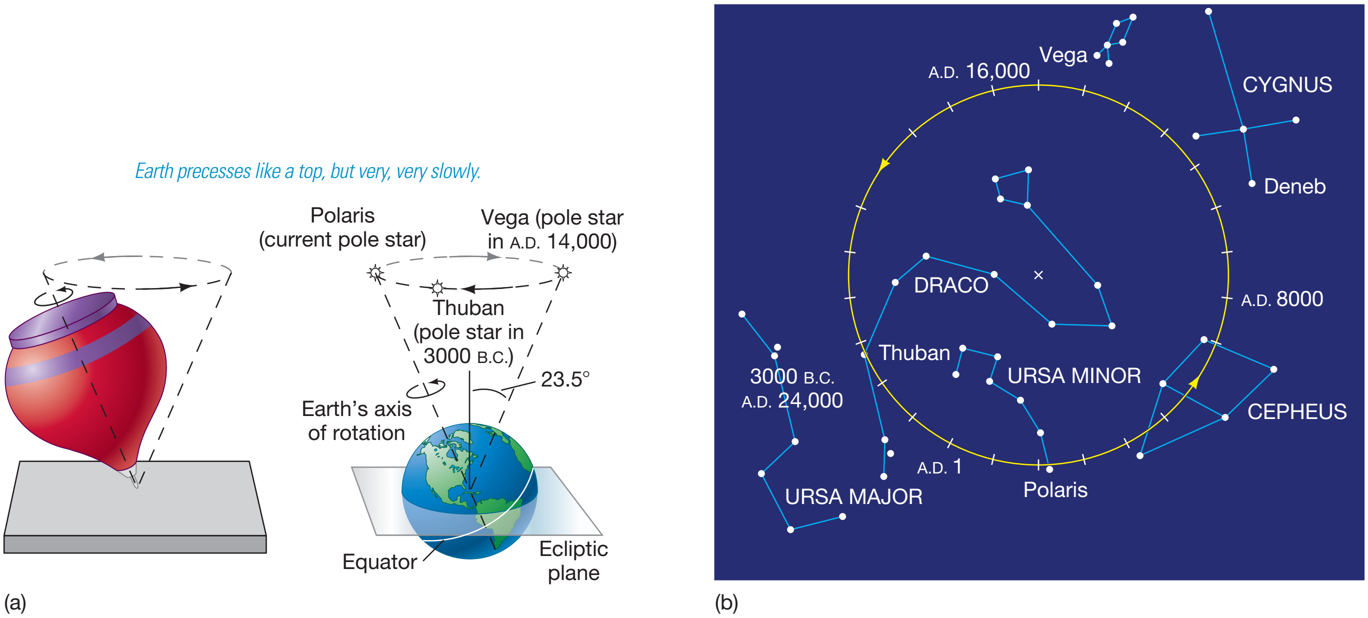


FIGURE 1.19 Precession (a) Earth's axis currently points nearly toward the star Polaris. About 12,000 years from now—almost halfway through one cycle of precession—Earth's axis will point toward a star called Vega, which will then be the "North Star." Five thousand years ago, the North Star was a star 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

