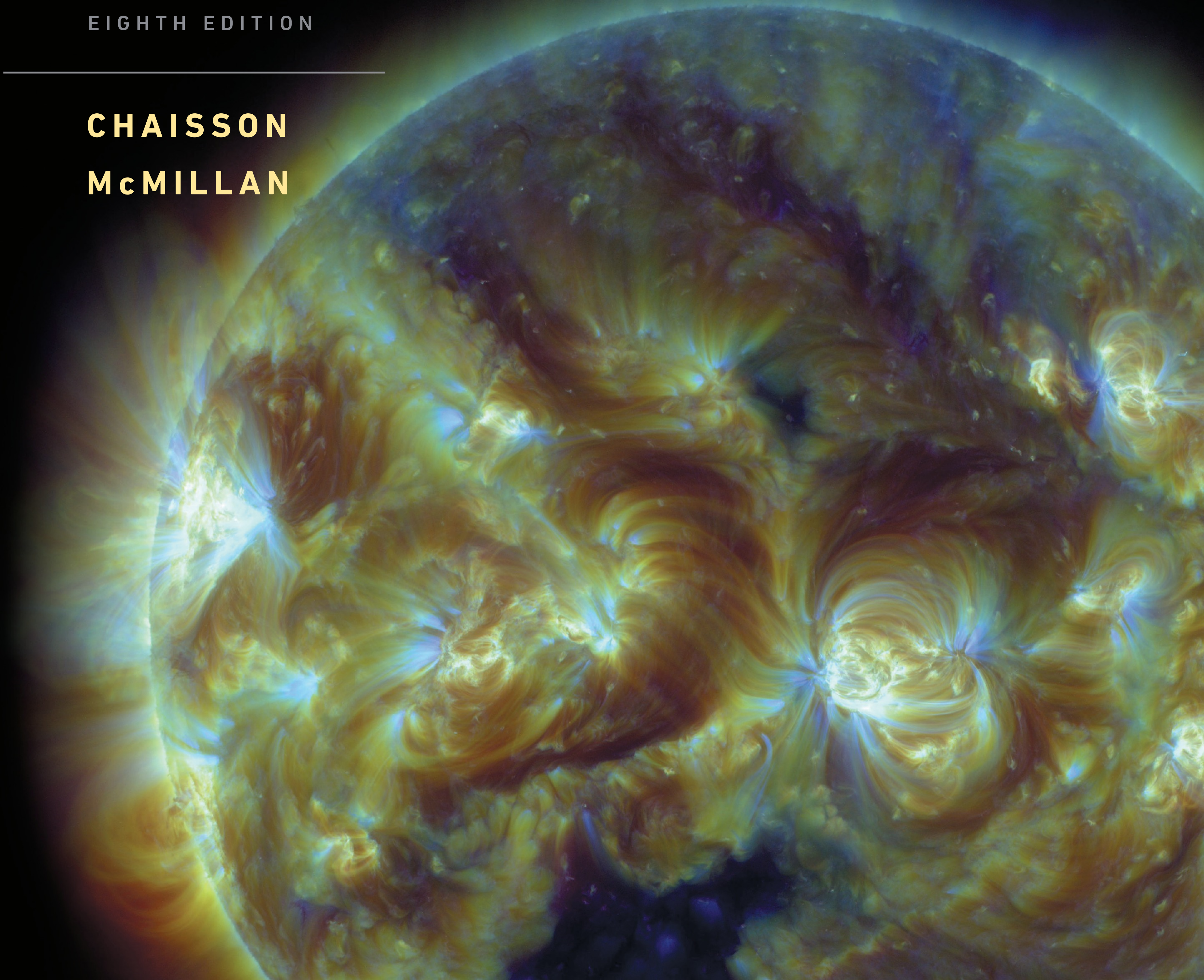
Astronomy

A BEGINNER'S GUIDE TO THE UNIVERSE

EIGHTH EDITION

CHAISSON
McMILLAN



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EIGHTH EDITION

Astronomy

A Beginner's Guide to the Universe

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PEARSON

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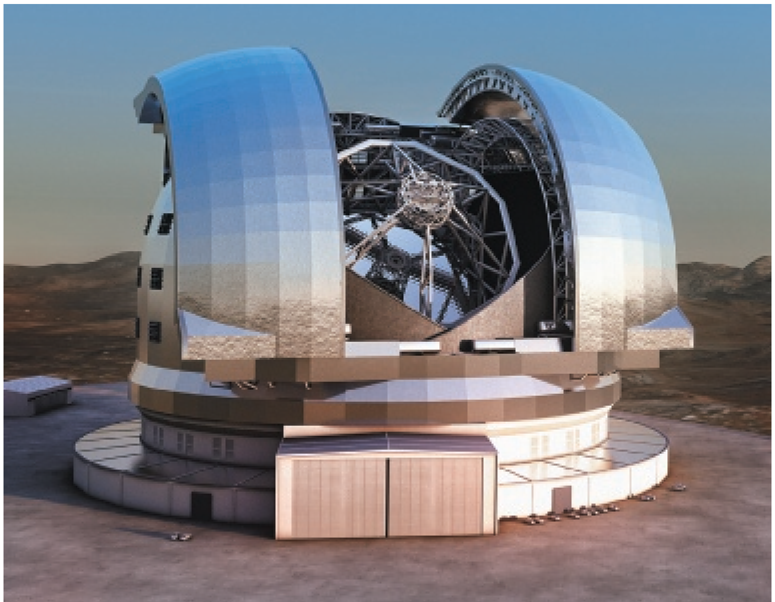

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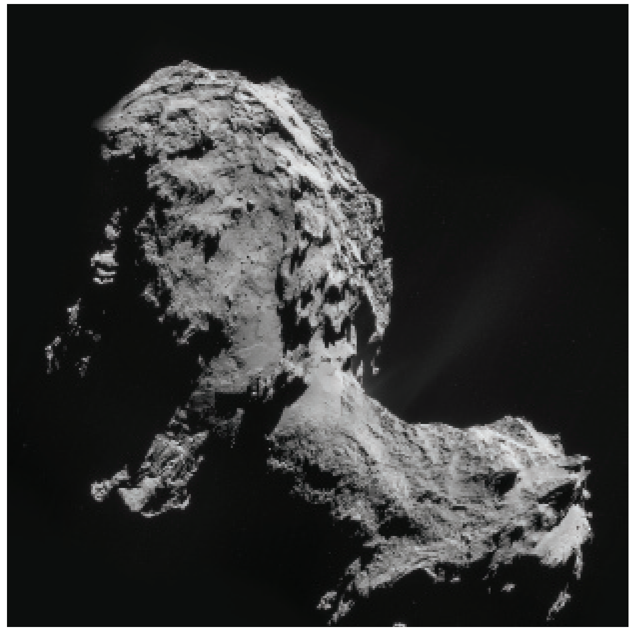

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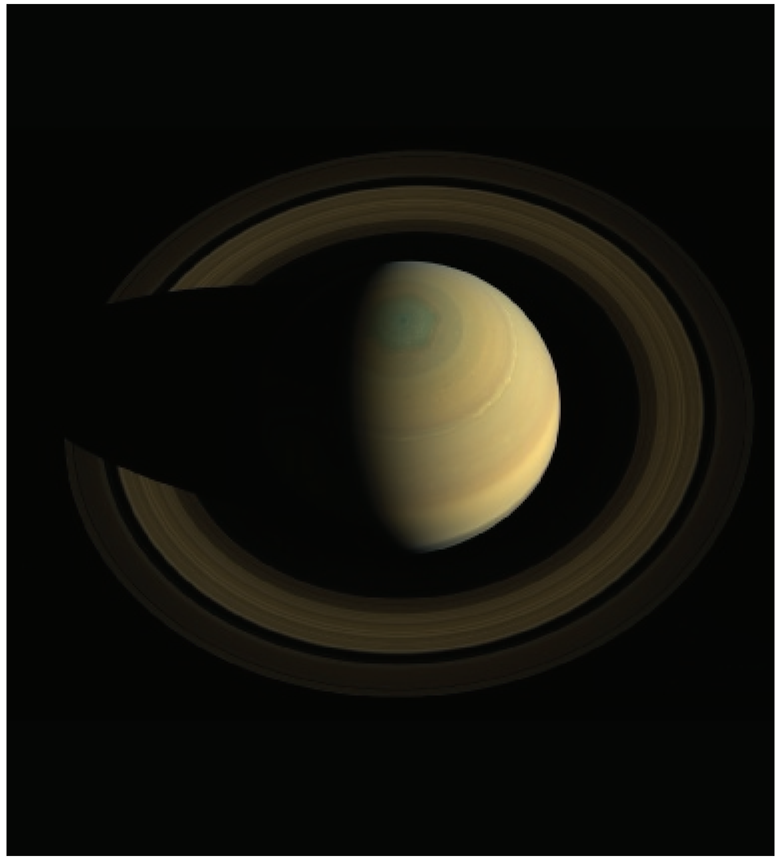

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Preface

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: A Beginner's Guide to the Universe has been written and designed for students who have taken no previous college science courses and who will likely not major in physics or astronomy. 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 that 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 of you—teachers and students alike—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 your comments have been incorporated into this edition.

Organization and Approach

As in previous editions, our organization follows the popular and effective "Earth out" progression. We have found that most students, especially those with little scientific background, are much more comfortable studying the relatively familiar solar system before tackling stars and galaxies. With Earth and Moon as our initial planetary models, we move through the solar system. Integral to our coverage of the solar system is a discussion of its formation. This line of investigation leads directly into a study of the Sun.

With the Sun as our model star, we broaden the scope of our discussion to include stars in general—their properties, their evolutionary histories, and their varied fates. This journey naturally leads us to coverage of the Milky Way Galaxy, which in turn serves as an introduction to our treatment of other galaxies. Finally, we reach cosmology and the large-scale structure and dynamics of the universe as a whole. Throughout, we strive to emphasize the dynamic nature of the cosmos—virtually every major topic, from planets to quasars, includes a discussion of how those objects formed and how they evolve.

We place much of the needed physics in the early chapters—an approach derived from years of experience teaching thousands of students. Additional physical principles are developed as needed later, both in the text narrative and in the *Discovery* and *More Precisely* boxes (described on p. xiv). We have made the treatment of physics, as well as the more quantitative discussions, as modular as possible, so that these topics can be deferred if desired. Instructors presenting this material in a one-quarter course, who wish to (or have time to) cover only the essentials of the solar system before proceeding on to the study of stars and the rest of the universe, may want to teach only Chapter 4 (the solar system) and then move directly to Chapter 9 (the Sun).

What's New in This Edition

Astronomy is a rapidly evolving field, and almost every chapter in the eighth edition has been updated with new and late-breaking information. Several chapters have also seen significant internal 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. Among the many improvements are the following:

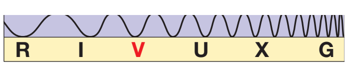
- New chapter-opening images reflecting the latest astronomical discoveries.
- Updated astronomical imagery throughout.
- Streamlined art program providing more direct and accurate representations of astronomical objects.
- Increased use of annotations to clarify figure content.
- Updates in Chapter 3 on the *Hubble Space Telescope* and its successor, the *James Webb Space Telescope;* new material on new very large ground-based telescopes now under construction.
- New imagery throughout from the recently completed *ALMA* interferometric array.
- Updated coverage in Chapter 4 of the *Dawn* mission to asteroids Vesta and Ceres and the *Rosetta* mission to comet 67 P/Churyumov–Gerasimenko.
- Updates in Chapter 4 on exoplanet properties, with a new focus on Earths and super-Earths; revised discussion of habitable zones and Earth-like worlds.
- Updates on global CO_2 levels and global warming in Chapter 5.
- Updated data in Chapter 5 on lunar interior structure following the *LCROSS* and *GRAIL* missions; new *Lunar Reconnaissance Orbiter* imagery of lunar surface features.
- Updated discussion in Chapter 6 of Mercury's surface and internal structure in light of the findings of the *Messenger* probe.
- Updated discussion of Mars in Chapter 6, including results from the *Curiosity* mission.
- Updates in Chapter 7 on storm systems on the outer planets, Jupiter's shrinking Great Red Spot, and Saturn's polar vortices.
- New *Discovery* feature in Chapter 7 on solar system exploration.

- Updated discussion in Chapter 8 of Ganymede's magnetism, subsurface water, and aurora; updated material on Enceladus and its internal ocean.
- New material and rewritten discussion in Chapter 8 of the Pluto system following the *New Horizons* flyby; updated discussion of trans-Neptunian objects.
- New higher-resolution *Solar Dynamics Observatory* imagery in Chapter 9 of the corona, sunspots, and coronal mass ejections.
- Improved diagrams and updated discussion of the sunspot cycle in Chapter 9.
- Updated text and *ALMA* imagery on star-forming regions in Chapter 11.
- New supernova imagery and discussion in Chapter 12.
- Updated discussion in Chapter 13 of gamma-ray bursts and hypernovae.
- Added new art to the discussion of Special Relativity in *More Precisely* 13-1.
- Updated discussion in Chapter 14 of Milky Way formation.
- Updated discussion in Chapter 14 of stellar orbits around the central supermassive black hole.
- New discussion in Chapter 14 of energetic outflows from the Galactic center.
- Updated discussion in Chapter 16 of hot gas in galaxy clusters.
- New discussion in Chapter 16 of the star formation history of the universe.
- Updated discussion in Chapter 16 of galactic cannibalism.
- Integrated treatment in Chapter 16 of tidal streams in the Milky Way.
- Updated discussion in Chapter 17 of the cosmic microwave background; new discussion of acoustic oscillations and their relevance to cosmology.
- Expanded discussion of extremophilic life in Chapter 18.

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 enrich 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 tightly tied to nearby discussion of important scientific facts and ideas.

Full-Spectrum Coverage and Spectrum Icons



Increasingly, astronomers are exploiting 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.

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.

Learning Outcomes Studies indicate that beginning students often 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 determine what mastery they should be able to demonstrate after reading the chapter and then structure their reading accordingly. The outcomes are numbered and keyed to the items in the Chapter Summary and the Review and Discussion section, which in turn refer back to passages in the text. This highlights the most important aspects of the chapter, helping students prioritize information and aiding their review of the material. The outcomes are organized and phrased in such a way as to make them objectively testable, affording students a means of gauging their own progress.

The Big Picture and The Big Question Each chapter begins with a Big Picture overview of not only the content of the chapter, but also the critical issues facing the topic covered in the chapter; its purpose is to help students see how chapter content is connected to a broad understanding of the universe.

The Big Picture is bookended with a similar feature called The Big Question at the end of each chapter; the Big Question poses a cosmic, open-ended question about the chapter's topic area that is intended to ignite students' curiosity about the still-unanswered questions at the forefront of astronomical knowledge and research.

THE BIG PICTURE

Light collected tonight from the most distant galaxies was emitted by those objects long before Earth even formed. Racing for billions of years across the darkened realms of the cosmos, a minute fraction of their radiation is now intercepted by our telescopes and spacecraft. Captured in the many images of this book, that radiation tells us not only about the properties of faraway galaxies, but also about the history of our Galaxy and the universe in which we live.

THE BIG QUESTION

Galactic research lags stellar research by about 50 years. That's because galaxies were discovered only in the 20th century, and we are still learning about them. How did they form, and how do they evolve? Those are the biggest questions regarding galaxies, and they will not be answered until more and better data accumulate, especially regarding the most distant systems. Will the much larger galaxy surveys now on the horizon help solve these important issues?

Data Points Data Points sidebars in each chapter, based on data captured from thousands of students, alert students to the statistically most common mistakes made when working problems on related topics in MasteringAstronomy.

Concept Links The connection between the astronomical material and the physical principles set forth early in the text is crucial. It is important that students, when they encounter, say, Hubble's law in Chapter 15, recall what they learned about spectral lines and the Doppler shift in Chapter 2. Similarly, the discussions of the masses of binary star components (Chapter 10) and of galactic rotation (Chapter 14) both depend on the discussion of Kepler's and Newton's laws in Chapter 1. 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 can 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 ∞, signal students that the topic under discussion is related in some significant way to ideas developed earlier and direct them to material that they might wish to review before proceeding.

MA **Interactive Figures and Photos** Icons throughout the text direct students to dynamic versions of art and photos on MasteringAstronomy™. Using online applets, students can manipulate factors such as time, wavelength, scale, and perspective to increase their understanding of these figures.

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, a full alphabetical glossary, defining each key term and locating its first use in the text, appears at the end of the book.

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

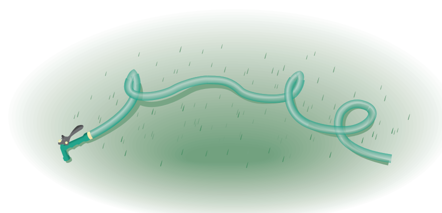
Why does a star get brighter as it runs out of fuel in its core?

Process of Science Checks Similar to Concept Checks, Process of Science Checks are aimed specifically at clarifying 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

Why are observations of star clusters so important to the theory of stellar evolution?

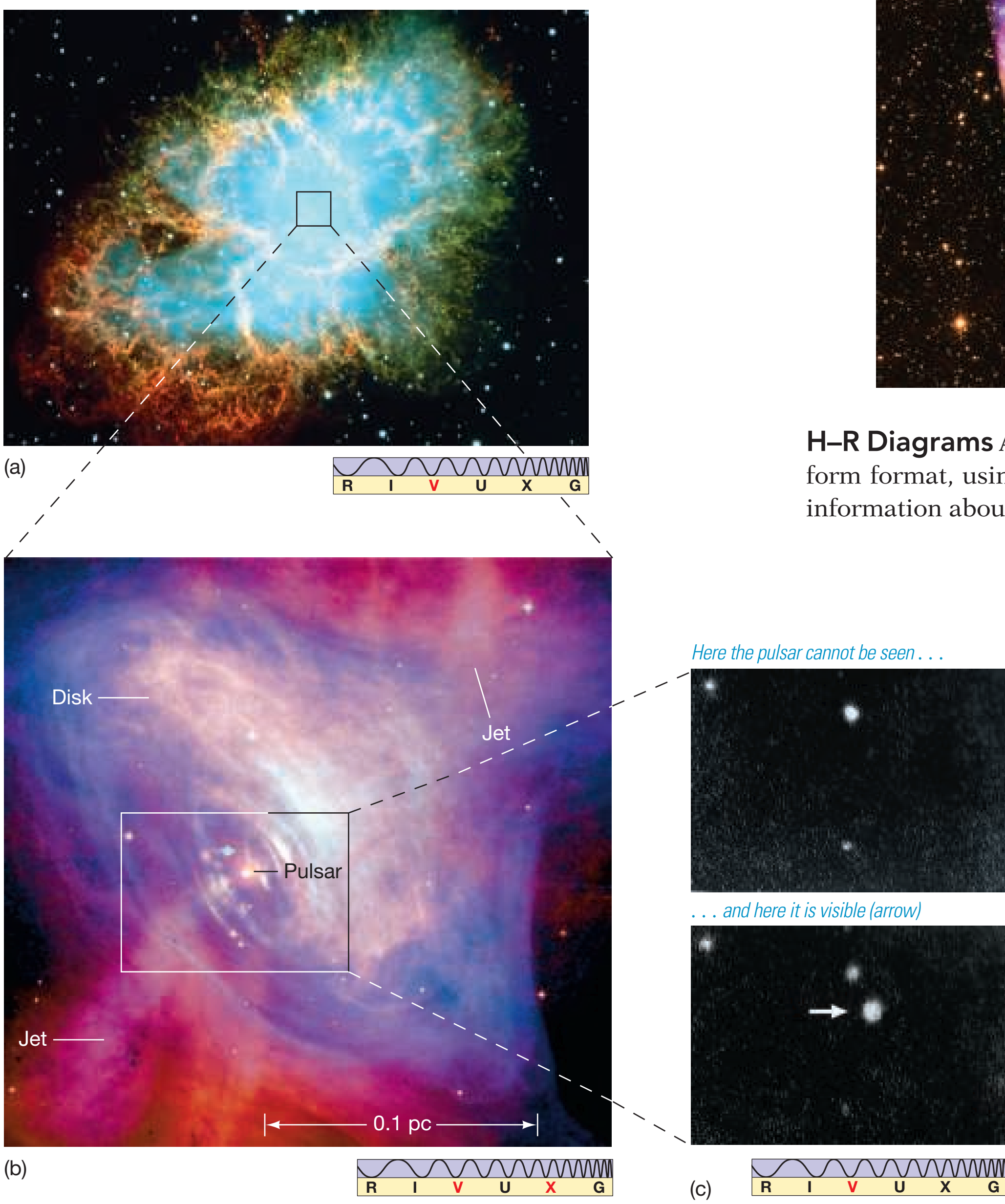
Visual Analogies Revised for clarity, visual analogies link art and analogy, explaining complex astronomical concepts with references to everyday experience.



A good analogy to a tangled solar magnetic field is a garden hose with loops and kinks.

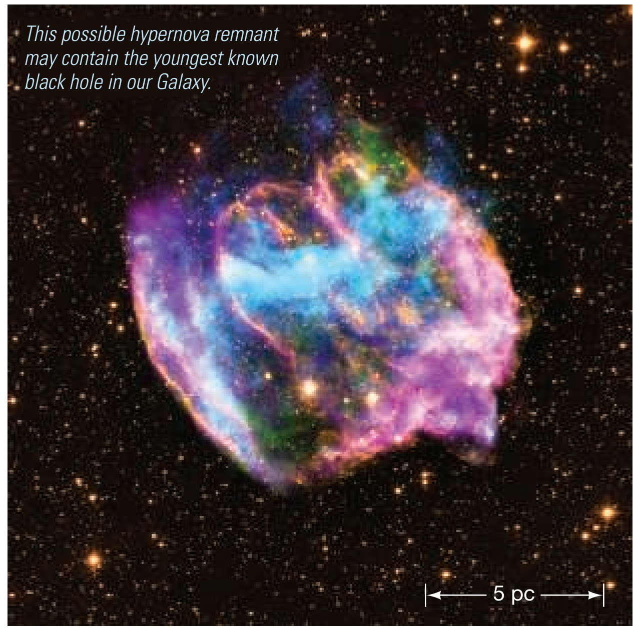
Compound Art It is rare that a single image, be it a photograph or an artist's conception, can capture all aspects of a complex subject. Wherever possible, multiple-part figures are used in an attempt to convey the greatest amount of information in the most vivid way:

- 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 13.4 Crab Pulsar** In the core of the Crab Nebula (a), the Crab pulsar (c) blinks on and off about 30 times each second. In the top frame, the pulsar is off; in the bottom frame, it is on (arrow). (b) This *Chandra* X-ray image of the Crab, superimposed on a *Hubble* optical image, shows the central pulsar, as well as rings of hot X-ray-emitting gas in the equatorial plane, driven outward by the pulsar wind. Also visible in the image is a jet of hot gas escaping perpendicular to the equatorial plane. *(ESO; NASA; UC/Lick Observatory)*

Figure Annotations 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 verbal and visual knowledge.