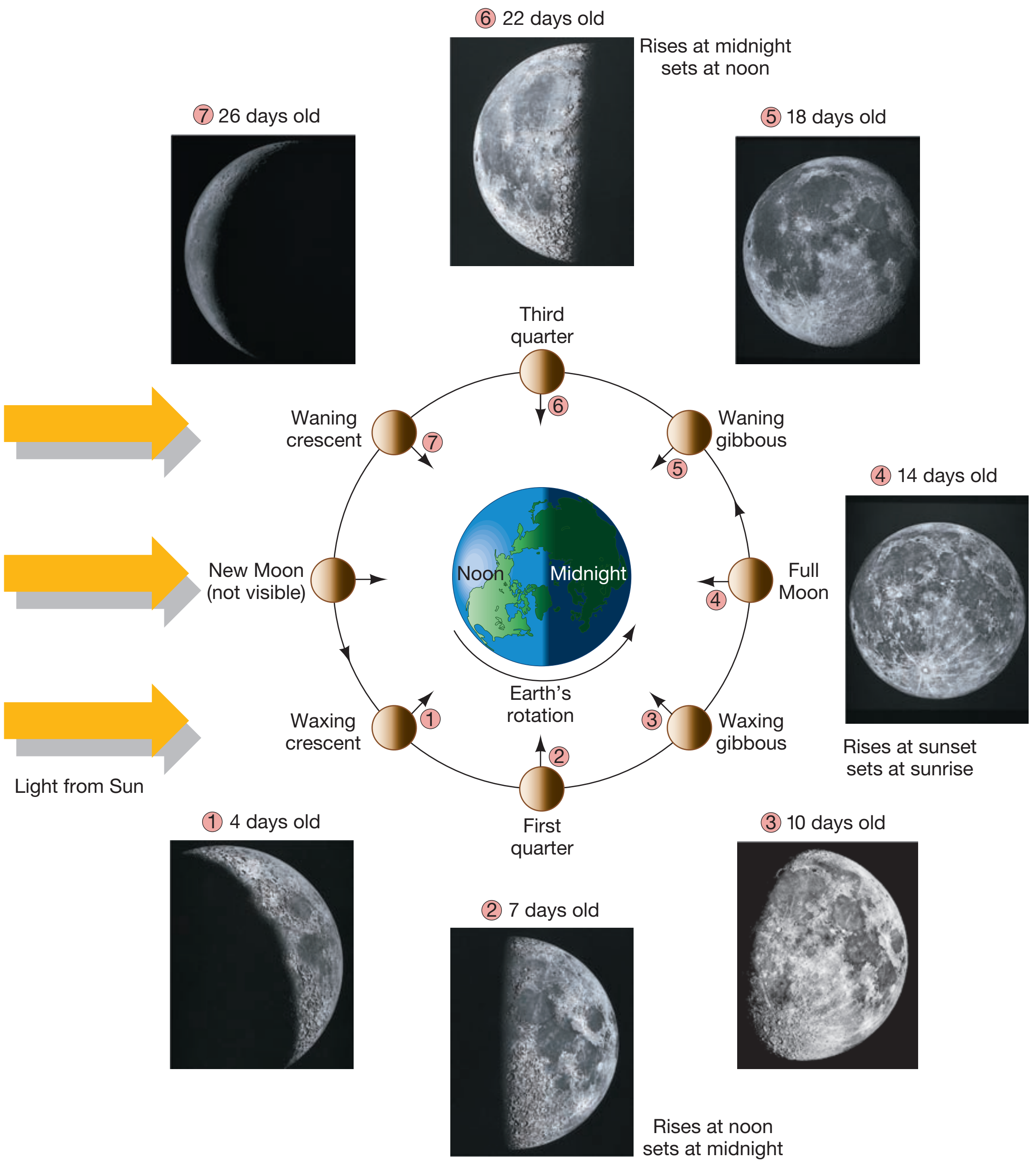


FIGURE 1.20 Lunar Phases Because the Moon orbits Earth, the visible fraction of the lunar sunlit face varies from night to night, although the Moon always keeps the same face toward our planet. (Note the location of the small, straight arrows, which mark the same point on the lunar surface at each phase 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.