H–R Diagrams All of the book's H–R diagrams are drawn in a uniform format, using real data. H–R diagrams help us organize our information about the stars and track their evolutionary histories.

▶ **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 allow instructors greater flexibility in setting the level of their coverage.

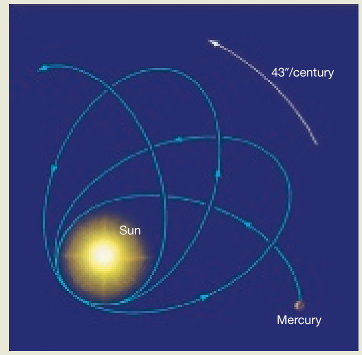
13.2 MORE PRECISELY

Tests of General Relativity

Special relativity is the most thoroughly tested and most accurately verified theory in the history of science. General relativity, however, is on somewhat less firm experimental ground. The problem with verifying general relativity is that its effects on Earth and in the solar system—the places where we can most easily perform tests—are very small. Just as special relativity produces major departures from Newtonian mechanics only when speeds approach the speed of light, general relativity predicts large departures from Newtonian gravity only when extremely strong gravitational fields are involved.

Here we consider just two "classical" tests of the theory—solar system experiments that helped ensure acceptance of Einstein's theory. Bear in mind, however, that there are no known tests of general relativity in the "strong-field" regime—that part of the theory that predicts black holes, for example—so the full theory has never been experimentally tested.

At the heart of general relativity is the premise that everything, including light, is affected by gravity because of the curvature of spacetime. Shortly after he published his theory in 1915, Einstein noted that light from a star should be deflected by a measurable amount as it passes the Sun. The closer to the Sun the light comes, the more it is deflected. Thus, the maximum deflection should occur for a ray that just grazes the solar surface. Einstein calculated that the deflection angle should be 1.75, a small but detectable amount.



Of course, it is normally impossible to see stars so close to the Sun. During a solar eclipse, however, when the Moon blocks the Sun's light, the observation does become possible, as illustrated in the figure at lower left. In 1919 a team of observers led by British astronomer Sir Arthur Eddington succeeded in meas-

14.2 DISCOVERY

Density Waves

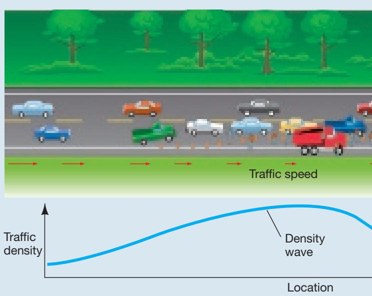
In the late 1960s, American astrophysicists C. C. Lin and Frank Shu proposed a way in which spiral arms in the Galaxy could persist for many Galactic rotations. They argued that the arms themselves contain no "permanent" matter. They should not be viewed as assemblages of stars, gas, and dust moving intact through the disk because such structures would quickly be destroyed by differential rotation. Instead, as described in the text, a spiral arm should be envisaged as a *density wave*—a wave of alternating compression and expansion sweeping through the Galaxy.

A wave in water builds up material temporarily in some places (crests) and lets it down in others (troughs). Similarly, as Galactic matter encounters a spiral density wave, the matter is compressed to form a region of higher than normal density. The matter enters the wave, is temporarily slowed down (by gravity) and compressed as it passes through, then continues on its way. This compression triggers the formation of new stars and nebulae. In this way, the spiral arms are formed and reformed repeatedly, without wrapping up.

The accompanying figure illustrates the formation of a density wave in a more familiar context—a traffic jam triggered by the presence of a repair crew moving slowly down the road. Cars slow down temporarily as they approach the crew, then speed up again as they pass the worksite and continue on their way. The result observed by a traffic helicopter flying overhead is a region of high traffic density concentrated around the work crew and moving with it. An observer on the side of the road, however, sees that the jam never contains the same cars for very long. Cars constantly catch up to the bottleneck, move slowly through it, then speed up again, only to be replaced by more cars arriving from behind.

The traffic jam is analogous to the region of high stellar density in a Galactic spiral arm. Just as the traffic density wave is not tied to any particular group of cars, the spiral arms are not attached to any particular piece of disk material. Stars and gas enter a spiral arm, slow down for a while, then exit the arm and continue on their way around the Galactic center. The result is a moving region of high stellar and gas density, involving different parts of the disk at different times. Notice also that, just as in our Galaxy, the traffic jam wave moves more slowly than, and independently of, the overall traffic flow.

We can extend our traffic analogy a little further. Most drivers are well aware that the effects of such a tie-up can persist long after the road crew has stopped work and gone home for the night. Similarly, spiral density waves can continue to move through the disk even after the disturbance that originally produced them has long since subsided. According to spiral density wave theory, this is precisely what has happened in the Milky Way Galaxy. Some disturbance in the past—an encounter with a satellite galaxy, perhaps, or the effect of the central bar—produced a wave that has



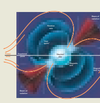
◀ **DISCOVERY Boxes** Exploring a wide variety of interesting topics, *Discovery* boxes provide the reader with insight into how scientific knowledge evolves and emphasizes the process of science.

CHAPTER REVIEW

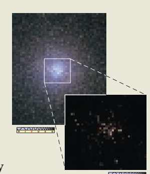
SUMMARY

LO1 A core-collapse supernova may leave behind an ultracompressed ball of material called a **neutron star** (p. 362). This is the remnant of the inner core that rebounded and blew the rest of the star apart. Neutron stars are extremely dense and, at formation, are predicted to be extremely hot, strongly magnetized, and rapidly rotating. They cool down, lose much of their magnetism, and slow down as they age.

LO2 According to the **lighthouse model** (p. 364), neutron stars, because they are magnetized and rotating, send regular bursts of electromagnetic energy into space. The beams are produced by charged particles confined by the strong magnetic fields. When we can see the beams from Earth, we call the source neutron star a **pulsar** (p. 362). The pulse period is the rotation period of the neutron star.

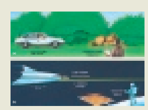


LO3 A neutron star that is a member of a binary system can draw matter from its companion, forming an accretion disk, which is usually a strong source of X-rays. As gas builds up on the star's surface, it eventually becomes hot enough to fuse hydrogen. When hydrogen burning starts on a neutron star, it does so explosively, and an **X-ray burster** (p. 366) results. The rapid rotation of the inner part of the accretion disk causes the neutron star to spin faster as new gas arrives on its surface. The eventual result is a very rapidly rotating neutron star—a **millisecond pulsar** (p. 366). Many millisecond pulsars are found in the

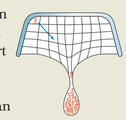


explosions involve the violent merger of neutron stars in a distant binary system, or the recollapse and subsequent violent explosion following a "failed" supernova in a very massive star.

LO5 Einstein's special theory of relativity deals with the behavior of particles moving at speeds comparable to the speed of light. It agrees with Newton's theory at low velocities, but makes many very different predictions for high-speed motion. All of its predictions have been repeatedly verified by experiment. The modern replacement for Newtonian gravity is Einstein's **general theory of relativity** (p. 373), which describes gravity in terms of the warping, or bending, of space by the presence of mass. The more mass, the greater the warping. All particles—including photons—respond to that warping by moving along curved paths.



LO6 The upper limit on the mass of a neutron star is about three solar masses. Beyond that mass, the star can no longer support itself against its own gravity, and it collapses to form a **black hole** (p. 373), a region of space from which nothing can escape. The most massive stars, after exploding in a supernova, form black holes rather than neutron stars. Conditions in and near black holes can only be described by general relativity. The radius at which the escape speed from a collapsing star equals the speed of light is called the **Schwarzschild radius** (p. 374). The surface of an imaginary sphere centered on the collapsing star and having a radius equal to the star's Schwarzschild radius is called the **event horizon** (p. 374).



▶ **Chapter Summaries** 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. Summary items are keyed to the Learning Outcomes presented at the start of the chapter.

End-of-Chapter Questions and Problems Many elements of the end-of-chapter material have seen substantial reorganization:

- Each chapter has 15 Review and Discussion questions, which may be used for in-class review or for assignment. The material needed to answer Review and Discussion questions can be found within the chapter. The Review and 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. A few (2–4) questions per chapter are marked as directly relevant to the Process of Science theme of the book, and each Learning Outcome is reflected in one of the Review and Discussion questions.
- Each chapter incorporates 15 Self-Test questions, roughly divided between true/false and multiple choice formats, designed to allow students to assess their understanding of the chapter material. As with the Review and Discussion questions, the Self-Test questions can be answered based on material presented in the chapter. Two of the multiple choice questions in each chapter are tied directly to a specific figure or diagram in the text to test students' comprehension of the visual material presented there. Answers to all these questions appear at the end of the book.
- The end-of-chapter material also includes 10 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 appear at the end of the book.
- The end-of-chapter material now includes a number of astronomical Activities relevant to the material presented in the text. Activities include both group and individual projects, ranging from basic naked-eye and telescopic observing exercises, to opinion polls, surveys and group discussion, and astronomical research on the Web.

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MasteringAstronomy has been revised in this edition with extensive new interactive opportunities in the item library for assignment and in the media-rich study area for open-ended student exploration, which students can use whether the instructor assigns homework or not.

Instructor Resource Manual Updated for the eighth edition, this manual provides sample syllabi and course schedules, an overview of each chapter, pedagogical tips, useful analogies, suggestions for classroom demonstrations, writing questions, answers to the end-of-chapter Review and Discussion questions, Conceptual Self-Test, and Problems, selected readings, and additional references and resources. The Instructor Resource Manual is available for download on the Pearson Instructor Resource Center (www.pearsonhighered.com/educator) and in the MasteringAstronomy Instructor Resource Area.

Test Bank This extensive file of approximately 2500 multiple-choice, true/false, fill-in-the-blank, short-answer and essay questions is newly updated and revised for the eighth edition. The questions are organized and referenced by chapter section and by question type. The Test Bank is available within TestGen® as well as electronically on the Pearson Instructor Resource Center (www.pearsonhighered.com/educator) and in MasteringAstronomy.

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

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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 and our more comprehensive text, *Astronomy Today*. To these many helpful colleagues, we offer our sincerest thanks.

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We would also like to express our gratitude to those that have contributed to our accompanying media products and print supplements, as well as Lola Judith Chaisson for assembling and drawing all the H-R diagrams for this edition.

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Special thanks are also in order to the project management team at Thistle Hill Publishing Services, Andrea Archer and Angela Williams Urquhart, and to interior and cover designer Jerilyn Bockorick for making the eighth edition look spectacular.

We are always interested in your feedback on this text. Please email us at aw.astronomy@pearson.com if you find any errors or have comments.

Eric Chaisson
Steve McMillan

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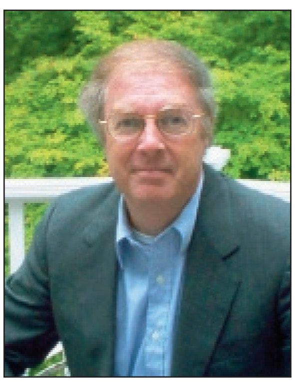

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Astronomy

A Beginner's Guide to the Universe

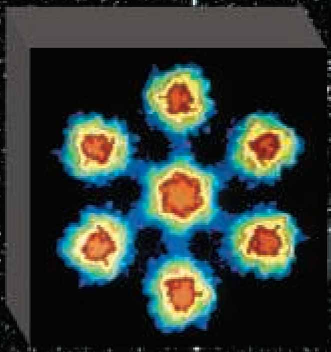
PART 1

Foundations

Astronomy is the study of the universe—the totality of all space, time, matter, and energy. It is a subject like no other, for it requires us to profoundly change our perspective and to consider sizes, scales, and times unfamiliar to us from everyday experience. To appreciate astronomy, we must broaden our view and expand our minds. We must think big!

Part 1 presents the basic methods used by astronomers to chart the space around us. We describe the progress of scientific knowledge, from stories of chariots and gods to today's well-tested ideas of planetary motion and quantum physics. We also delve into the microscopic realm of atoms and molecules, whose properties hold keys to understanding the universe on macroscopic scales.

The images here illustrate the range of scales encountered in Part 1, from atoms to humans to Earth itself.



Atoms ~10^{-10} m

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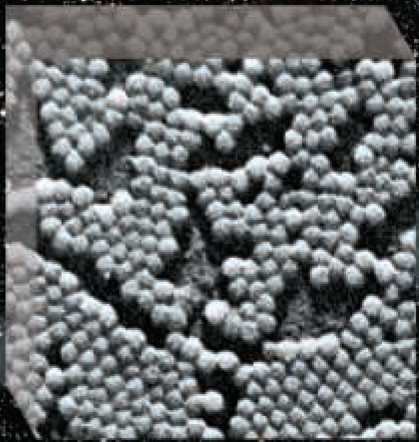
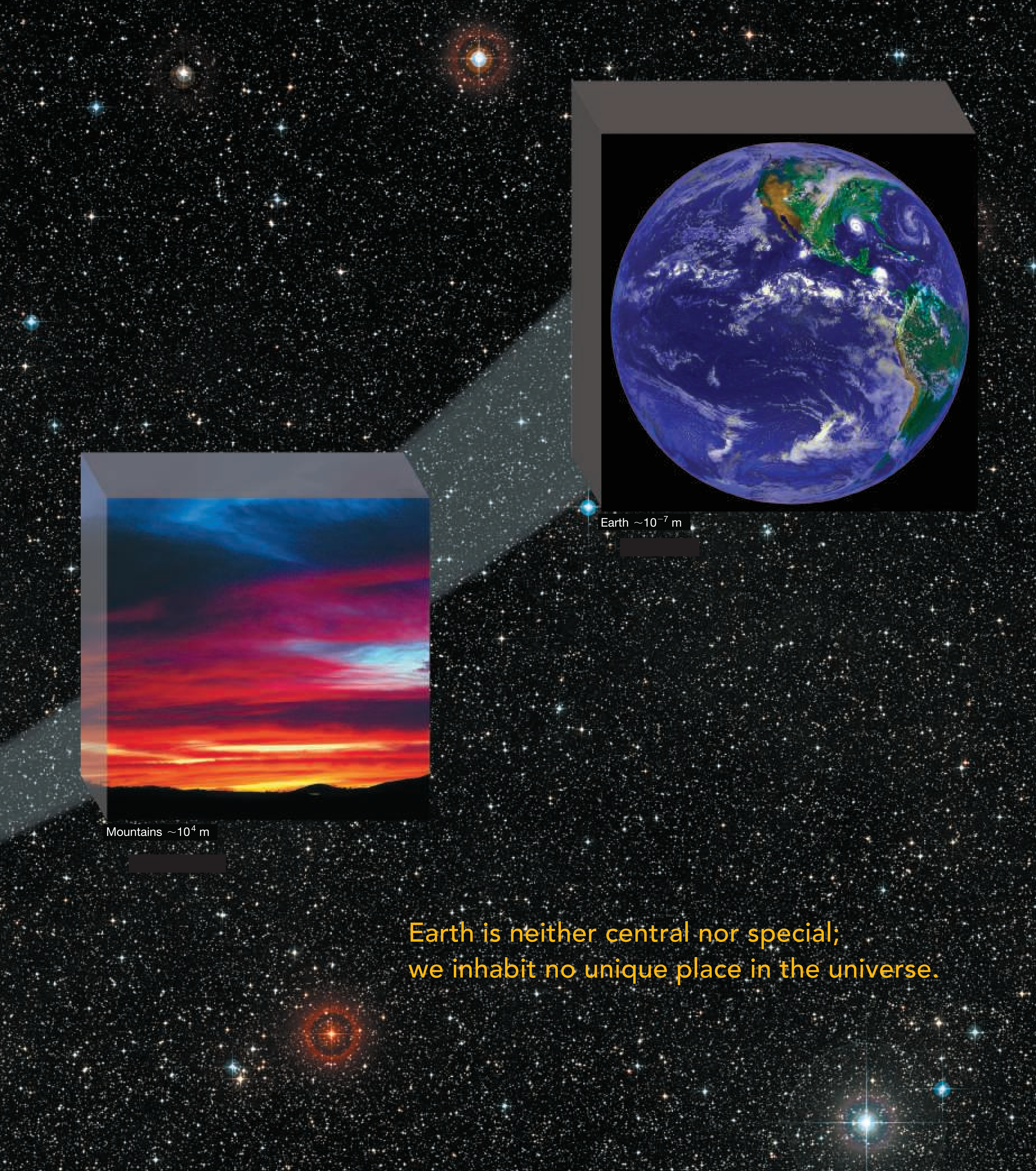


Cells ~10^{-5} m

[redacted]

Humans ~2 m

[redacted]


Mountains ~10^4 m
Earth ~10^-7 m
Earth is neither central nor special;
we inhabit no unique place in the universe.

0

Charting the Heavens

The Foundations of Astronomy

Nature offers no greater splendor than the starry sky on a clear, dark night. Silent and jeweled with the constellations of ancient myth and legend, the night sky has inspired wonder throughout the ages—a wonder that leads our imaginations far from the confines of Earth and out into the distant reaches of space and time. Astronomy, born in response to that wonder, is built on two basic traits of human nature: the need to explore and the need to understand. 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.

LEARNING OUTCOMES

Studying this introductory chapter will enable you to:

- **LO1** Arrange the basic levels of structure in the universe in order of increasing size.
- **LO2** Describe the celestial sphere, and explain how astronomers use constellations and angular measurement to locate objects in the sky.
- **LO3** Account for the apparent motions of the Sun and the stars in terms of Earth's actual motion, and explain how the axial tilt of our planet causes the seasons.
- **LO4** Explain the changing appearance of the Moon, and describe how the relative motions of Earth, the Sun, and the Moon lead to eclipses.
- **LO5** Give an example of how simple geometric reasoning can be used to measure the distances and sizes of otherwise inaccessible objects.
- **LO6** Distinguish between scientific theories, hypotheses, and observations, and describe how scientists combine observation, theory, and testing to understand the universe.

THE BIG PICTURE

Although early astronomy was defined by just the few thousand stars visible to the unaided eye, stars exist everywhere throughout the universe. Roughly as many stars reside in the observable universe as there are grains of sand in all Earth's beaches—about a hundred sextillion, or 10^{23}.

◂ 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 stretching across the sky. 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 large telescopes of the European Southern Observatory, a major astronomical facility located high in the Chilean Andes. (ESO/Y. Beletsky)

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0.1 The "Obvious" View

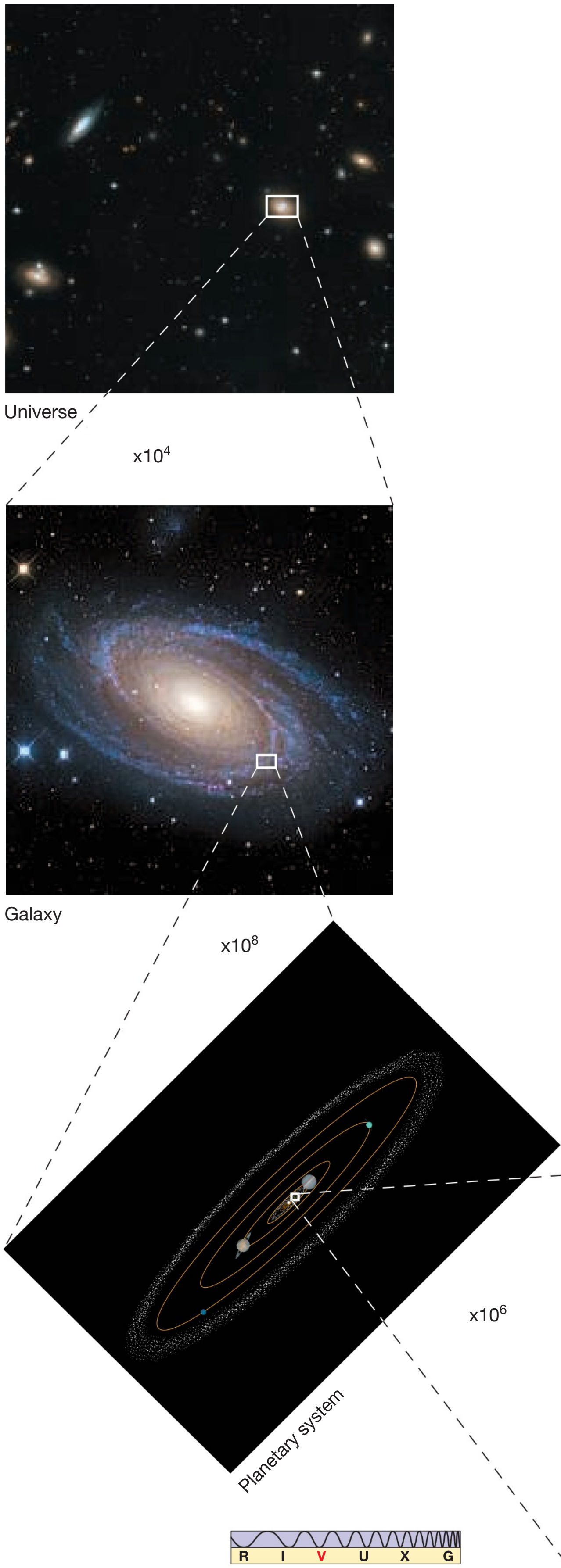
Our Place in Space

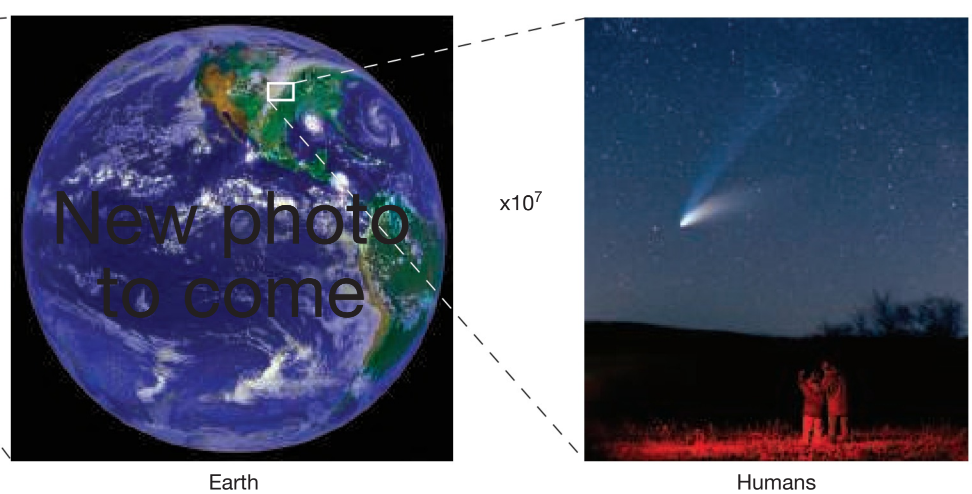
Of all the scientific insights achieved to date, one stands out boldly: Earth is neither central nor special. We inhabit no unique place in the universe. We live on an ordinary rocky **planet** called Earth, one of eight known planets orbiting an average **star** called the Sun, a middle-aged star near the edge of a huge collection of stars called the Milky Way Galaxy, one **galaxy** among countless billions of others spread throughout the observable **universe.** Figure 0.1 illustrates the enormous range of scales of these very different objects.

Today, our scientific understanding of the cosmos extends as far as we can see, spanning the vast reaches of intergalactic space. But the modern view of the universe depicted here is in many ways the "punch line" of the story presented in this text. It is the culmination of countless scientific discoveries, large and small—the work of generations of astronomers. How have astronomers achieved the perspective sketched in Figure 0.1? Our study of the universe, the science of **astronomy,** begins by examining the sky.

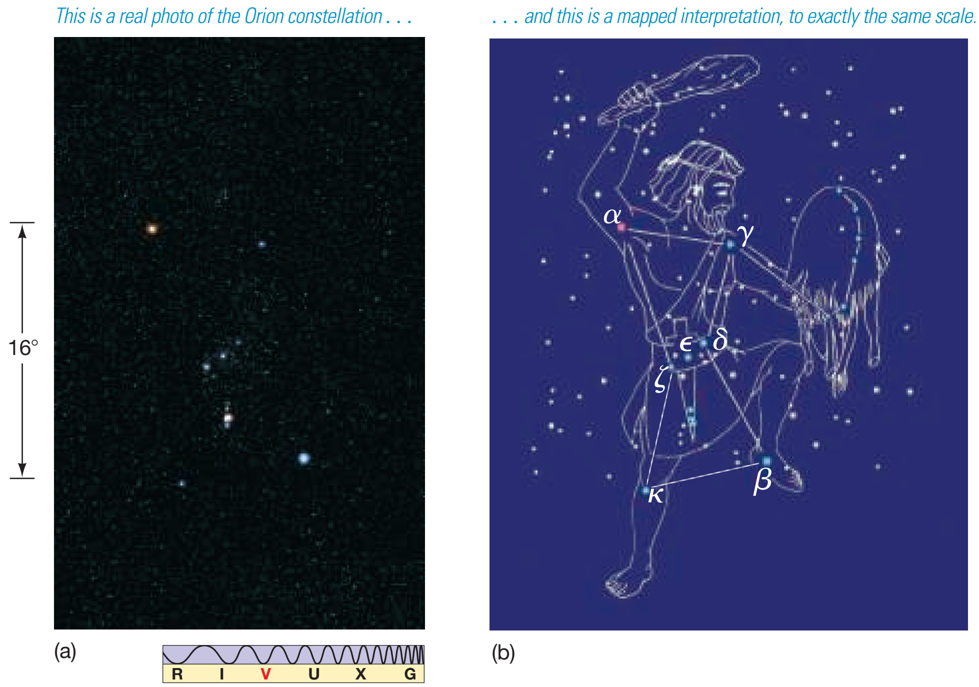
Constellations in the Sky

Between sunset and sunrise on a clear night, we can see some 3000 points of light. Include the view from the opposite side of Earth, and nearly 6000 stars are visible to the unaided eye. A natural human tendency is to see patterns and relationships between objects even when no true connection exists, and people long ago connected the brightest stars into configurations called **constellations.** In the Northern Hemisphere, most constellations were named after mythological heroes and animals. Figure 0.2 shows a constellation especially prominent in the northern night sky from October through March: the hunter Orion, named for a mythical Greek hero famed, among other things, for his amorous pursuit of the





▼ **FIGURE 0.1 Size and Scale in the Universe** The bottom right of this figure shows humans on Earth, a view that widens progressively in the other four scenes from bottom to top—Earth, the solar system, a galaxy, and truly deep space. The numbers within the dashed zooms indicate approximately the increase in scale between successive images: Earth is 10 million times larger than humans, our solar system in turn is some million times larger than Earth, and so on. (See the Preface for an explanation of the icon at the bottom, which here indicates that these images were made in visible light.) *(NASA; J. Lodrigus; NOAA)*



▶ **FIGURE 0.2 Constellation Orion INTERACTIVE** (a) A photograph of the group of bright stars that make up the constellation Orion. (b) The stars 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 Figure 0.3). 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)*

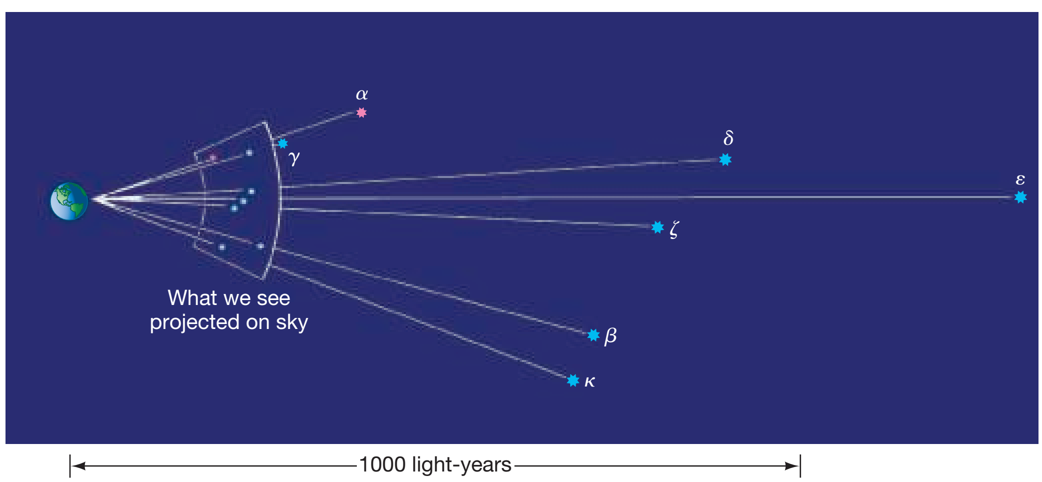
Pleiades, the seven daughters of the giant Atlas. According to Greek mythology, the gods placed the Pleiades among the stars to protect them from Orion, who still stalks them nightly across the sky. Many other constellations have similarly fabulous connections with ancient cultures.

The stars making up a particular constellation are generally not close together in space. They merely are bright enough to observe with the naked eye and happen to lie in the same direction in the sky as seen from Earth. Figure 0.3 illustrates this point for Orion, showing the true relationships between that constellation's brightest stars. Although constellation patterns have no real significance, the terminology is still used today. Constellations provide a convenient means for astronomers to specify large areas of the sky, much as geologists use continents or politicians use voting precincts to identify certain localities on Earth. In all, there are 88 constellations, most of them visible from North America at some time during the year.

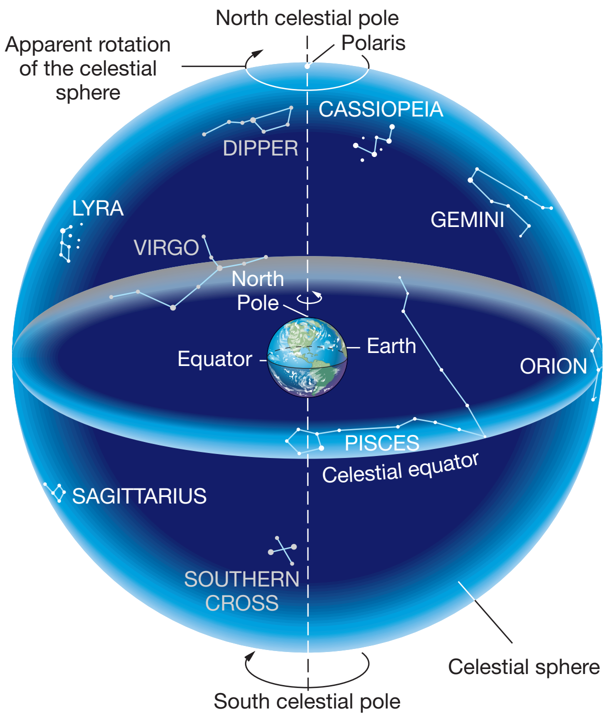
The Celestial Sphere

Over the course of a night, the constellations appear to move across the sky from east to west. However, ancient sky-watchers noted that the *relative* positions of stars (to each other) remained unchanged as this nightly march took place. It was natural for early astronomers to conclude that the stars were attached to a **celestial sphere** surrounding Earth—a canopy of stars like an astronomical painting on a vast heavenly ceiling. Figure 0.4 shows how early astronomers pictured the stars as moving with this celestial sphere as it turned around a fixed Earth. Figure 0.5 shows how stars appear to move in circles around a point in the sky very close to the star Polaris (better known as the Pole Star or the North Star). To early astronomers, this point represented the axis around which the celestial sphere turned.

From our modern standpoint, the apparent motion of the stars is the result of the spin, or **rotation,** not of the celestial sphere, but of Earth. Even though we now know that a revolving celestial sphere is an incorrect



▶ **FIGURE 0.3 Orion in 3D** The true three-dimensional relationships among the most prominent stars in Orion. The distances in light-years were measured by the European *Hipparcos* satellite in the 1990s. (See Section 10.1.)



▲ **FIGURE 0.4 The Celestial Sphere** INTERACTIVE 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.

CONCEPT CHECK

Earth isn't really enclosed in a sphere with stars attached. Why then do astronomers find it convenient to retain the fiction of the celestial sphere? What vital piece of information about stars is lost when we talk about their positions "on" the sky?

description of the heavens, astronomers still use the idea as a convenient fiction that helps us visualize the positions of stars in the sky. The point where Earth's rotation axis (the line through the center around which the planet rotates) intersects the celestial sphere in the Northern Hemisphere is known as the **north celestial pole;** it is directly above Earth's North Pole. The star Polaris happens to lie close to the north celestial pole, which is why its direction indicates due north. In the Southern Hemisphere, the extension of Earth's axis in the opposite direction defines the **south celestial pole.** (There are no bright stars conveniently located near the south celestial pole and hence no "southern Pole Star.") Midway between the north and south celestial poles lies the **celestial equator,** representing the intersection of Earth's equatorial plane (the plane through Earth's center, perpendicular to the rotation axis) with the celestial sphere.

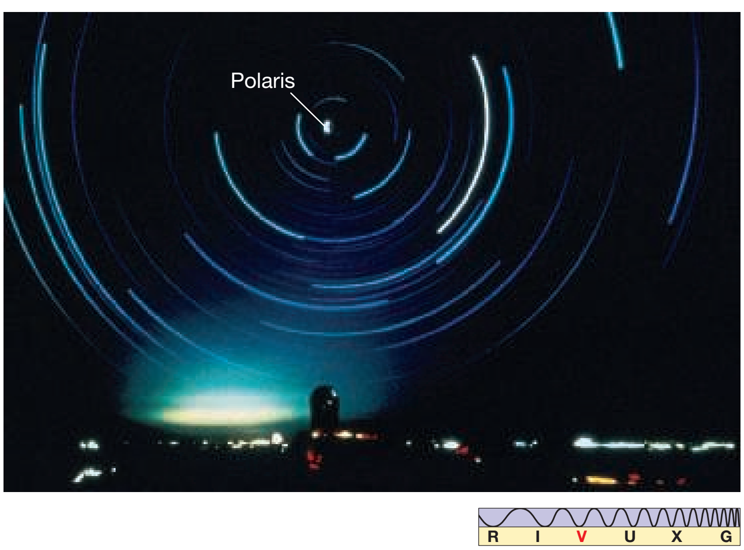
Celestial Coordinates

The simplest method of locating stars in the sky is to specify their constellation and then rank the stars in that constellation in order of brightness. The brightest star is denoted by the Greek letter α (alpha), the second brightest by β (beta), and so on. For example, Betelgeuse and Rigel, the two brightest stars in the constellation Orion, are also known as α Orionis and β Orionis, respectively (see Figures 0.2 and 0.3). (Precise observations show that Rigel is actually brighter than Betelgeuse, but the names are now permanent.) Because there are many more stars in any given constellation than there are letters in the Greek alphabet, this method is of limited use. However, for naked-eye astronomy, where only bright stars are involved, it is quite satisfactory.

For more precise measurements, astronomers find it helpful to use a system of **celestial coordinates** on the sky. If we think of the stars as being attached to the celestial sphere centered on Earth, then the familiar system of angular measurement on Earth's surface—latitude and longitude (Figure 0.6a)—extends quite naturally to the sky. The celestial analogs of latitude and longitude are called **declination** and **right ascension,** respectively (Figure 0.6b). Just as latitude and longitude are tied to Earth, right ascension and declination are fixed on the celestial sphere. Although the stars appear to move across the sky because of Earth's rotation, their celestial coordinates remain constant over the course of a night.

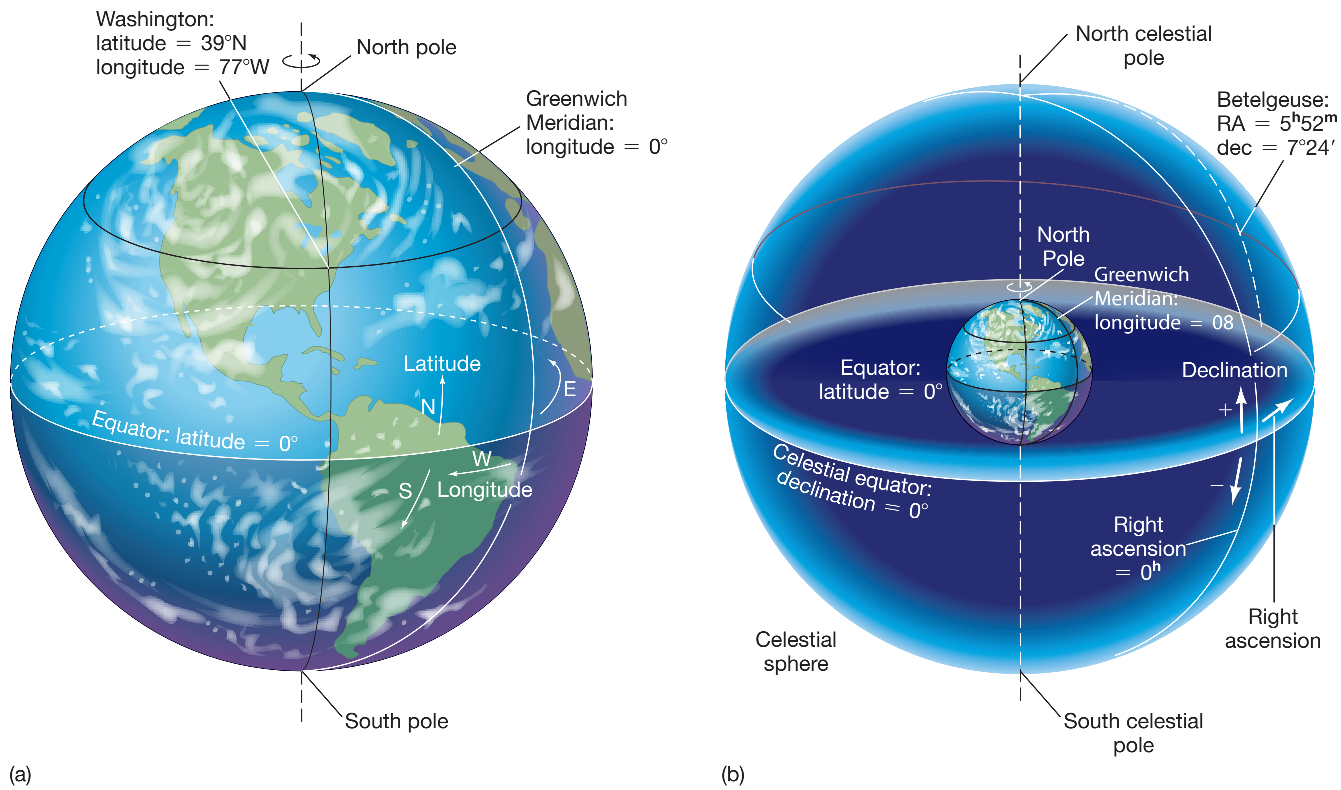
Declination (dec) is measured in *degrees* (°) north or south of the celestial equator, just as latitude is measured in degrees north or south of Earth's equator (see *More Precisely 0-1*). The celestial equator is at a declination of 0°, the north celestial pole is at +90°, and the south celestial pole is at −90° (the plus sign here just means "north of the celestial equator"; minus means "south"). Right ascension (RA) is measured in angular units called *hours, minutes,* and *seconds,* and it increases in the eastward direction. Like the choice of the Greenwich Meridian as the zero-point of longitude on Earth, the choice of zero right ascension is quite arbitrary—it is conventionally taken to be the position of the Sun in the sky at the instant of the vernal equinox (to be discussed in the next section).

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



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

◀ **FIGURE 0.5 The Northern Sky** INTERACTIVE Time-lapse photograph of the northern sky. Each trail traces the path of a single star across the night sky. The concentric circles are centered near the North Star, Polaris. *(AURA)*



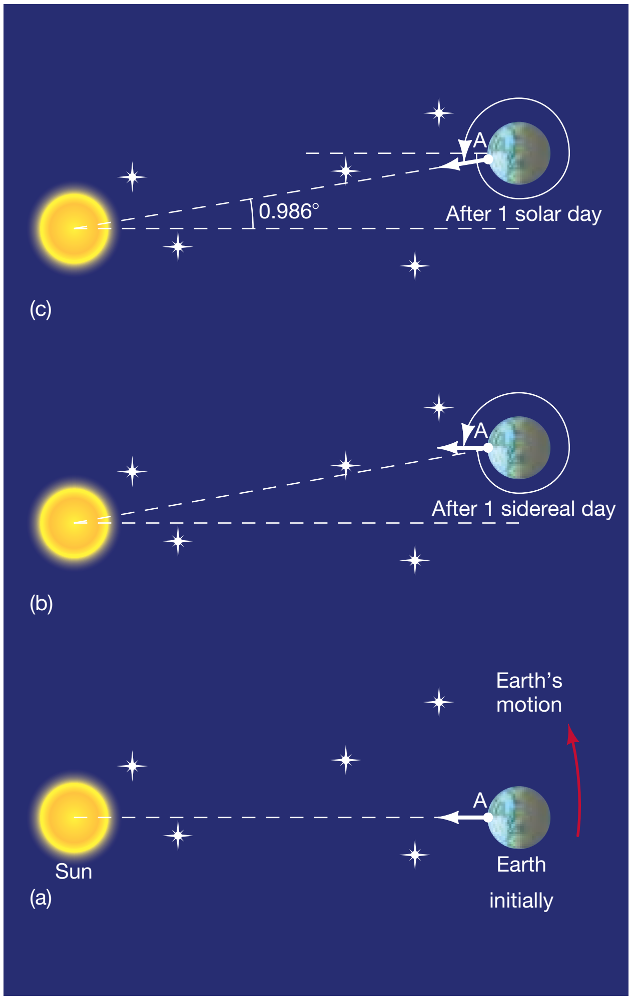
▲ **FIGURE 0.6 Right Ascension and Declination**
(a) Longitude and latitude allow us to locate a point on the surface of Earth by specifying its distance (as an angle) east or west of the Greenwich Meridian, and north or south of the equator. For example, to find Washington, D.C., on Earth, look 77° west of Greenwich and 39° north of the equator. (b) Similarly, right ascension and declination specify locations on the sky. To locate the star Betelgeuse on the celestial sphere; look 5^h52^m east of the vernal equinox (the line on the sky with a right ascension of zero) and 7°24′ north of the celestial equator.

0.2 Earth's Orbital Motion

Day-to-Day Changes

We measure time by the Sun. The rhythm of day and night is central to our lives, so it is not surprising that the period of time from one sunrise (or noon, or sunset) to the next, the 24-hour **solar day,** is our basic social time unit. As we have just seen, this apparent daily progress of the Sun and other stars across the sky, known as **diurnal motion** 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 shifted a little compared with the night before—you can confirm this for yourself by noting over the course of a week or two which stars are visible near the horizon just after sunset or just before dawn. 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.

The reason for the difference in length between a solar day and a sidereal day is sketched in Figure 0.7. 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. Therefore, each day Earth has to rotate through slightly more than 360° in order for the Sun to return to the same apparent location in the sky. As a result, the interval of time between noon one day and noon the next (a solar day) is slightly greater than the 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 takes about 3.9 minutes to rotate through this angle, the solar day is 3.9 minutes longer than the sidereal day.