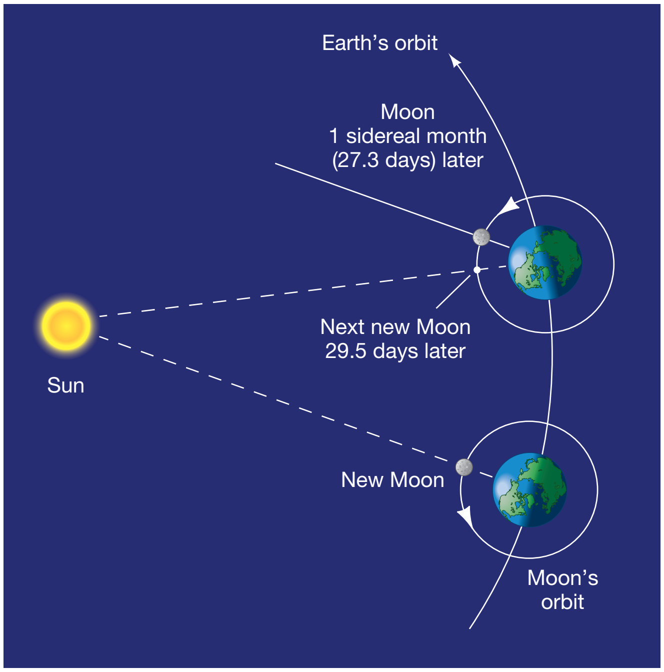


FIGURE 1.21 Sidereal Month The difference between a *synodic* and a *sidereal* month stems from the motion of Earth relative to the Sun. Because Earth orbits the Sun in 365 days, in the 29.5 days from one new Moon to the next (1 synodic month), Earth moves through an angle of approximately 29°. Thus, 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).*

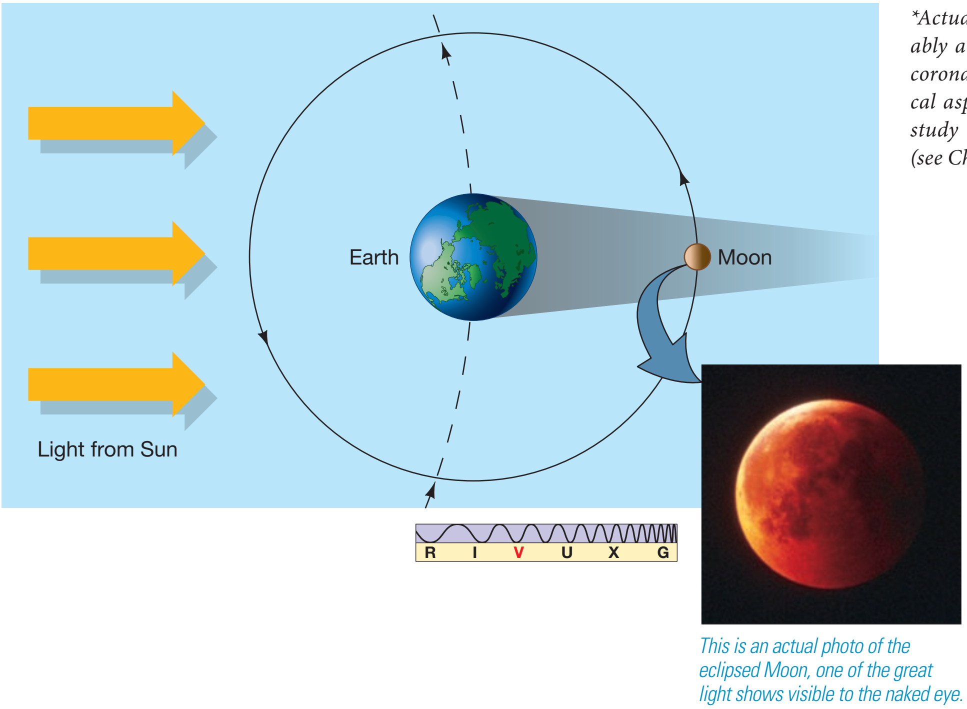
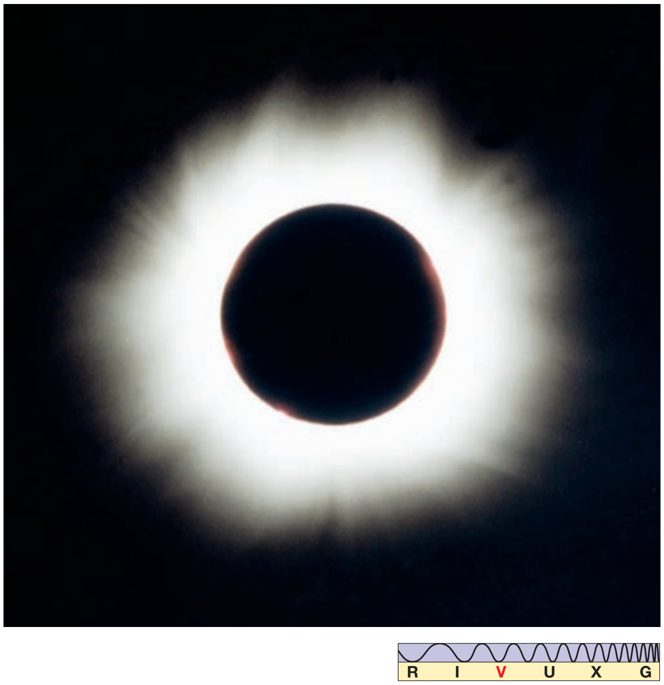