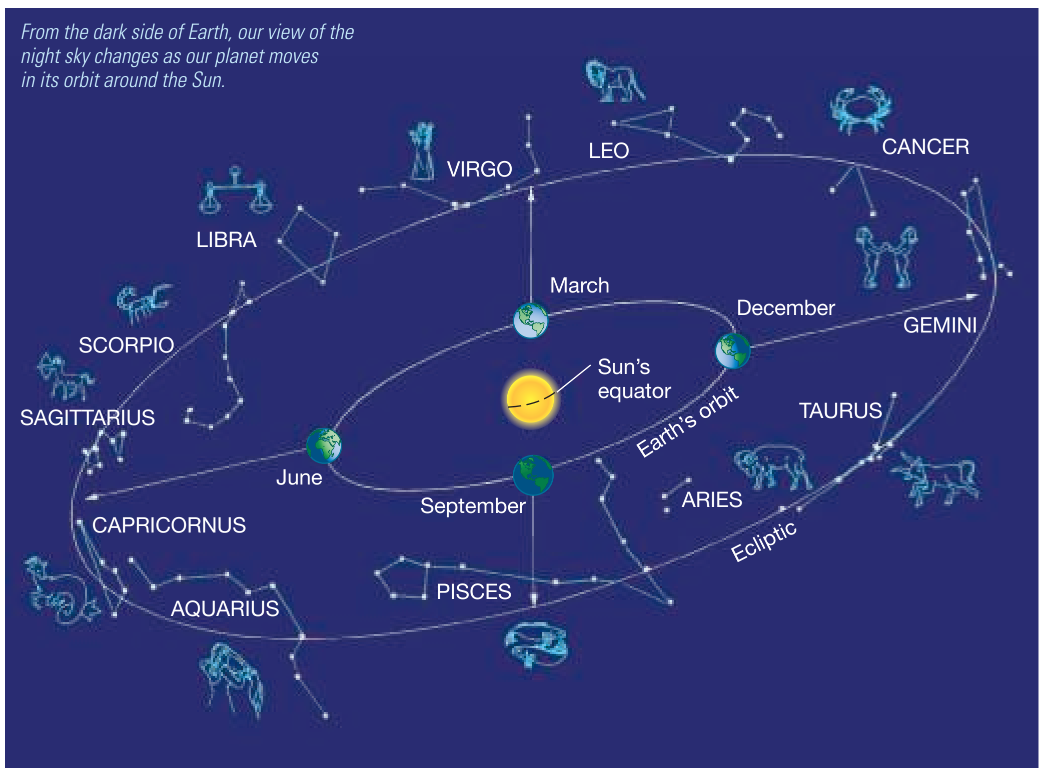
▲ **FIGURE 0.7 Solar and Sidereal Days** A sidereal day is Earth's true rotation period—the time taken for our planet to return to the same orientation in space relative to the distant stars. A solar day is the time from one noon to the next. The difference in duration between the two is easily explained because Earth revolves around the Sun at the same time it rotates on its axis. Frames (a) and (b) are one sidereal day apart, when 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° (c), and the solar day exceeds the sidereal day by about 4 minutes. Note that the diagrams are not drawn to scale; the 1° angle is actually much smaller than that shown here.

Seasonal Changes

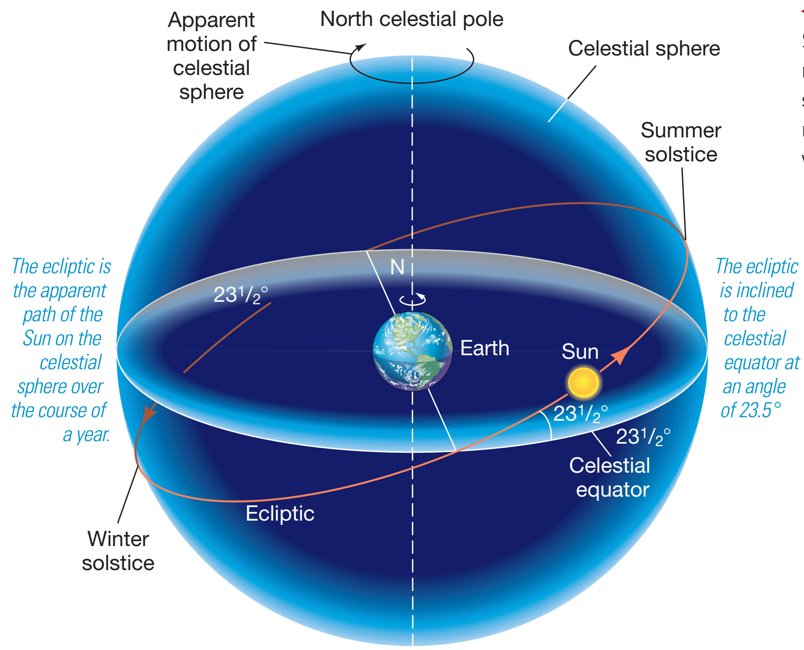
Because Earth revolves around the Sun, our planet's darkened hemisphere faces in a slightly different direction each night. The change is only about 1° per night (Figure 0.7)—too small to be easily discerned with the naked eye from one evening to the next. However, the change is clearly noticeable over the course of weeks and months, as illustrated in Figure 0.8. In 6 months, Earth moves to 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 slowly (at a rate of 1° per day) 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 during the year 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. They are collectively known as the **zodiac.**

As illustrated in Figure 0.9, the ecliptic forms a great circle on the celestial sphere, inclined at an angle of about 23.5° to the celestial equator. In reality, as shown in Figure 0.10, the plane defined by 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 its orbital plane.

The point on the ecliptic where the Sun is at its northernmost point above the celestial equator (see Figure 0.9) is known as the **summer solstice** (from the Latin words *sol,* meaning "sun," and *stare,* "to stand"). As indicated in Figure 0.10, it represents the point on Earth's orbit where our planet's North Pole is oriented closest to 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 on that date, points north of the equator spend the greatest fraction of their time in sunlight, so the summer solstice corresponds to the longest day of the year (that is, the greatest number of daylight hours—Earth's rotation period doesn't change!) in Earth's Northern Hemisphere and the shortest day in Earth's Southern Hemisphere.



▶ **FIGURE 0.8 The Zodiac** INTERACTIVE 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 year. For example, in June, when the Sun is "in" Gemini, Sagittarius and Capricornus are visible at night.



◀ **FIGURE 0.9 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.

Six months later, the Sun is at its southernmost point below the celestial equator (Figure 0.9)—or, equivalently, Earth's North Pole is oriented farthest from the Sun (Figure 0.10). We have reached the **winter solstice** (December 21), the shortest day in Earth's Northern Hemisphere and the longest in the Southern Hemisphere.

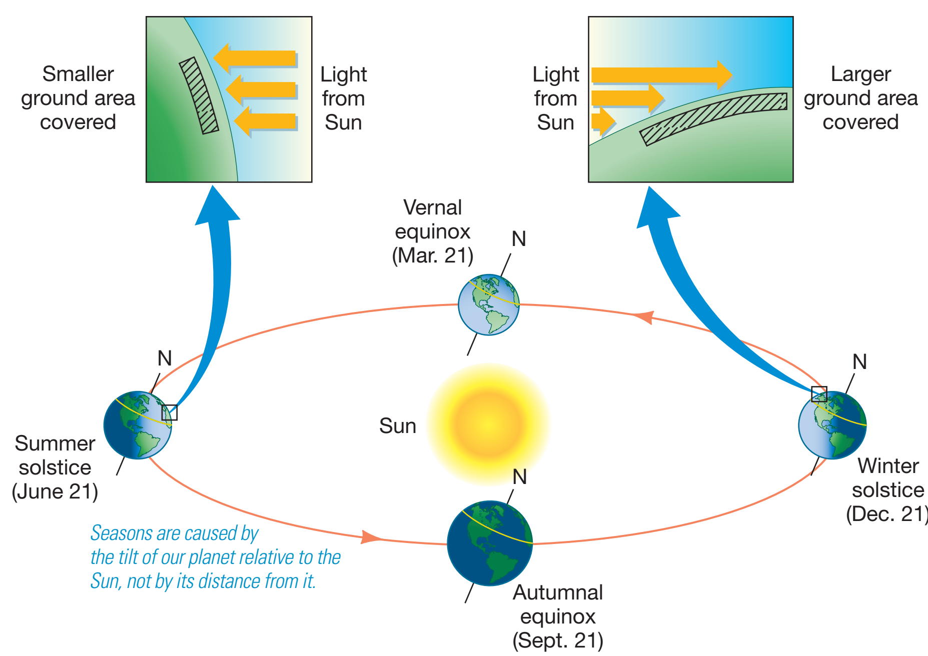
MA ANIMATION/VIDEO Summer Solstice

MA ANIMATION/VIDEO Winter Solstice

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 0.10, 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 Earths in the figure. (For definiteness, they correspond to a latitude of 45° north—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 0.10, 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.

A popular misconception is that the seasons have something to do with Earth's distance from the Sun. Figure 0.11 illustrates why this is not the case. It shows

▶ **FIGURE 0.10 Seasons INTERACTIVE** 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 (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.

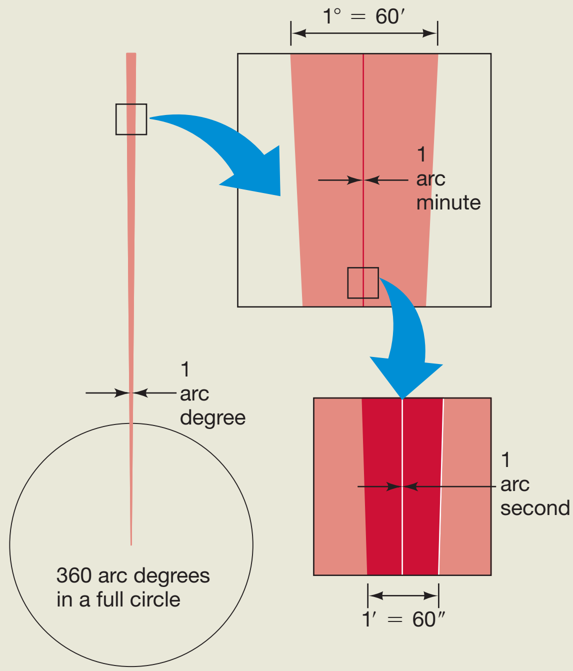


0.1 MORE PRECISELY

Angular Measure

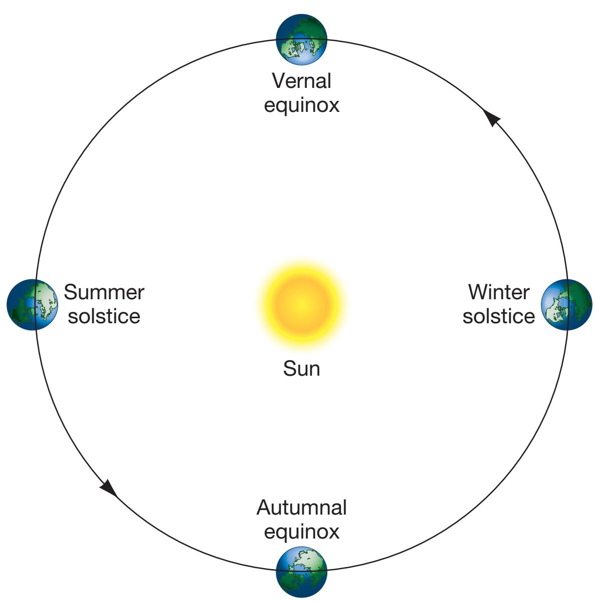
The size and scale of astronomical objects are often specified by measuring lengths and angles. The concept of length measurement is fairly intuitive. The concept of angular measurement may be less familiar, but it too can become second nature if you remember a few simple facts:

- A full circle contains 360 arc degrees (or 360°). Therefore, 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 an arc degree, called arc minutes; there are 60 arc minutes (60′) in 1 arc degree. Both the Sun and the Moon project an angular size of 30 arc minutes on the sky. Your little finger, held at arm's length, does about the same, covering about a 40-arc minute 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 1/60 of an arc degree, and an arc second is $1/60 \times 1/60 = 1/3600$ of an arc degree. An arc second is an extremely small unit of angular measure—it is the angular size of a centimeter-size object (a dime, say) at a distance of about 2 kilometers (a little over a mile).



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

ANIMATION/VIDEO The Equinoxes MA



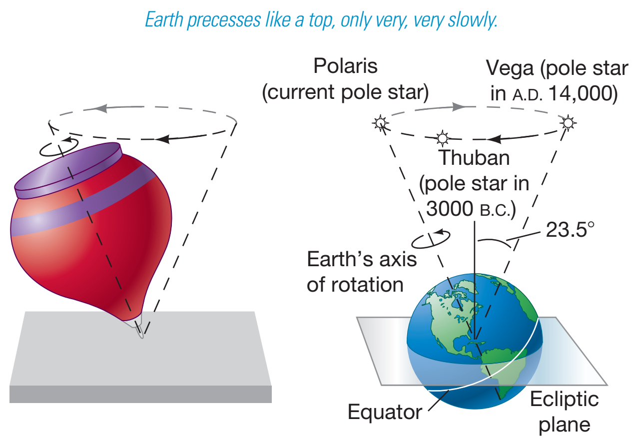
▲ **FIGURE 0.11 Earth's Orbit** Seen face on, Earth's orbit around the Sun is almost indistinguishable from a perfect circle. The distance from Earth to the Sun varies only slightly over the course of a year and is *not* the cause of the seasonal temperature variations we experience on our planet.

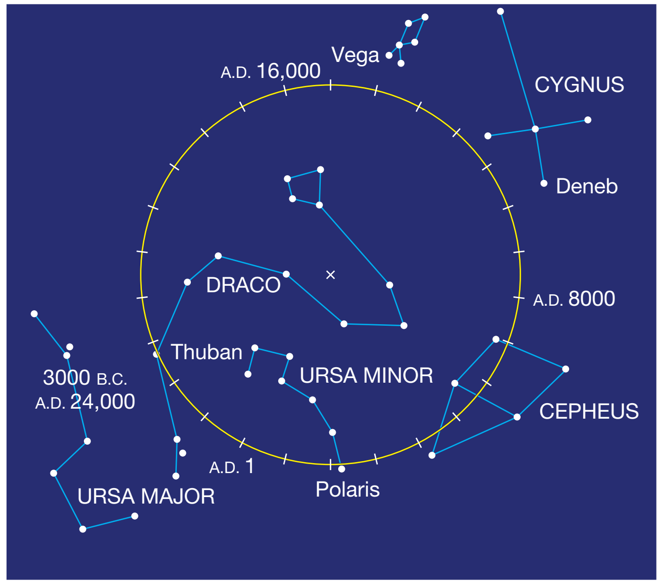
Earth's orbit face on, instead of almost edge-on, as in Figure 0.10. Notice that the orbit is almost perfectly circular, so the distance from Earth to the Sun varies very little (in fact, by only about 3 percent) over the course of a year—not nearly enough to explain the seasonal changes in temperature. 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 0.9)—that is, where Earth's rotation axis is perpendicular to the line joining Earth to the Sun (Figure 0.10)—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 Earth's Northern Hemisphere), as the Sun crosses from the northern into the southern celestial hemisphere, we have the **autumnal equinox** (on September 21). The **vernal equinox** occurs in spring, on or near March 21, as the Sun crosses the celestial equator moving north. The vernal equinox plays an important role in human timekeeping. The interval of time from one vernal equinox to the next—365.242 solar days—is known as one **tropical year.**

Long-Term Changes

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 solar days long, about 20 minutes longer than a tropical year. The reason for this slight difference is a phenomenon known as **precession.** 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





▲ **FIGURE 0.12 Precession** INTERACTIVE (a) Earth's axis currently points nearly toward the star Polaris. Some 12,000 years from now, 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 and depicts the direction toward which Earth's pole points on the sky. Each tick mark represents 1000 years.

perpendicular to the plane of the ecliptic always remains close to 23.5°. Figure 0.12 illustrates Earth's precession, which is caused by the combined gravitational pulls of the Moon and the Sun (see Chapter 1). During a complete cycle of precession, taking about 26,000 years, Earth's axis traces out a cone. Because of this slow shift in the orientation of Earth's rotation axis, the vernal equinox, which defines the tropical year, drifts slowly around the ecliptic over the course of the precession cycle. Notice in Figure 0.12(b) that most of the time there is *no* bright "Pole Star" marking due north.

The tropical year is the year 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 mid-February! By using the tropical year instead, we ensure that July and August will always be (northern) summer months. However, in 13,000 years' time, Orion, now a prominent feature of the northern winter sky, will be a summer constellation.

CONCEPT CHECK

Earth is actually farthest from the Sun during northern summer. Why, then, is it hottest in North America during this season?

0.3 The Motion of the Moon

Early astronomers had very practical reasons for studying the sky. Some stars (such as Polaris) served as navigational guides, while others served as primitive calendars to predict planting and harvesting seasons. By observing repeating patterns in the sky and associating them with events on Earth, astronomers began to establish concrete connections between celestial events and everyday life and took the first steps toward true scientific understanding of the heavens. In a real sense, then, human survival depended on astronomical knowledge. The ability to predict and even explain astronomical events was undoubtedly a highly prized, and perhaps jealously guarded, skill.

The Moon also played an important role in ancient astronomy. Calendars and religious observances were often tied to its phases and cycles, and even today the calendars of most of the world's major religions are still based wholly or partly on the lunar orbit. The Moon's regularly changing appearance (as well as its less regular, but much more spectacular, eclipses) was an integral part of the framework within which ancient astronomers sought to understand the universe. We will study the Moon's physical properties in more detail in Chapter 5. Here we continue our inventory of the sky with a brief description of the motion of our nearest neighbor in space.

DATA POINTS

Lunar Phases

More than half of all students tested using Mastering had difficulty ordering the Moon's phases as the Moon orbits Earth. Some points to remember:

- From night to night the Moon moves from west to east across the sky relative to the stars—right to left, as viewed from the Northern Hemisphere.
- The sunlit part of the moon grows (waxes) from west to east between the new and full phases and shrinks (wanes) from west to east from full to new.

SELF-GUIDED TUTORIAL
Phases of the Moon

Lunar Phases

Apart from the Sun, the Moon is by far the brightest object in the sky. Like the Sun, the Moon appears to move relative to the background stars. Unlike the Sun, however, the explanation for this motion is the obvious one—the Moon really does revolve around Earth.

The Moon's appearance undergoes a regular cycle of changes, or **phases,** taking a little more than 29 days to complete. (The word *month* is derived from the word *Moon.*) Figure 0.13(a) 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* (grow) a little each night and is visible as a growing *crescent* (frame 1 of Figure 0.13a). One week after new Moon, half of the lunar disk (the circular face we would see if the Moon were completely illuminated) can be seen (frame 2). This phase is known as a **quarter Moon.** During the next week, the Moon continues to wax, passing through the *gibbous* phase (more than half of the lunar disk visible, frame 3), until 2 weeks after new Moon the **full Moon** (frame 4) is visible. During the next 2 weeks, the Moon *wanes* (shrinks), passing in turn through the gibbous, quarter, and crescent phases (frames 5–7), eventually becoming new again.

The location of the Moon in the sky, as seen from Earth, depends on its 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 often only becomes visible late in the day as the Sun's light fades. By this time the Moon is already high in the sky. These connections between lunar phase and rising/setting times are indicated on Figure 0.13(a).

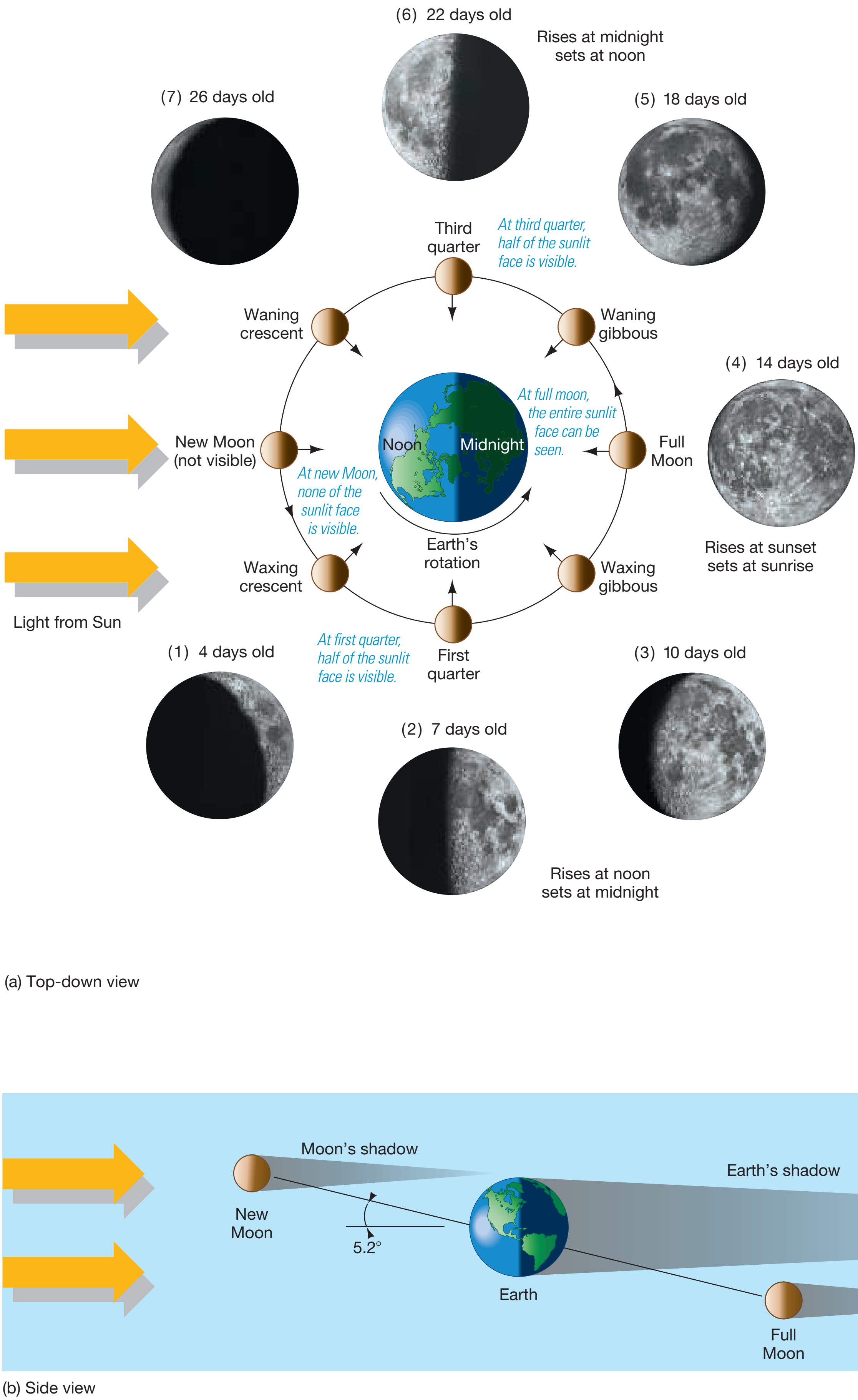
Unlike the Sun and the other stars, the Moon emits no light of its own. Instead, it shines by reflected sunlight, giving rise to the phases we see. As indicated in Figure 0.13(a), half of the Moon's surface is illuminated by the Sun at any moment, but not all of the Moon's sunlit face can be seen because of the Moon's position with respect to Earth and the Sun. When the Moon is full, we see the entire "day lit" face because the Sun and the Moon are in opposite directions from Earth in the sky. The Sun's light is not blocked by Earth at the full phase because, as shown in Figure 0.13(b), the Moon's orbit is inclined at a small angle (5.2°) to the plane of the ecliptic, so the alignment of the three bodies is not perfect. (The sizes of Earth and the Moon are greatly exaggerated in these figures.) In the case of a new Moon, the Moon and the Sun are in nearly the same part of the sky, and the sunlit side of the Moon is oriented away from us—at new Moon the Sun is almost behind the Moon, from our perspective.

Notice, by the way, that the Moon always keeps the same face toward Earth—as indicated on the figure, it rotates on its axis in exactly the same time it takes to orbit Earth. This is called *synchronous rotation.*We will discuss the reason for it in Chapter 5.

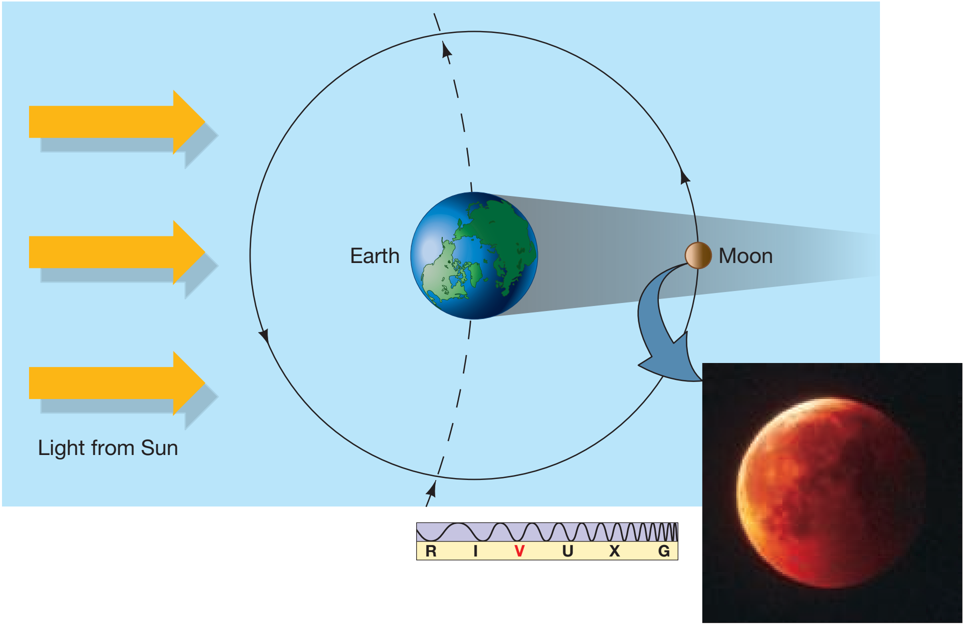
As it revolves around Earth, the Moon's position in the sky changes with respect to the stars. In one **sidereal month** (27.3 days), the Moon completes one revolution and returns to its starting point on the celestial sphere, having traced out a great circle in the sky. The time required for the Moon to complete a full cycle of phases, one **synodic month,** is a little longer—about 29.5 days. The synodic month is a little longer than the sidereal month for the same basic reason that a solar day is slightly longer than a sidereal day (Figure 0.7): 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.

Eclipses

From time to time—but only at new or full Moon—the Sun, Earth, and the Moon line up precisely, 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 0.13 Lunar Phases** (a) Because the Moon orbits Earth, this top-down view shows how 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 that mark the same point on the lunar surface at each phase shown.) The complete cycle of lunar phases takes about 29 days to complete. Rising and setting times for some phases are also indicated. (b) A side view shows how the Moon's orbit is inclined at about 5° to the ecliptic, so not all orbital configurations produce an eclipse. *(Insets: UC/Lick Observatory)*



This is an actual photo of the eclipsed Moon, one of the great light shows visible to the naked eye.

▲ **FIGURE 0.14 Lunar Eclipse** **INTERACTIVE** 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)*

ANIMATION/VIDEO
Solar Eclipse in Indiana
MA

▲ **FIGURE 0.15 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. *(Bencho Angelov)*

Figure 0.14. From Earth we see the curved edge of Earth's shadow begin to cut across the face of the full Moon and slowly "eat" its way into the circular lunar disk.

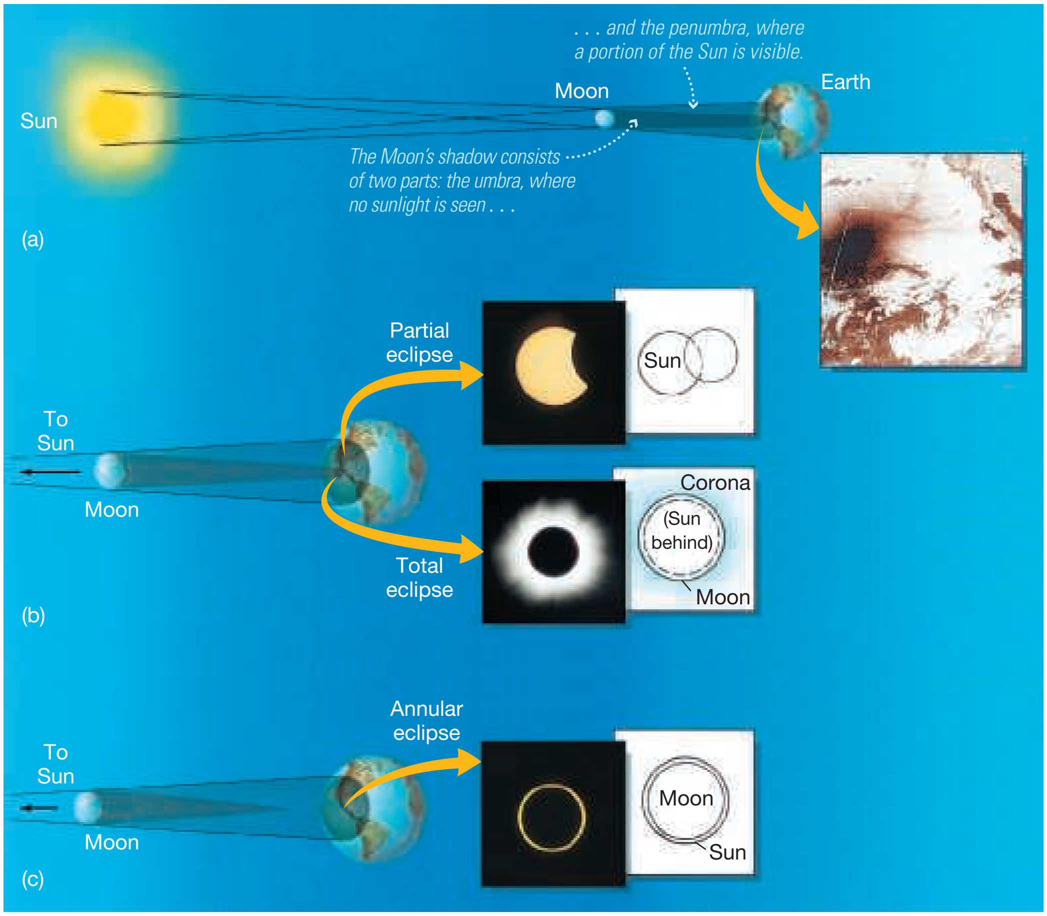
Usually the alignment of the Sun, Earth, and the Moon is imperfect, so the shadow never completely covers the Moon. Such an occurrence is known as a **partial eclipse.** Occasionally, however, the entire lunar surface is obscured in a **total eclipse** (such as that shown in the inset in Figure 0.14). 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 being refracted (bent) by Earth's atmosphere 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** (Figure 0.15). 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 blocked. By pure chance the Sun and Moon have almost exactly the same angular size as seen from Earth—the Sun is much bigger than the Moon, but it also lies much farther away (see *More Precisely 0-1*). Consequently, during a total solar eclipse, we can often see the Sun's ghostly outer atmosphere, or *corona,* its faint glow becoming temporarily visible when the rest of the Sun's glare is obscured. In a *partial solar eclipse,* the Moon's path is slightly off center, and only a portion of the Sun's face is covered.

Unlike a lunar eclipse, which is simultaneously visible from all locations on Earth's night side, a total solar eclipse can be seen from only a small portion of the daytime side. The Moon's shadow on Earth's surface is about 7000 kilometers wide—roughly twice the diameter of the Moon. Outside that shadow, no eclipse is seen. However, only within the central region of the shadow, in the **umbra,** is the eclipse total. The umbra is the part of a shadow (in this case, the Moon's) where all light from the source is blocked. Within the shadow but outside the umbra, in the **penumbra,** some but not all of the Sun's light is blocked and the eclipse is partial, with less and less of the Sun being obscured the farther one travels from the shadow's center.

The connections between the umbra, the penumbra, and the relative locations of Earth, Sun, and Moon are illustrated in Figure 0.16. The umbra is always very small—even under the most favorable circumstances, its diameter never exceeds 270 kilometers. Because the Moon's shadow sweeps across Earth's surface at a speed of more than 1700 kilometers per hour, the duration of a total solar eclipse at any given point can never exceed 7.5 minutes (270 km divided by 1700 km/hour, times 60 minutes per hour).

The Moon's orbit around Earth is not exactly circular. As a result, the Moon may be far enough from Earth at the moment of an eclipse that its disk fails to cover the disk of the Sun completely, even though their centers coincide. In that case, there is no *region of totality*—the umbra never reaches Earth at all, and a thin ring of sunlight can still be seen surrounding the Moon. Such an occurrence, called an **annular eclipse** (from the word *annulus,* meaning "ring"), is depicted at the bottom of Figure 0.16. Roughly half of all solar eclipses are annular.



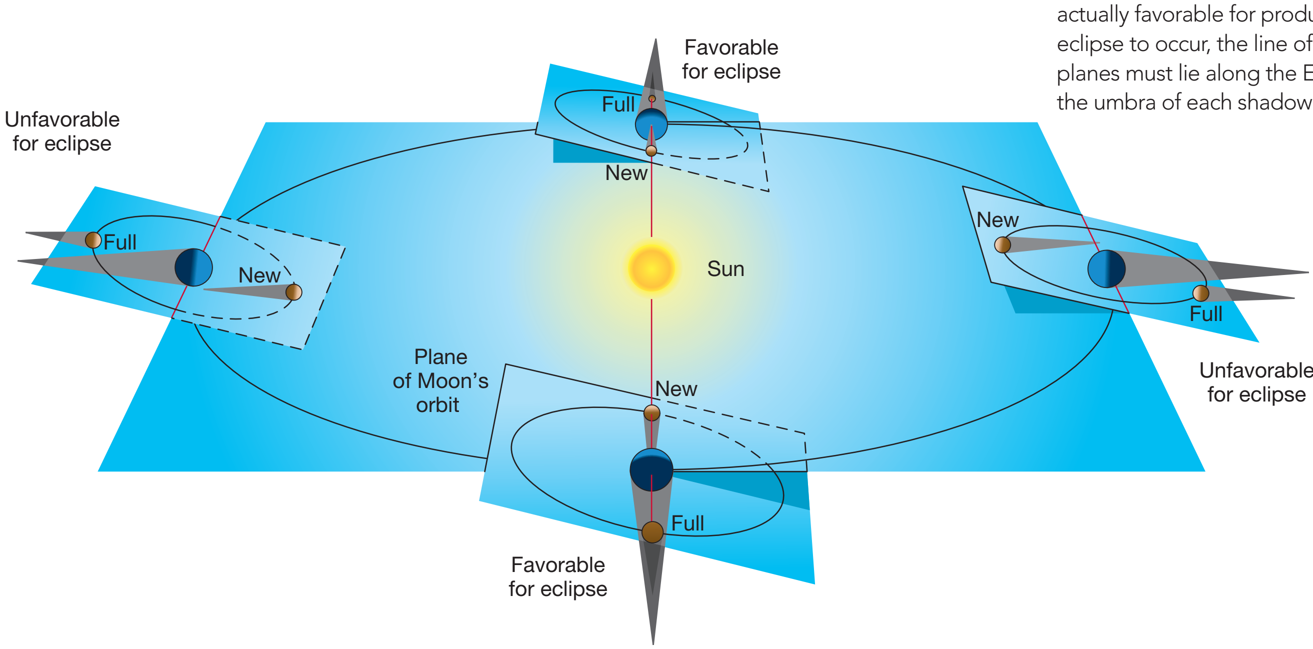
◀ **FIGURE 0.16 Solar Eclipse Types INTERACTIVE** (a) The Moon's shadow consists of two parts: the umbra, where no sunlight is seen, and the penumbra, where a portion of the Sun is visible. (b) Situated in the umbra, we see a total eclipse; in the penumbra, we see a partial eclipse. (c) If the Moon is 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)*

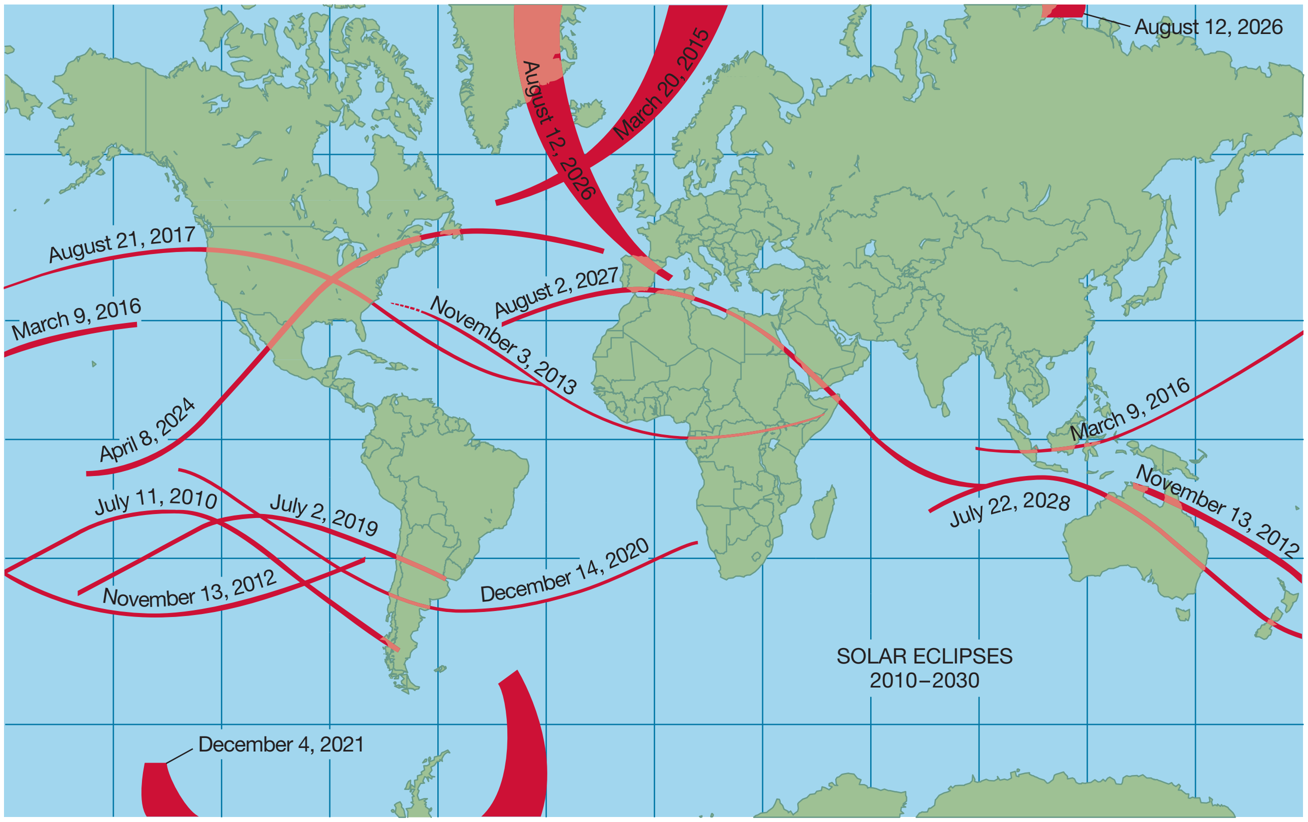
CONCEPT CHECK

If Earth's distance from the Sun were to double, would you still expect to see total solar eclipses? What if the distance became half its present value?

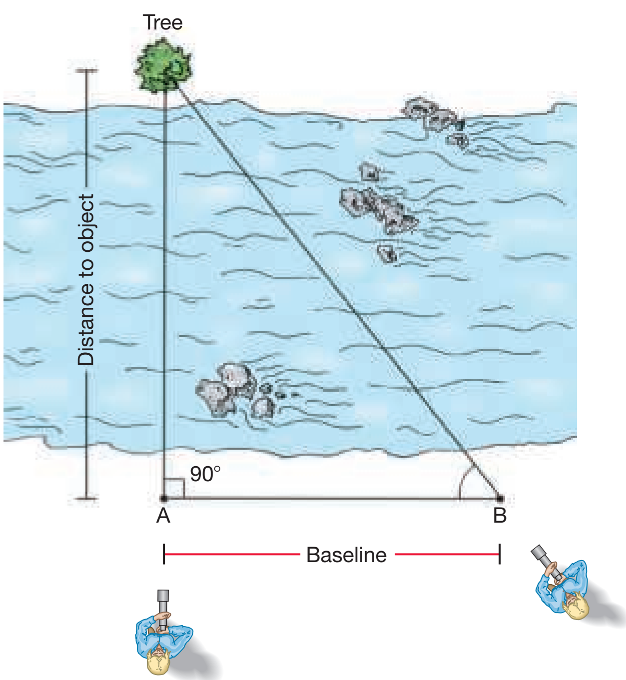
Because the Moon's orbit is slightly inclined to the plane of the ecliptic (Figure 0.13b), we don't see a lunar eclipse at every full Moon. The Moon is usually above or below the ecliptic when a full Moon occurs and, hence, is untouched by Earth's shadow. Similarly, most new Moons do not result in solar eclipses. The chance that a new (or full) Moon will occur just as the Moon happens to cross the ecliptic plane (so Earth, Moon, and Sun are perfectly aligned, as illustrated in Figure 0.17) is quite low. As a result, eclipses are relatively infrequent events. On average, there

▼ **FIGURE 0.17 Eclipse Geometry** An eclipse occurs when Earth, Moon, and Sun are precisely aligned. If the Moon's orbital plane lay in exactly the plane of the ecliptic, this alignment would occur once a month. However, the Moon's orbit is inclined at about 5° to the ecliptic, so not all configurations are actually favorable for producing an eclipse. For an eclipse to occur, the line of intersection of the two planes must lie along the Earth–Sun line. For clarity, only the umbra of each shadow is shown (see Figure 0.16).





▲ **FIGURE 0.18 Eclipse Tracks** Regions of Earth that saw or will see total solar eclipses between the years 2009 and 2030. Each track represents the path of the Moon's umbra across Earth's surface during an eclipse. High-latitude tracks are broader because sunlight strikes Earth's surface at an oblique angle near the poles and because of the projection of the map.



▲ **FIGURE 0.19 Triangulation** Surveyors often use simple geometry to estimate the distance to a faraway object by triangulation. By measuring the angles at A and B and the length of the baseline, the distance can be calculated without the need for direct measurement (or getting wet!).

are 7 total lunar eclipses and 15 total or annular solar eclipses each decade. Because we know the orbits of Earth and the Moon to great accuracy, we can predict eclipses far into the future. Figure 0.18 shows the location and duration of all total and annular eclipses of the Sun between 2010 and 2030.

0.4 The Measurement of Distance

So far we have considered only the *directions* to the Sun, Moon, and stars, as seen from Earth. But knowing the direction to an object is only part of the information needed to locate it in space. Before we can make a systematic study of the heavens, we must find a way of measuring *distances,* too. One distance-measurement method, called **triangulation,** is based on the principles of Euclidean geometry and is widely used today in both terrestrial and astronomical settings. Modern surveyors use this age-old geometrical idea to measure the distances to faraway objects. In astronomy, it forms the foundation of the family of distance-measurement techniques that together make up the **cosmic distance scale.**

Imagine trying to measure the distance to a tree on the other side of a river. The most direct method would be to lay a tape across the river, but that's not always practical. A smart surveyor would make the measurement by visualizing an imaginary triangle (hence, the term *triangulation*), sighting the tree (measuring its direction) on the far side of the river from two positions on the near side, as illustrated in Figure 0.19. The simplest triangle is a right triangle, in which one of the angles is exactly 90°, so it is often convenient to set up one observation position directly opposite the object, as at point A, although this isn't necessary for the method to work. The surveyor then moves to another observation position at point B, noting the distance covered between A and B. This distance is called the **baseline** of the imaginary triangle. Finally, the surveyor, standing at point B, sights toward the tree and notes the angle formed at point B by the intersection of this sight line and the baseline. No further observations are required. Knowing the length of one side (AB) and two angles (the right angle at A and the angle at B) of the triangle, and using elementary trigonometry, the surveyor can construct the remaining sides and angles and so establish the distance from A to the tree.

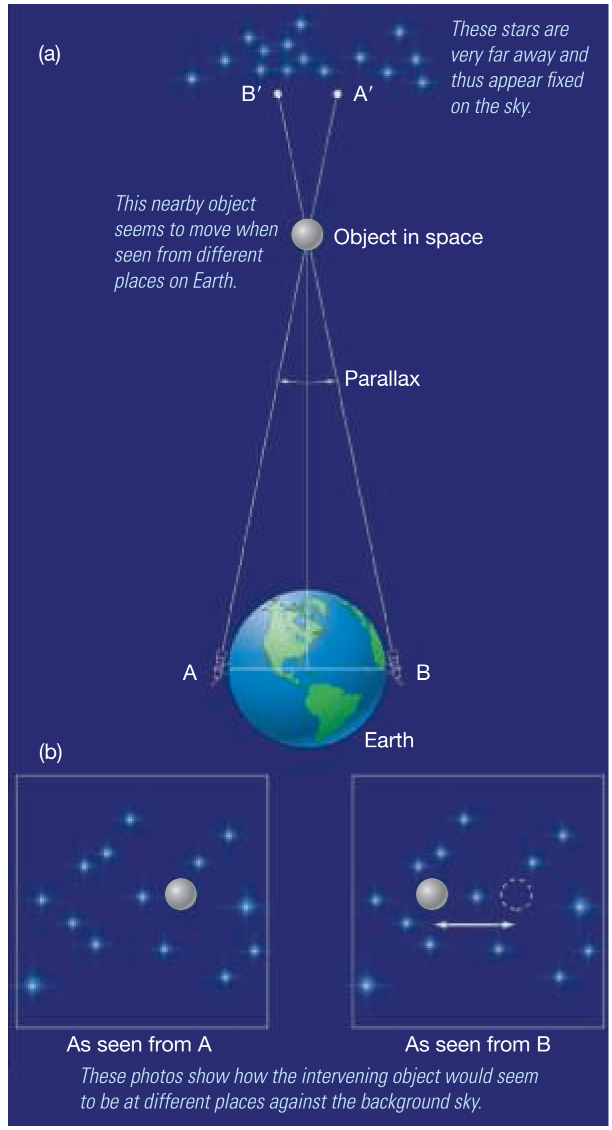
Obviously, for a fixed baseline, the triangle becomes longer and narrower as the tree's distance from A increases. Narrow triangles cause problems because it is hard to measure the angles at A and B with sufficient accuracy. A surveyor on Earth can "fatten" the triangle by lengthening the baseline, but in astronomy there are limits on how long a baseline we can choose. For example, consider an imaginary triangle extending from Earth to a nearby object in space, perhaps a neighboring planet. The triangle is now extremely long and narrow, even for a relatively nearby object (by cosmic standards). Figure 0.20(a) illustrates a case in which the longest baseline possible on Earth—Earth's diameter, measured from point A to point B—is used. In principle, we could sight the planet from opposite sides of Earth, measuring the angles at A and B. However, in practice it is easier to measure the third angle of the imaginary triangle. Here's how.