FIGURE 1.22 Lunar Eclipse When the Moon passes through Earth's shadow, we see a darkened, copper-colored Moon, as shown by the partial eclipse in the inset photograph. The red coloration is caused by sunlight deflected by Earth's atmosphere onto the Moon's surface. *(Inset: G. Schneider)*

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 1.23 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)*

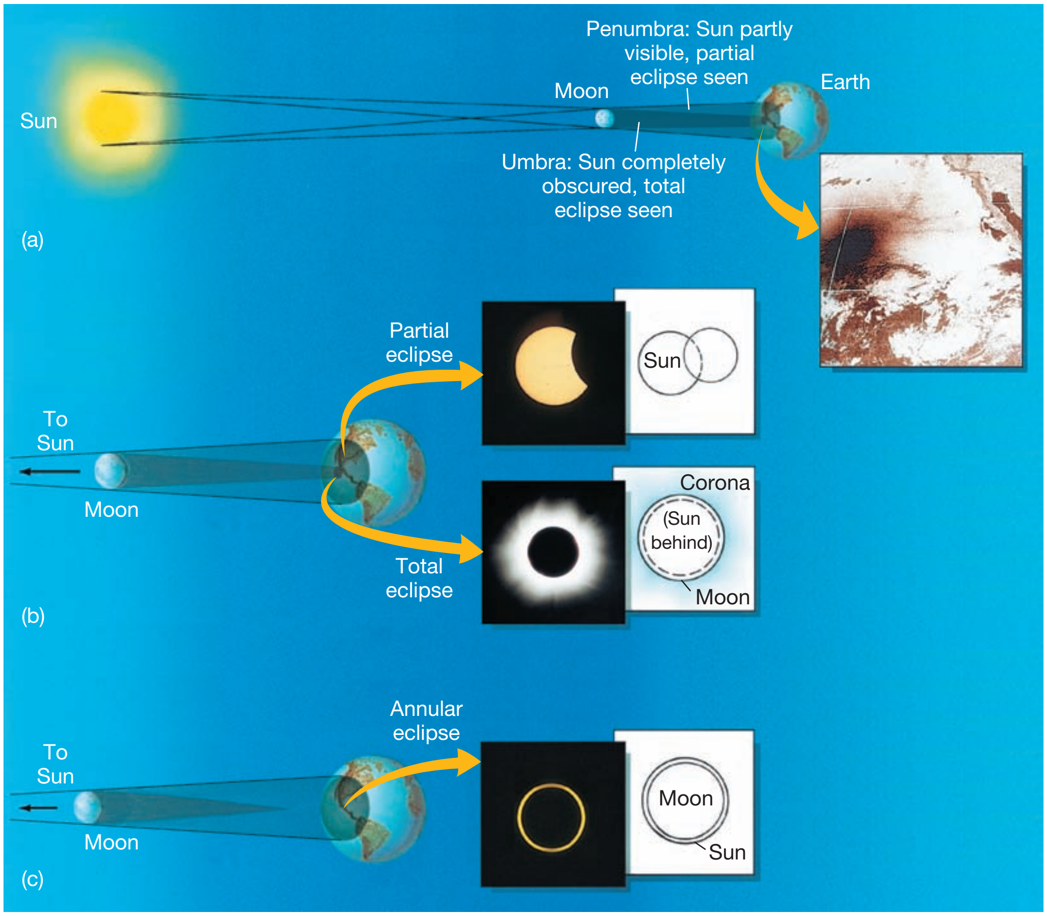


FIGURE 1.24 Types of Solar Eclipse (a) The Moon's shadow consists of two parts: the umbra, where no sunlight is seen, and the penumbra, where a portion of the Sun is visible. (b) If we are in the umbra, we see a total eclipse; in the penumbra, we see a partial eclipse. (c) If the Moon is too far from 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