The observers each sight toward the planet, taking note of its position *relative to some distant stars* seen on the plane of the sky. The observer at A sees the planet at apparent location A′ (pronounced "A prime") relative to those stars, as indicated in Figure 0.20(a). The observer at B sees the planet at location B′. If each observer takes a photograph of the same region of the sky, the planet will appear at slightly different places in the two images, as shown in Figure 0.20(b). (The positions of the background stars appear unchanged because of their much greater distance from the observer.) This apparent shift of a foreground object relative to the background as the observer's location changes is known as **parallax.** The size of the shift in Figure 0.20(b), measured as an angle on the celestial sphere, is equal to the third angle of the imaginary triangle in Figure 0.20(a).

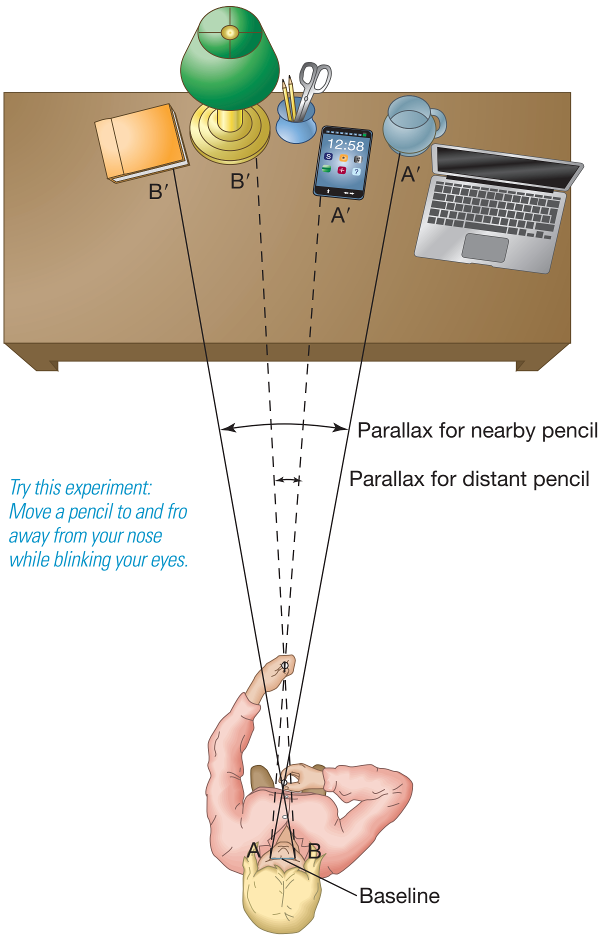
The closer an object is to the observer, the larger the parallax. To see this for yourself, hold a pencil vertically just in front of your nose (see Figure 0.21). Look at some far-off object—a distant wall, say. Close one eye, then open it while closing the other. You should see a large shift in the apparent position of the pencil relative to the wall—a large parallax. In this example, one eye corresponds to point A in Figure 0.20, the other eye to point B. The distance between your eyeballs is the baseline, the pencil represents the planet, and the distant wall the remote field of stars. Now hold the pencil at arm's length, corresponding to a more distant object (but still not as far away as the distant stars). The apparent shift of the pencil will be smaller. By moving the pencil farther away, you are narrowing the triangle and decreasing the parallax. If you were to paste the pencil to the wall, corresponding to the case where the object of interest is as far away as the background star field, blinking would produce no apparent shift of the pencil at all.

The amount of parallax is inversely proportional to an object's distance. Small parallax implies large distance. Conversely, large parallax implies small distance. Knowing the amount of parallax (as an angle) and the length of the baseline, we can easily derive the distance through triangulation.

Surveyors of the land routinely use these simple geometric techniques to map out planet Earth (*Discovery 0-1* presents an early example). As surveyors of the sky, astronomers use the same basic principles to chart the universe.



▲ **FIGURE 0.20 Parallax INTERACTIVE** (a) A triangle can be imagined to extend from Earth to a nearby object in space. The group of stars at the top represents a background field of very distant stars. (b) Hypothetical photographs of the same star field showing the nearby object's apparent shift, relative to the distant unshifted stars.

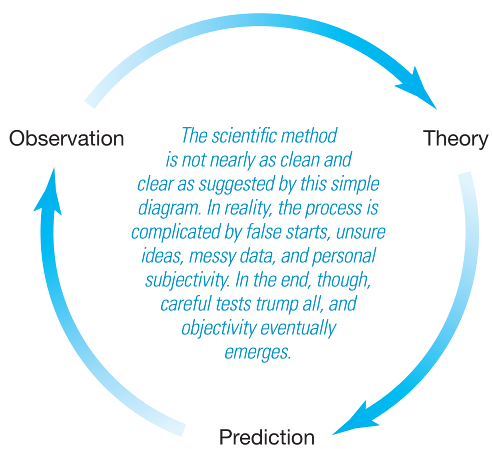


◀ **FIGURE 0.21 Parallax Geometry** Parallax is inversely proportional to an object's distance. An object near your nose has a much larger parallax than an object held at arm's length.

SELF-GUIDED TUTORIAL
Stellar Parallax

CONCEPT CHECK

Why is elementary geometry essential for measuring distances in astronomy?



▲ **FIGURE 0.22 Scientific Method** Scientific theories evolve through a combination of observation, theory, and prediction, which in turn suggests 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.

0.5 Science and the Scientific Method

Science is a step-by-step process for investigating the physical world, based on natural laws and observed phenomena. However, the scientific facts just presented did not come easily or quickly. Progress in science is often slow and intermittent and may require a great deal of patience before significant progress is made. The earliest known 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 testable earthly experience. However, history shows that some early scientists did come to realize 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. Experimentation and observation became central parts of the process of inquiry.

Theories and Models

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), accounting 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 they do not, the theory must be reformulated or rejected, no matter how appealing it originally seemed. The process is illustrated schematically in Figure 0.22. This approach to investigation, combining thinking and doing—that is, theory and experiment—is known as the **scientific method.** It lies at the heart of modern science, separating science from pseudoscience, fact from fiction.

Notice that there is no end point to the process depicted in Figure 0.22. 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. The process can fail at any point in the cycle. If a theory cannot explain an experimental result or observation, or if its predictions are demonstrated to be untrue, it must be discarded or amended. And if it makes no predictions at all, then it has no scientific value.

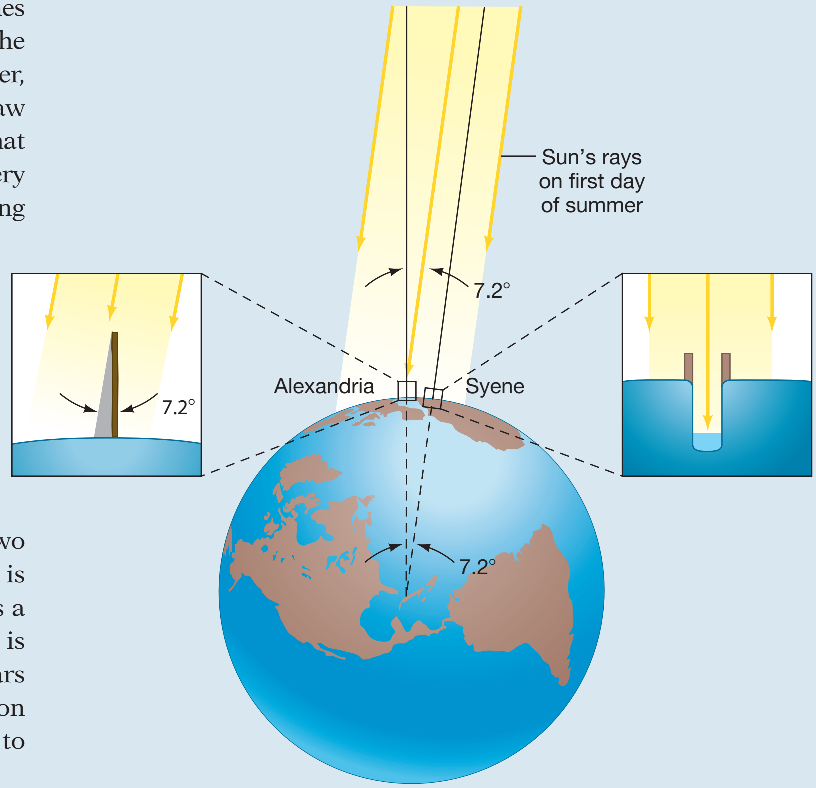
Scientific theories share several important defining characteristics:

- They must be *testable*; that is, they must admit the possibility that both their underlying assumptions and their predictions can 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 "understand 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 0.22.
- They should be *simple*. This is a practical outcome of centuries of scientific experience—the most successful theories tend to be the simplest ones that fit the facts. This view is often encapsulated in a principle known as *Occam's razor* (after the 14th-century English philosopher William of Ockham):

0.1 DISCOVERY

Sizing Up Planet Earth

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



What could have caused this discrepancy between the two measurements? As illustrated in the figure, the explanation is simply that Earth's surface is not flat, but *curved*. Our planet is a sphere. Eratosthenes was not the first to realize that Earth is spherical—the philosopher Aristotle had done that over 100 years earlier (Section 0.5)—but he was apparently the first to build on this knowledge, combining geometry with direct measurement to infer our planet's size. Here's how he did it.

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

$$\frac{7.2°}{360°} = \frac{5000 \text{ stadia}}{\text{Earth's circumference}}.$$

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

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

If two competing theories both explain the facts and make the same predictions, then the simpler one is better. A good theory should contain no more complexity than is absolutely necessary.

- Finally, most scientists have the additional prejudice that a theory should in some sense be *elegant*. When a clearly stated simple principle naturally explains several phenomena previously thought to be 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 notion that theories must be tested and may be proven wrong sometimes leads people to minimize 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 1.4) is "only" a theory, but calculations based on it have guided human spacecraft throughout the solar system. Electromagnetism and quantum mechanics (Chapter 2) are theories, too, yet they form the foundation for most of 20th- (and 21st-) century technology. Facts about the universe are a dime a dozen. Theories are the intellectual "glue" that combine seemingly unrelated facts into a coherent and interconnected whole.

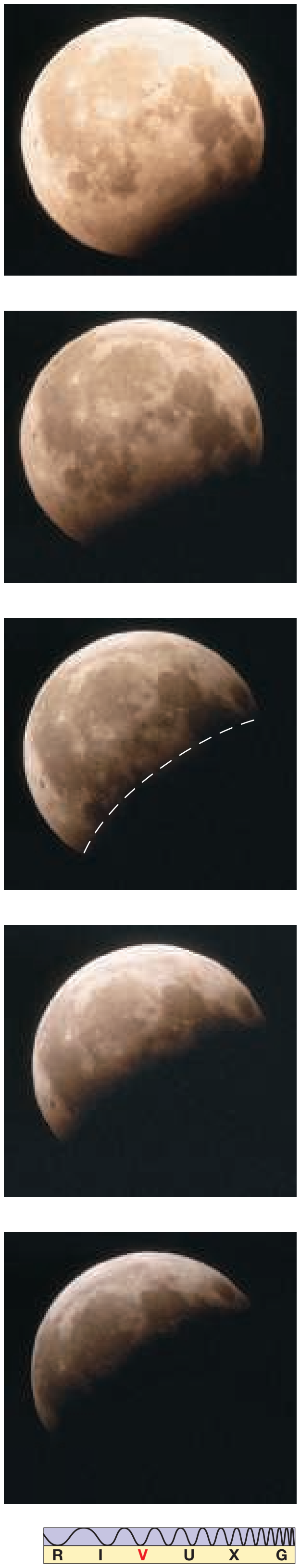
An Early Application

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 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. Still, his brilliance extended into many areas now thought of as modern science. He noted that, during a lunar eclipse (Section 0.3), Earth casts a curved shadow onto the surface of the Moon. Figure 0.23 shows a series of photographs taken during a recent lunar eclipse. Earth's shadow, projected onto the Moon's surface, is indeed slightly curved (as indicated by the dashed line). 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 the lunar eclipse method.

Today, scientists worldwide use an approach that relies heavily on testing ideas. They gather data, form a working hypothesis that explains the data, and then explore 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.

Don't think that the scientific method is perfect. We will see many examples in this book of good scientists making mistakes by following incorrect lines of reasoning, or simply placing too much faith in faulty observations. Nevertheless, used properly over a period of time, this rational, methodical approach enables us to arrive at conclusions that are mostly free of the personal biases and human failings of any one scientist. The scientific method is designed to yield—eventually—an objective view of the universe we inhabit.



▲ **FIGURE 0.23 A Lunar Eclipse** These photographs show Earth's shadow sweeping across the Moon during an eclipse. Aristotle reasoned that Earth was the cause of the shadow and concluded that Earth must be round. *(G. Schneider)*

The Universe Today

Our conception of the cosmos has changed a lot since ancient times. The modern universe is much larger, far more complex, and infinitely stranger than anything early astronomers ever imagined. In sharp contrast to the predictable and orderly heavens of the ancients, the universe we inhabit today is dynamic, expanding, evolving, and yet (we must admit) apparently dominated by fundamental forces that still lie beyond our understanding. Despite this, scientific inquiry today is guided by the same fundamental principles that led our ancestors to uncover the basic workings of the universe—gravity, light, relativity, quantum physics, and the Big Bang that brought our cosmos into being.

Experiment and observation are integral parts of the process of modern science. Untestable theories, or theories unsupported by experimental evidence, rarely gain any measure of acceptance in scientific circles. Observation, theory, and testing are cornerstones of the scientific method, a technique whose power will be demonstrated again and again throughout our text.

CONCEPT CHECK

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

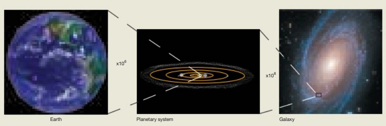
THE BIG QUESTION

Take another look at the spectacular photo at the start of this chapter (p. 4). Think about all those stars—about 100 billion in our Galaxy alone. We cannot help but wonder: Are there planets around some of those stars and perhaps intelligent beings on some of those planets? This grandest of all unsolved questions about the universe now lies at the heart of modern astronomy.

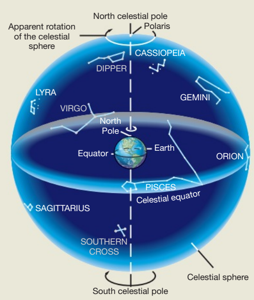
CHAPTER REVIEW

SUMMARY

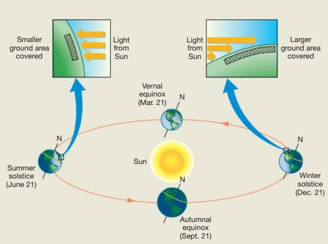
LO1 The **universe** (p. 6) is the totality of all space, time, matter, and energy. **Astronomy** (p. 6) is the study of the universe. In order of increasing size, the basic constituents of the cosmos are **planets** (p. 6), **stars** (p. 6), **galaxies** (p. 6), and the universe itself. They differ enormously in scale—a factor of a billion billion from planet Earth to the entire observable universe.



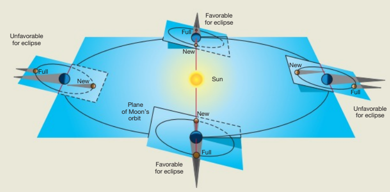
LO2 Early observers grouped the stars visible to the naked eye into patterns called **constellations** (p. 6), which they imagined were attached to a vast **celestial sphere** (p. 7) centered on Earth. Constellations have no physical significance, but are still used to label regions of the sky. **Celestial coordinates** (p. 8) are a more precise way of specifying a star's location on the celestial sphere.



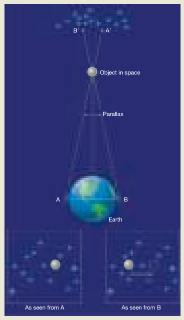
LO3 The nightly motion of the stars across the sky is due to Earth's **rotation** (p. 7) on its axis. Because of Earth's **revolution** (p. 9) around the Sun, we see different stars at night at different times of the year. The Sun's apparent yearly path around the celestial sphere (or the plane of Earth's orbit around the Sun) is called the **ecliptic** (p. 10). We experience **seasons** (p. 11) because Earth's rotation axis is inclined to the ecliptic plane. At the **summer solstice** (p. 10), the Sun is highest in the sky, and the length of the day is greatest. At the **winter solstice** (p. 11), the Sun is lowest and the day is shortest. Because of **precession** (p. 12), the orientation of Earth's axis changes slowly over thousands of years.



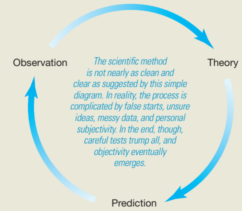
LO4 As the Moon orbits Earth, it keeps one face permanently turned toward our planet. We see lunar **phases** (p. 14) as the fraction of the Moon's sunlit face visible to us varies. A **lunar eclipse** (p. 14) occurs when the Moon enters Earth's shadow. A **solar eclipse** (p. 16) occurs when the Moon passes between Earth and the Sun. An eclipse may be **total** (p. 16) if the body in question (Moon or Sun) is completely obscured, or **partial** (p. 16) if only part of the surface is affected. If the Moon is too far from Earth for its disk to completely hide the Sun, an **annular eclipse** (p. 16) occurs. Because the Moon's orbit around Earth is slightly inclined to the ecliptic, solar and lunar eclipses are relatively rare events.



LO5 Astronomers use **triangulation** (p. 18) to measure the distances to planets and stars, forming the foundation of the **cosmic distance scale** (p. 18), the family of distance-measurement techniques used to chart the universe. **Parallax** (p. 19) is the apparent motion of a foreground object relative to a distant background as the observer's position changes. The larger the **baseline** (p. 19)—the distance between the two observation points—the greater the parallax.



LO6 **Science** (p. 20) is a step-by-step process for investigating the physical world. The **scientific method** (p. 20) is a methodical approach employed by scientists to explore the universe around us in an objective manner. A **theory** (p. 20) is a framework of ideas and assumptions used to explain some set of observations and make predictions about the real world. These predictions in turn are amenable to further observational testing. In this way, the theory expands and science advances.



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

REVIEW AND DISCUSSION

1. **LO1** Compare the size of Earth with that of the Sun, the Milky Way Galaxy, and the entire universe.
2. **LO2** What is a constellation? Why are constellations useful for mapping the sky?
3. Why does the Sun rise in the east and set in the west each day? Does the Moon also rise in the east and set in the west? Why? Do stars do the same? Why?
4. How and why does a day measured by the Sun differ from a day measured by the stars?
5. How many times in your life have you orbited the Sun?
6. Why do we see different stars at different times of the year?
7. **LO3** Why are there seasons on Earth?
8. What is precession, and what is its cause?
9. **LO4** If one complete hemisphere of the Moon is always lit by the sun, why do we see different phases of the Moon?
10. What causes a lunar eclipse? A solar eclipse? Why aren't there lunar and solar eclipses every month?
11. **POS** Do you think an observer on another planet might see eclipses? Why or why not?
12. What is parallax? Give an everyday example.
13. Why is it necessary to have a long baseline when using triangulation to measure the distances to objects in space?
14. **LO5** What two pieces of information are needed to determine the diameter of a faraway object?
15. **LO6 VIS** What is the scientific method? In what ways does science differ from religion?

CONCEPTUAL SELF-TEST: TRUE OR FALSE?/MULTIPLE CHOICE

1. Our Galaxy is about 1 million times larger than Earth. (T/F)
2. The stars in a constellation are physically close to one another. (T/F)
3. The solar day is longer than the sidereal day. (T/F)
4. The seasons are caused by the precession of Earth's axis. (T/F)
5. A lunar eclipse can occur only during the full phase. (T/F)
6. The angular diameter of an object is inversely proportional to its distance from the observer. (T/F)
7. If we know the distance of an object from Earth, we can determine the object's size by measuring its parallax. (T/F)
8. If Earth rotated twice as fast as it currently does, but its motion around the Sun stayed the same, then (a) the night would be twice as long; (b) the night would be half as long; (c) the year would be half as long; (d) the length of the day would be unchanged.
9. A long, thin cloud that stretched from directly overhead to the western horizon would have an angular size of (a) 45°; (b) 90°; (c) 180°; (d) 360°.
10. When a thin crescent of the Moon is visible just before sunrise, the Moon is in its (a) waxing phase; (b) new phase; (c) waning phase; (d) quarter phase.
11. If the Moon's orbit were a little larger, solar eclipses would be (a) more likely to be annular; (b) more likely to be total; (c) more frequent; (d) unchanged in appearance.
12. If the Moon orbited Earth twice as fast, but in the same orbit, the frequency of solar eclipses would (a) double; (b) be cut in half; (c) stay the same.
13. **VIS** According to Figure 0.8 (The Zodiac), in January the Sun is in the constellation (a) Cancer; (b) Gemini; (c) Leo; (d) Aquarius.
14. **VIS** In Figure 0.19 (Triangulation), using a longer baseline would result in (a) a less accurate distance to the tree; (b) a more accurate distance to the tree; (c) a smaller angle at point B; (d) a greater distance across the river.
15. **VIS** In Figure 0.20 (Parallax), a smaller Earth would result in (a) a smaller parallax angle; (b) a shorter distance measured to the object; (c) a larger apparent displacement; (d) stars appearing closer together.

PROBLEMS

The number of squares preceding each problem indicates its approximate level of difficulty.

1. ■ The vernal equinox is now just entering the constellation Aquarius. In what constellation will it lie in the year A.D. 10,000?
2. ■ Given that Earth orbits at 150,000,000 km from the Sun, through what distance does Earth move in a second? An hour? A day?
3. ■■■ How, and by roughly how much, would the length of the solar day change if Earth's rotation were suddenly to reverse direction?
4. ■■ How long does it take for the Moon to move a distance equal to its own diameter of angular 0.5°?
5. ■■ Given that the distance to the Moon is 384,000 km, and taking the Moon's orbit around Earth to be circular, estimate the speed (in kilometers per second) at which the Moon orbits Earth.
6. ■■■ Use reasoning similar to that illustrated in Figure 0.7 to verify that the length of the synodic month (the time from one full Moon to the next; Section 0.3) is 29.5 days.
7. ■ The baseline in Figure 0.19 is 100 m and the angle at B is 60°. By constructing the triangle on a piece of graph paper, determine the distance from A to the tree.
8. ■■ Use reasoning similar to that in *Discovery 0-1* (but now using a circle centered on the object and containing the baseline) to determine the distance to an object if its parallax, as measured from either end of a 1000-km baseline, is (a) 1°; (b) 1′; (c) 1″.
9. ■ What would the measured angle in *Discovery 0-1* have been if Earth's circumference were 100,000 km instead of 40,000 km?
10. ■ What angle would Eratosthenes have measured (see *Discovery 0-1*) had Earth been flat?

ACTIVITIES

Collaborative

1. On a clear night, sketch a 10°-wide patch of the sky containing the Moon, with the Moon initially toward the west side of the patch. (See Individual Activity 3 below for how to estimate angles on the sky.) Repeat the observation of the same collection of stars every hour over the course of a night (take turns!). The Moon's position relative to the stars will change noticeably even in a few hours. What is the Moon's angular speed, in degrees per hour? Now observe the Moon at the *same* time each night over the course of a month. Sketch its appearance and note its position on the sky each night. Can you interpret its changing phase in terms of the relative positions of Earth, the Sun, and the Moon? (See Figure 0.13.)
2. Consider Figure 0.18, which shows solar eclipse paths on a world map. Write a description of which two eclipses you would most like to observe together and where and when you would go to observe them. Explain why you chose the dates and sites you did.

Individual

1. Find the star Polaris, also known as the North Star, in the evening sky. Identify any separate pattern of stars in the same general vicinity of the sky. Wait several hours, at least until after midnight, and then locate Polaris again. Has Polaris moved? What has happened to the nearby pattern of stars? Why?
2. Consider the curved star trails shown in Figure 0.5, a time-lapse photograph of the northern sky. They are arcs of circles centered on Polaris. What was the exposure time used for the photograph? How long would you need to take a similar picture from (a) the planet Mercury? (b) Jupiter's moon Europa? (Jump ahead to Chapters 6 or 8 to find the rotation periods of these bodies.)
3. Hold your little finger out at arm's length. Can you cover the disk of the Moon? The Moon projects an angular size of 30′ (half a degree); your finger should more than cover it. You can use this fact to make some basic sky measurements. As a simple rule, your little finger at arm's length is about 1° across, your middle three fingers are about 4° across, and your clenched fist is about 10° across. If the constellation Orion is visible, use this information to estimate the angular size of Orion's belt and the angular distance between Betelgeuse and Rigel. Compare your findings with Figure 0.2(a).

1

The Copernican Revolution

The Birth of Modern Science

Living in the Space Age, we have become accustomed to the modern view of our place in the universe. Images of Earth taken from space leave little doubt that we inhabit just one planet among several, and no one seriously questions the idea that we orbit the Sun. Yet there was a time, not so long ago, when our ancestors maintained that Earth had a special role in the cosmos and lay at the center of all things. Our view of the universe—and of ourselves—has undergone a radical transformation since those early days. Humankind has been torn from its throne at the center of the cosmos and relegated to an unremarkable position on the periphery of the Milky Way Galaxy. But in return we have gained a wealth of scientific knowledge. The story of how this came about is the story of the rise of science and the genesis of modern astronomy.

THE BIG PICTURE

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

◀ Exploration is at the heart of modern science. This engraving from a 19th-century popular science text presents a stylized depiction of the medieval worldview: the sky as a domed firmament arcing over Earth's surface. Here, a traveler finds the place where Earth and Sky meet and, pushing through the gap between them, sees the wonders of the larger universe. The image was intended primarily as a counterpoint to the then-modern view of the universe, but it also serves as a metaphor for the scientific transformation that occurred during the Renaissance—when scientists broke through the artificial constraints of cultural orthodoxy to discover the intellectual riches that lay beyond.

LEARNING OUTCOMES

Studying this chapter will enable you to:

- **LO1** Explain how geocentric models of the solar system accounted for the apparent retrograde motion of the planets.
- **LO2** Explain how retrograde motion actually arises from the orbital motions of the planets around the Sun.
- **LO3** Describe the scientific developments that led to the modern view of the solar system, and identify the main contributions of Copernicus, Tycho, Galileo, and Kepler.
- **LO4** State Kepler's laws of planetary motion.
- **LO5** Explain how astronomers have measured the true size of the solar system.
- **LO6** State Newton's laws of motion and his law of universal gravitation, and explain how they enable us to measure the masses of astronomical bodies.

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1.1 The Motions of the Planets

Over the course of a night, the stars slide smoothly across the sky. ∞ *(Sec. 0.1)* Over the course of a month, the Moon moves smoothly and steadily along its path in the sky relative to the stars, passing through its familiar cycle of phases. ∞ *(Sec. 0.3)* Over the course of a year, the Sun progresses along the ecliptic at an almost constant rate, varying little in brightness from day to day. ∞ *(Sec. 0.2)* This basic predictability of the night sky provided ancient cultures with a means of tracking the seasons and organizing their activities (see *Discovery 1-1*).

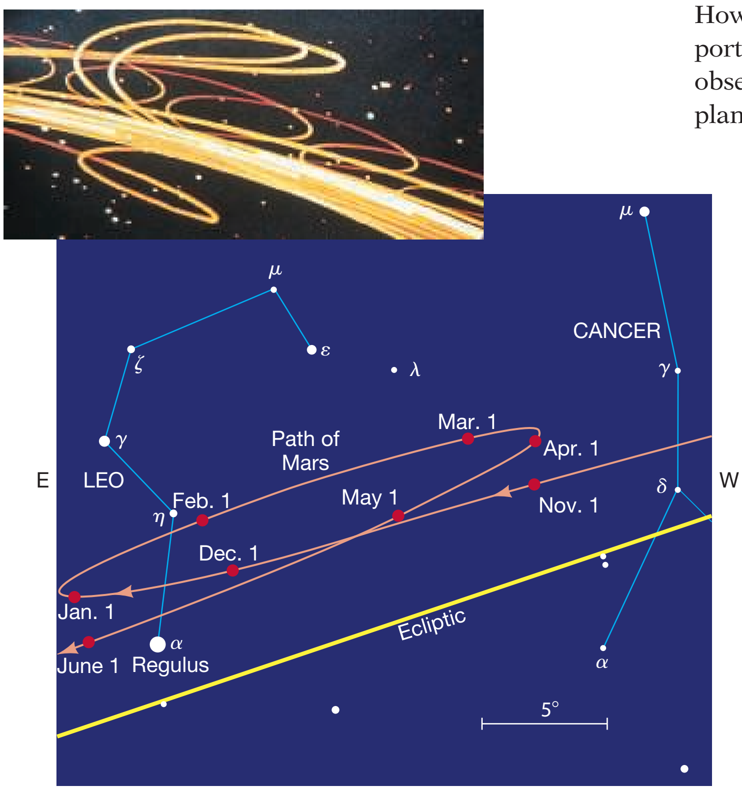
But ancient astronomers were also aware of five other bodies in the sky—the planets Mercury, Venus, Mars, Jupiter, and Saturn—whose behavior was not so easy to grasp. The explanation for their motion would change forever our perception of the universe and our place in it.

Wanderers in the Heavens

Planets do not behave in nearly as orderly a fashion as do the Sun, Moon, and stars. They vary in brightness and don't maintain fixed positions in the sky. Planets never stray far from the ecliptic and generally traverse the celestial sphere from west to east, like the Sun. But, they speed up and slow down as they go, and at times even appear to loop back and forth relative to the stars, as shown in Figure 1.1. Indeed, the word *planet* derives from the Greek word *planetes*, meaning "wanderer." Astronomers refer to the planets' normal eastward motion as *prograde* motion. The backward (westward) loops are **retrograde motion.**

Unlike the Sun and stars, but like the Moon, the planets produce no visible light of their own. Instead, they shine by reflected sunlight. Ancient astronomers correctly reasoned that the apparent brightness of a planet in the night sky is related to its distance from Earth—a planet appears brightest when closest to us. However, Mars, Jupiter, and Saturn are always brightest during the retrograde portions of their orbits. The challenge facing astronomers was to explain the observed motions of the planets and to relate those motions to the variations in planetary brightness.

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



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

The Geocentric Universe

The earliest models of the solar system followed the teachings of the Greek philosopher Aristotle (384–322 B.C.) and were **geocentric,** meaning that Earth lay at the center of the universe and all other bodies moved around it. (Figures 0.4 and 0.9 illustrate the basic geocentric view.) ∞ *(Sec. 0.2)* These models employed what Aristotle had taught was the perfect form: the circle. The simplest possible description—uniform motion around a circle having Earth at its center—provided a fairly good approximation to the orbits of the Sun and the Moon, but it could not account for the variations in planetary brightness, nor for their retrograde motion. A better model was needed.

◂ **FIGURE 1.1 Planetary Motions** Planets normally move from west to east relative to the background stars. Occasionally—roughly once per year—they change direction and temporarily undergo retrograde motion (east to west). The main illustration shows a retrograde loop in the motion of the planet Mars. The inset depicts the movements of several planets over the course of several years, as reproduced on the inside dome of a planetarium. *(Inset: Museum of Science, Boston)*

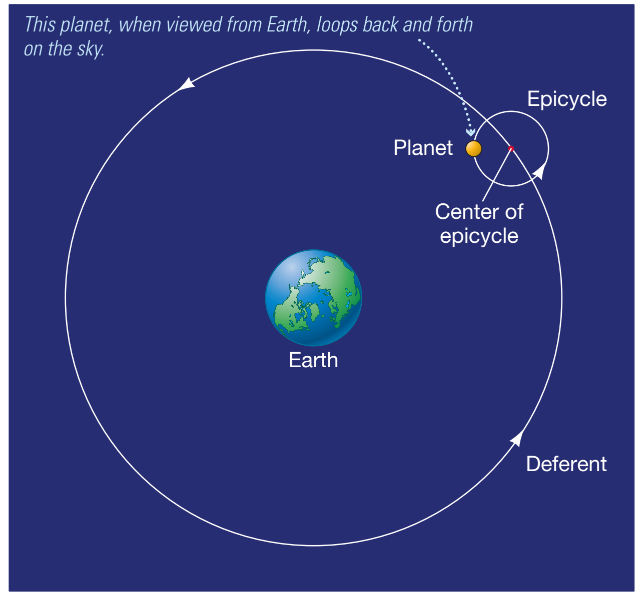
In the first step toward this new model, each planet was taken to move uniformly around a small circle, called an **epicycle,** whose *center* moved uniformly around Earth on a second and larger circle, the **deferent** (Figure 1.2). The motion was therefore composed of two separate circular orbits, creating the possibility of retrograde at certain times. Also, the distance from the planet to Earth would vary, accounting for changes in brightness. By tinkering with the relative sizes of epicycle and deferent and with the speeds at which the planet and epicycle moved, early astronomers managed to bring this model into good agreement with the observed paths of planets in the sky. It predicted quite well the positions of the known planets, according to the accuracy of observations at the time.

However, as the number and the quality of observations increased, astronomers had to introduce small corrections into the simple epicyclic model to bring it into line with new observations. The center of the deferents had to be shifted away from Earth's center, and the motion of the epicycles had to be imagined uniform with respect not to Earth, but to yet another point in space. Around A.D. 140 a Greek astronomer named Claudius Ptolemaeus (known today as Ptolemy) constructed perhaps the best geocentric model of all time. Illustrated in simplified form in Figure 1.3, it described remarkably well the observed paths of the five planets then known, as well as the paths of the Sun and the Moon. However, to achieve its explanatory and predictive power, the full **Ptolemaic model** required a series of no fewer than 80 circles. To account for the paths of the Sun, Moon, and all eight planets known today would require a vastly more complex set.

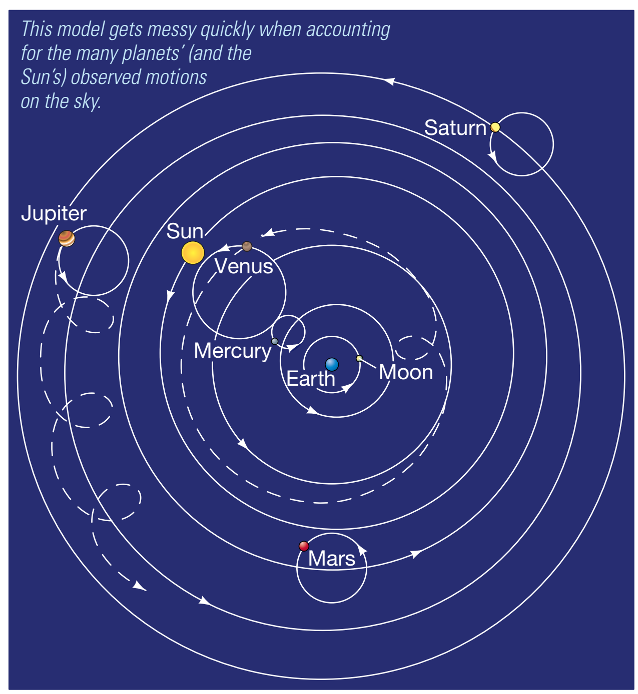
Today our scientific training leads us to seek simplicity, because simplicity in science has so often proved to be an indicator of truth. ∞ ***(Sec. 0.5)*** The intricacy of a model as complicated as the Ptolemaic system is a clear sign of a fundamentally flawed theory. We now recognize that the major error lay in the assumption of a geocentric universe, compounded by the insistence on uniform circular motion, the basis of which was largely philosophical, rather than scientific, in nature.

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

The Aristotelian school did present several arguments in favor of their views, the strongest asking—in fact, quite correctly—If the vantage point from which we view the stars changes over the course of a year, then why don't we see stellar parallax? ∞ ***(Sec. 0.4)*** We now know that there is stellar parallax as Earth orbits the Sun, but because the stars are so distant, it is less than 1 arc second, even for the closest stars. Early astronomers simply would not have noticed it (it was conclusively measured only in the latter half of the 19th century). We will encounter many instances in astronomy where correct reasoning led to the wrong conclusions because it was based on inadequate data.



▲ **FIGURE 1.2 Geocentric Model** To explain retrograde motion, in the geocentric model of the solar system, each planet was thought to follow a small circular orbit (the epicycle) about an imaginary point that itself traveled in a large, circular orbit (the deferent) about Earth.



▶ **FIGURE 1.3 Ptolemaic Model INTERACTIVE** The basic features, drawn roughly to scale, of Ptolemy's geocentric model of the inner solar system, a model that enjoyed widespread popularity prior to the Renaissance. To avoid confusion, partial paths (dashed) of only two planets, Venus and Jupiter, are drawn here.

1.1 DISCOVERY

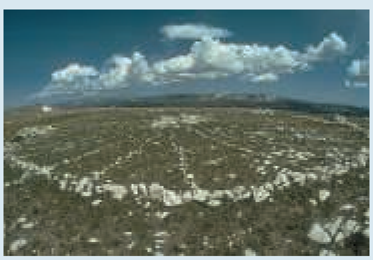
Ancient Astronomy

Many ancient societies took a keen interest in the changing nighttime sky. Seafarers needed to navigate their ships and farmers had to know when to plant their crops. Cultures all over the world built elaborate structures to serve, at least in part, as primitive calendars to predict celestial events. Often, the keepers of the secrets of the sky enshrined their knowledge in myth and ritual, and these astronomical sites were also used for religious ceremonies.

(M. Boulton)

Perhaps the best known such site is Stonehenge, in England, shown above. This ancient stone circle dates from the Stone Age and probably served as a kind of three-dimensional almanac. Many of the stones are aligned (within a degree or so) with important astronomical events, such as the rising Sun on the summer solstice and the rising and setting of the Sun and the Moon at other key times of the year, allowing its builders to track the seasons.

The Big Horn Medicine Wheel in Wyoming (below) is similar to Stonehenge in design, and perhaps also in intent. Some researchers have identified alignments between the Medicine Wheel's spokes and the rising and setting Sun at solstices and equinoxes, and with some bright stars, suggesting that its builders—the Plains Indians—were familiar with the changing night sky. Others dispute the accuracy of the alignments, however, suggesting that the wheel's purpose was more symbolic than practical. A similar controversy swirls around the Caracol temple (bottom right of the same figure) in the Mayan city of Chitzen Itza, built around A.D. 1000 on Mexico's Yucatán peninsula. Were its windows aligned with astronomical events, such as the rising of Venus, or did it have some different purpose? Experts disagree. Researchers do seem to agree that the Sun Dagger (bottom right), in Chaco Canyon, New Mexico, is a genuine astronomical calendar that probably aided agriculture. The rock is sculpted so that a thin streak of light passes precisely through the center of a carved spiral pattern at noon on the summer solstice.



(G. Gerster)

(H. Lapahie Jr.)

(J. Cornell)

The ancient Chinese also observed the heavens. Their astrology attached particular importance to "omens" such as comets and "guest stars" that appeared suddenly in the sky and then slowly faded away, and they kept careful records of such events. Perhaps the best-known guest star was one that appeared in A.D. 1054 and was visible in the daytime sky for many months. We now know that the event was a *supernova*, the explosive death of a giant star (see Chapter 13). It left behind a remnant that is still detectable today, nine centuries later. The Chinese data are a prime source of historical information for supernova research.

A vital link between the astronomy of ancient Greece and that of modern Europe was provided by astronomers in the Muslim world. This 16th-century illustration shows Turkish astronomers at work in the Istanbul Observatory. From the depths of the Dark Ages to the beginning of the Renaissance, Islamic astronomy flourished, preserving and adding to the knowledge of the Greeks. Its influence on modern astronomy is widespread. Many techniques used in trigonometry were developed by Islamic astronomers in response to practical problems, such as determining the precise dates of holy days or the direction of Mecca at any given location on Earth. Many astronomical terms, such as *azimuth*, *zenith*, and the names of many stars—for example, Rigel, Betelgeuse, and Vega—all bear witness to this extended period of Muslim scholarship.

(Istanbul University Library)

The Heliocentric Model of the Solar System

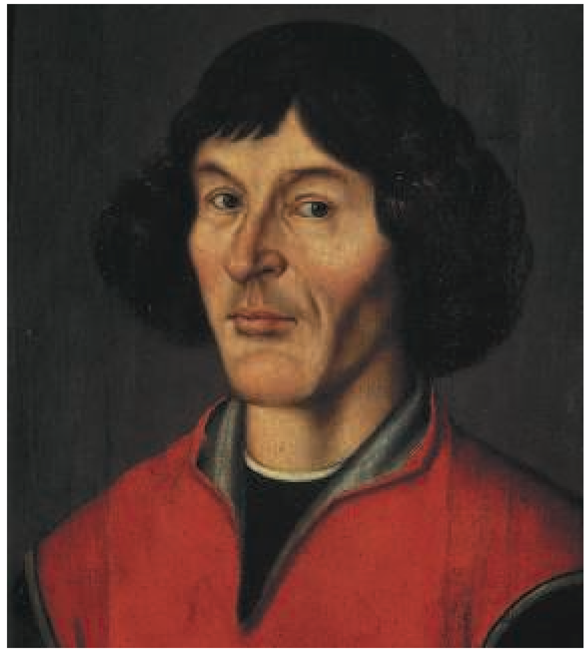
The Ptolemaic picture of the universe survived, more or less intact, for almost 13 centuries until a 16th-century Polish cleric, Nicholas Copernicus (Figure 1.4), rediscovered Aristarchus's **heliocentric** (Sun-centered) model. Copernicus asserted that Earth spins on its axis and, like all other planets, orbits the Sun. Not only does this model explain the observed daily and seasonal changes in the heavens, as we have seen, but it also naturally accounts for planetary **retrograde motion** and brightness variations. The critical realization that Earth is not at the center of the universe is now known as the **Copernican revolution.**

Figure 1.5 shows how the Copernican view explains both the changing brightness of a planet (in this case, Mars) and its apparent looping motions. If we suppose that Earth moves faster than Mars, then every so often Earth "overtakes" that planet. Each time this happens, Mars appears to move backward in the sky, in much the same way as a car we overtake on the highway seems to slip backward relative to us. Furthermore, at these times Earth is closest to Mars, so Mars appears brightest, as observed. Notice that in the Copernican picture the planet's looping motions are only apparent—in the Ptolemaic view, they were real.

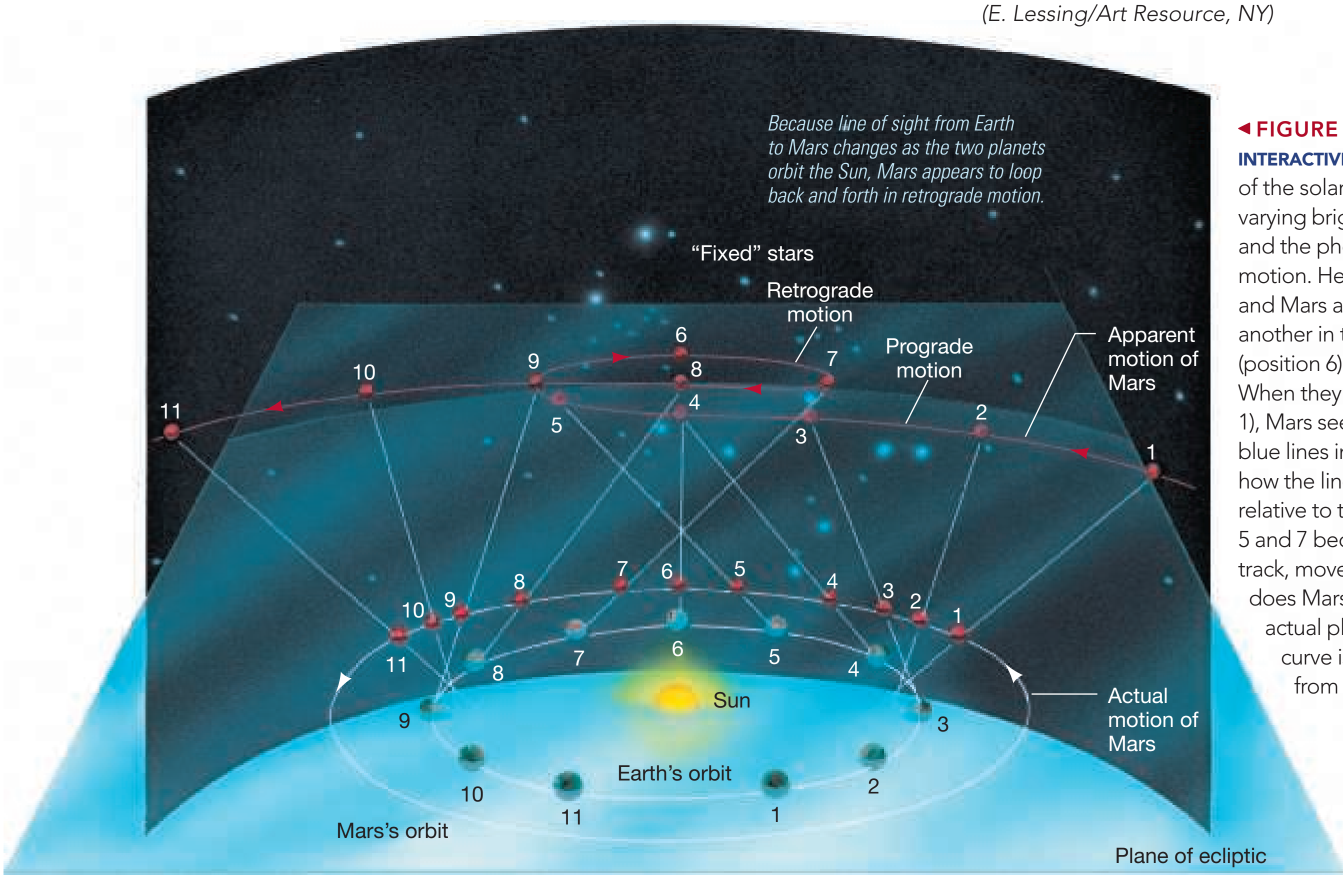
Copernicus's major motivation for introducing the heliocentric model was simplicity. Even so, he still clung to the idea of circles to model the planets' motions. To bring his theory into agreement with observations, he was forced to retain the idea of epicyclic motion, though with the deferent centered on the Sun rather than on Earth and with smaller epicycles than in the Ptolemaic picture. Thus, he retained unnecessary complexity and actually gained little in accuracy over the geocentric model. For Copernicus the primary attraction of heliocentricity was its simplicity, its being "more pleasing to the mind." To this

PROCESS OF SCIENCE CHECK

In terms of the scientific method presented in Chapter 0, what were the principal advantages of the heliocentric theory over the geocentric model? *(Sec. 0.5)*



▲ **FIGURE 1.4 Nicholas Copernicus (1473–1543)** *(E. Lessing/Art Resource, NY)*



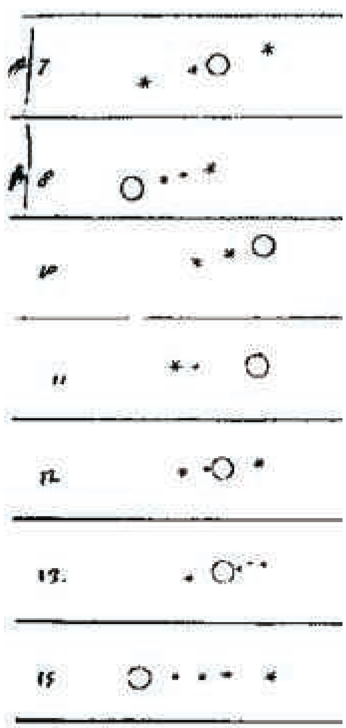
◀ **FIGURE 1.5 Retrograde Motion** **INTERACTIVE** The Copernican model of the solar system explains both the varying brightnesses of the planets and the phenomenon of retrograde motion. Here, for example, when Earth and Mars are relatively close to one another in their respective orbits (position 6), Mars seems brighter. When they are farther apart (position 1), Mars seems dimmer. Follow the blue lines in numerical order, and note how the line of sight moves backward relative to the stars between locations 5 and 7 because Earth, on the inside track, moves faster in its orbit than does Mars. The white curves are actual planetary orbits. The red curve is Mars's motion as seen from Earth.

▲ **FIGURE 1.6 Galileo Galilei (1564–1642)** *(Scala/Art Resource, NY)*

CONCEPT CHECK

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

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



▲ **FIGURE 1.7 Galilean Moons** The four large moons of Jupiter, as sketched by Galileo on seven nights between January 7 and 15, 1610. They are now known as the Galilean moons. (*From Sidereus Nuncius*)

day, scientists still are guided by simplicity, symmetry, and elegance in modeling the universe. ∞ *(Sec. 0.5)*

Copernicus's ideas were never widely accepted during his lifetime. By relegating Earth to a noncentral and undistinguished place within the solar system, heliocentricity contradicted the conventional wisdom of the time and violated the religious doctrine of the Roman Catholic Church. Copernicus surely discussed and debated his theory with his fellow scholars, but, possibly because he wished to avoid direct conflict with the Church, his book *On the Revolution of the Celestial Spheres* was not published until 1543, the year he died. Only later, when others extended and popularized the heliocentric model—and as supporting observational evidence began to mount—did the Copernican theory gain widespread recognition.

1.2 The Birth of Modern Astronomy

In the century following the death of Copernicus, two scientists—Galileo Galilei and Johannes Kepler—made indelible imprints on the study of astronomy. Each achieved fame for his discoveries and made great strides in popularizing the Copernican viewpoint.

Galileo's Historic Observations

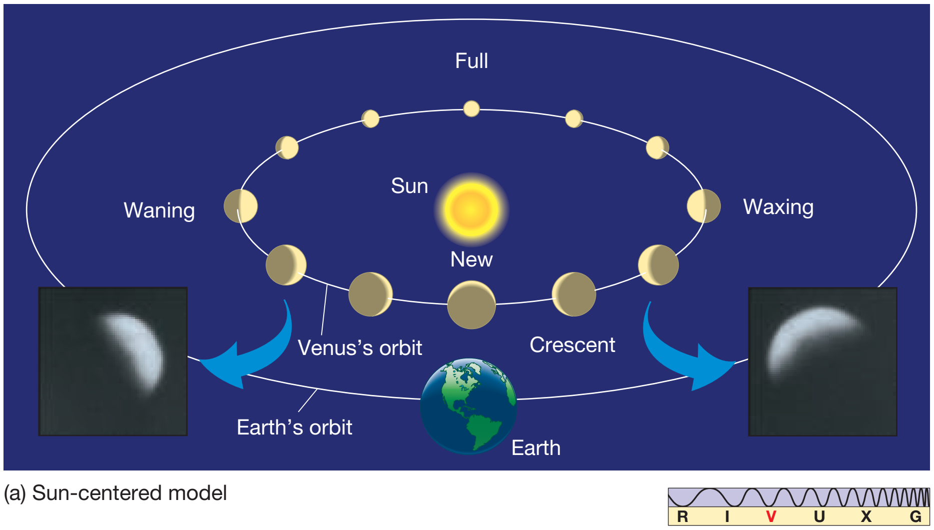
Galileo Galilei (Figure 1.6) was an Italian mathematician and philosopher. By his willingness to perform experiments to test his ideas—a radical approach in those days—and by embracing the brand-new technology of the telescope, he revolutionized the way science was done, so much so that he is now widely regarded as the father of experimental science. The telescope was invented in Holland in 1608. Having heard of the invention (but without having seen one), Galileo built one for himself in 1609 and aimed it at the sky. What he saw conflicted greatly with the philosophy of Aristotle and strongly supported the ideas of Copernicus.

Using his telescope, Galileo discovered the following:

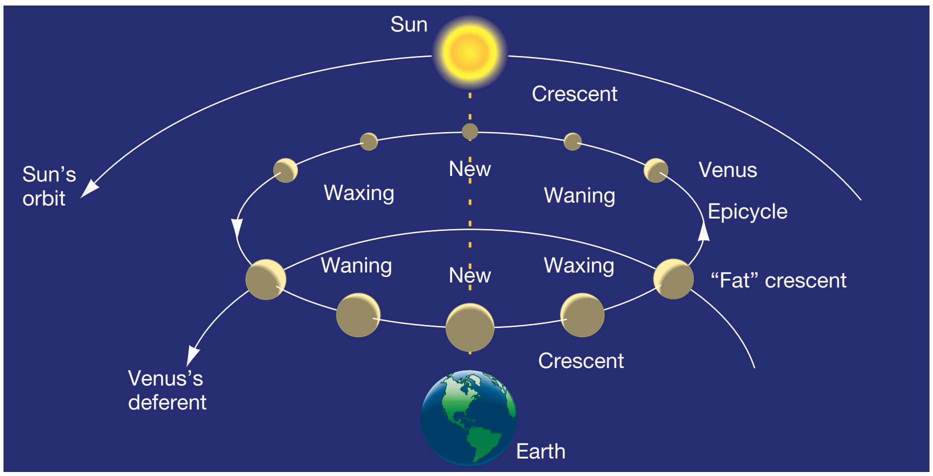
- The Moon has mountains, valleys, and craters—terrain in many ways reminiscent of that on Earth.
- The Sun has imperfections—dark blemishes now known as *sunspots* (see Chapter 9). By noting the changing appearance of these sunspots from day to day, Galileo inferred that the Sun *rotates* approximately once per month around an axis roughly perpendicular to the ecliptic plane.
- Four small points of light, invisible to the naked eye, orbit the planet Jupiter. He realized that they were *moons* (Figure 1.7) circling that planet just as our Moon orbits Earth. To Galileo, the fact that another planet had moons provided the strongest support for the Copernican model. Clearly, Earth was not the center of all things.
- Venus shows a complete cycle of *phases* (Figure 1.8), much like the familiar monthly changes exhibited by our own Moon. This finding can be explained only by the planet's motion around the Sun.

All these observations ran directly counter to the accepted scientific beliefs of the day. They showed that Earth is not the center of all things and that at least one planet orbited the Sun.

In 1610 Galileo published his observational findings and his controversial conclusions supporting the Copernican theory, challenging both scientific orthodoxy and the religious dogma of the day. In 1616 his ideas were judged heretical, both his works and those of Copernicus were banned by the Church, and Galileo



(a) Sun-centered model



(b) Ptolemy's model

◀ **FIGURE 1.8 Venus Phases INTERACTIVE** Both the Ptolemaic and the Copernican models of the solar system predict that Venus should show phases as it moves in its orbit. (a) In the Copernican picture, when Venus is directly between Earth and the Sun, its unlit side faces us and the planet is invisible to us. As Venus moves in its orbit, progressively more of its illuminated face is visible from Earth. Note the connection between the orbital phase and the apparent size of the planet: Venus seems much larger in its crescent phase than when it is full because it is much closer to us during its crescent phase. This is the behavior actually observed. The insets at bottom left and right are photographs of Venus taken at two of its crescent phases *(Courtesy of New Mexico State University)*. (b) In the Ptolemaic model, the full phase of the planet cannot be explained. Seen from Earth, Venus reaches only a "fat crescent," yet never a full phase, then begins to wane as it nears the Sun. (Note that both these views are from a sideways perspective; from overhead, both orbits are very nearly circular, as shown in Figure 1.14.)

was instructed to abandon his astronomical pursuits. Instead, he continued to collect and publish data supporting the heliocentric view. These actions brought Galileo into direct conflict with the Church. The Inquisition forced him, under threat of torture, to retract his claim that Earth orbits the Sun, and he was placed under house arrest in 1633. He remained imprisoned for the rest of his life. Not until 1992 did the Church publicly forgive Galileo's "crimes."

CONCEPT CHECK

In what ways did Galileo's observations of Venus and Jupiter conflict with the prevailing view at the time?

Ascendancy of the Copernican System

The Copernican revolution illustrates how the scientific method, although affected at any given time by the subjective whims, human biases, and even sheer luck of individual researchers, does ultimately lead to objectivity. ∞ *(Sec. 0.5)* Over time, groups of scientists checking, confirming, and refining experimental tests can neutralize the subjective attitudes of individuals. Heliocentricity was only confirmed observationally some three centuries after Copernicus published his work and more than 2000 years after Aristarchus had proposed the concept. Nonetheless, objectivity *did in fact* eventually prevail.

▲ **FIGURE 1.9 Johannes Kepler (1571–1630)**
(E. Lessing/Art Resource, NY)

▲ **FIGURE 1.10 Tycho Brahe** The astronomer in his observatory Uraniborg, on the island of Hveen, in Denmark. *(Joan Bleau/ Newberry Library/SuperStock)*

1.3 The Laws of Planetary Motion

At about the time Galileo was becoming famous for his telescopic observations, Johannes Kepler (Figure 1.9), a German mathematician and astronomer, announced his discovery of a set of simple laws that accurately described the motions of the planets. While Galileo was the first "modern" observer who used telescopic observations of the skies to confront and refine his theories, Kepler was a pure theorist. He based his work almost entirely on the observations of another scientist. Those observations, which predated the telescope by several decades, had been made by Kepler's employer, Tycho Brahe (1546–1601), arguably one of the greatest observational astronomers who ever lived.

Brahe's Complex Data

Tycho, as he is often called, was an eccentric aristocrat and a skillful observer. Born in Denmark, he was educated at some of the best universities in Europe, where he studied astrology, alchemy, and medicine. Most of his observations, which predated the invention of the telescope by several decades, were made at his own observatory, named Uraniborg, in Denmark (Figure 1.10). There, using instruments of his own design, Tycho maintained meticulous and accurate records of the stars, the planets, and noteworthy celestial events.

In 1597, having fallen out of favor with the Danish court, Tycho moved to Prague. Kepler joined Tycho in Prague in 1600 and was put to work trying to find a theory to explain Brahe's planetary data. When Tycho died a year later, Kepler inherited not only Brahe's position as Imperial Mathematician of the Holy Roman Empire, but also his most priceless possession: the accumulated observations of the planets, spanning several decades. Tycho's observations, though made with the naked eye, were nevertheless of very high quality. Kepler set to work seeking a unifying principle to explain the motions of the planets without the need for epicycles. The effort occupied much of the remaining 29 years of his life.

Kepler's goal was to find a simple description of the solar system, within the basic framework of the Copernican model, that fit Tycho's complex mass of detailed observations. In the end, he had to abandon Copernicus's original simple notion of circular planetary orbits, but even greater simplicity emerged as a result. Kepler determined the shapes and relative sizes of each planet's orbit by triangulation, not from different points on Earth, but from different points on Earth's orbit, using observations made at many different times of the year. ∞ *(Sec. 0.4)* Noting where the planets were on successive nights, he inferred the speeds at which they moved. After long years working with Brahe's data and after many false starts and blind alleys, Kepler succeeded in summarizing the motions of all the known planets, including Earth, in the three **laws of planetary motion** that now bear his name.

Kepler's Simple Laws

Kepler's first law addresses the *shapes* of the planetary orbits:

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

An **ellipse** is simply a flattened circle. Figure 1.11 illustrates a means of constructing an ellipse using a piece of string and two thumbtacks. Each point at which the string is pinned is called a **focus** (plural: foci) of the ellipse. The long axis of the ellipse, containing the two foci, is known as the *major axis*. Half the length of this long axis is referred to as the **semimajor axis,** a conventional measure of the ellipse's size.

The **eccentricity** of the ellipse is equal to the distance between the foci divided by the length of the major axis. The length of the semimajor axis and the eccentricity are all we need to describe the size and shape of a planet's orbital path. (A circle is an ellipse in which the two foci happen to coincide, so the eccentricity is zero. The semimajor axis of a circle is simply its radius.) Figure 1.12 illustrates how two other useful quantities—the planet's **perihelion** (its point of closest approach to the Sun) and its **aphelion** (greatest distance from the Sun)—can be computed from its orbital semimajor axis and eccentricity.

In fact, no planet's elliptical orbit is nearly as elongated as the one shown in Figure 1.11. With one exception (Mercury), the planets' orbits have such small eccentricities that our eyes would have trouble distinguishing them from true circles. Only because the orbits are so nearly circular were the Ptolemaic and Copernican models able to come as close as they did to describing reality.

Kepler's second law, illustrated in Figure 1.13, addresses the *speed* at which a planet traverses different parts of its orbit:

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

While orbiting the Sun, a planet traces the arcs labeled A, B, and C in Figure 1.13 in equal times. Notice, however, that the distance traveled along arc A is greater than the distance traveled along arc B or arc C. Because the time is the same and the distance is different, the speed must vary: When a planet is close to the Sun, as in sector A, it moves much faster than when farther away, as in sector C.

These laws are not restricted to planets. They apply to *any* orbiting object. Spy satellites, for example, move very rapidly as they swoop close to Earth's surface, not because they are propelled by powerful onboard rockets, but because their highly eccentric orbits are governed by Kepler's laws.

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

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

This law becomes particularly simple when we choose the (Earth) year as our unit of time and the **astronomical unit** as our unit of length. One **astronomical unit** (AU) is the semimajor axis of Earth's orbit around the Sun—the average distance between Earth and the Sun. Using these units for time and distance, we can conveniently write Kepler's third law for any planet in the form

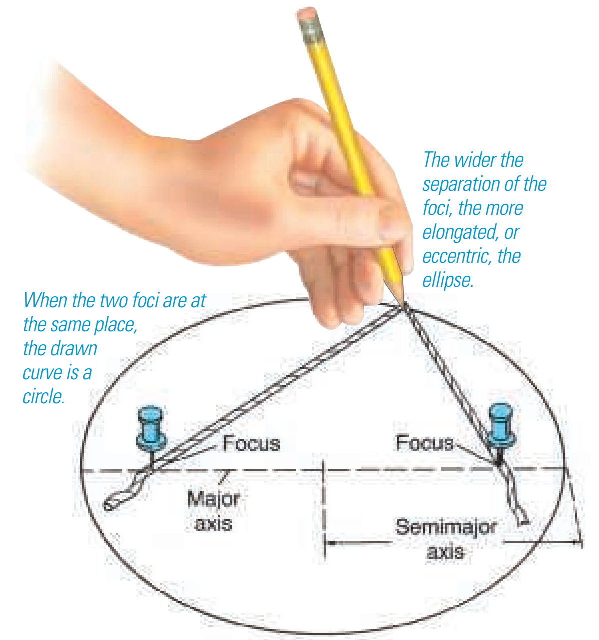
$$P^2 \text{ (in Earth years)} = a^3 \text{ (in astronomical units)},$$

where P is the planet's sidereal orbital period and a is its semimajor axis.

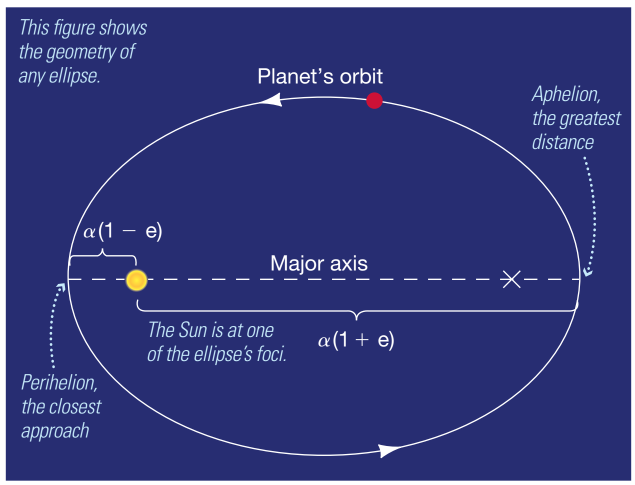
Table 1.1 presents some basic data describing the orbits of the eight major planets of the solar system. The semimajor axis of each planet's orbit is measured in astronomical units—that is, relative to the size of Earth's orbit—and all orbital periods are measured in years. Renaissance astronomers knew these properties for the innermost six planets only. However, *all* the known bodies orbiting the Sun obey Kepler's laws, *not just the six planets on which he based his conclusions.* The rightmost column lists the ratio P^2/a^3. As we have just seen, in the units used in the table, Kepler's third law implies that this number should equal 1 in all cases. The small deviations of P^2/a^3 from 1 in the cases of Uranus and Neptune are caused by the gravitational attraction between those two planets (see Chapter 7).

CONCEPT CHECK

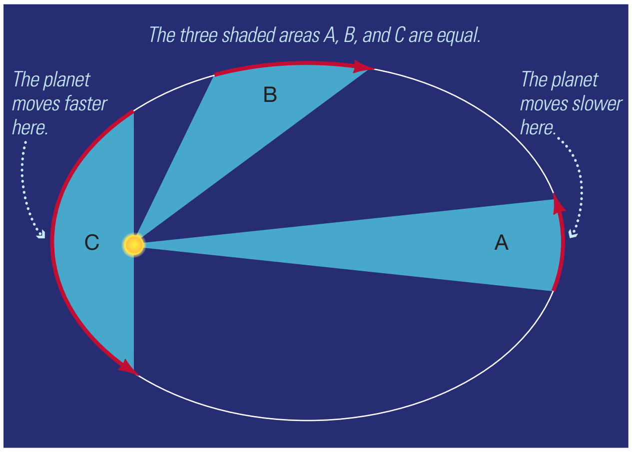
In what ways did Galileo and Kepler differ in their approach to science? In what ways did each advance the Copernican view of the universe?



▲ **FIGURE 1.11 Ellipse INTERACTIVE** An ellipse can be drawn using a string, a pencil, and two thumbtacks.



▲ **FIGURE 1.12 Orbital Properties INTERACTIVE** A planet's perihelion and aphelion are related in a simple way to the orbital semimajor axis *a* and eccentricity *e*. Note that while the Sun resides at one focus, the other focus (depicted by an X) is empty and has no particular significance. No planet in our solar system has an orbital eccentricity as large as shown here (see Table 1.1), but some meteorites and all comets do (see Chapter 4).



▲ **FIGURE 1.13 Kepler's Second Law INTERACTIVE** A line between a planet and the Sun sweeps out equal areas in equal intervals of time. Any object traveling along the elliptical path would take the same amount of time to cover the distance indicated by the three red arrows. Planets move faster when closer to the Sun.

CONCEPT CHECK

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

CONCEPT CHECK

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

TABLE 1.1 Some Planetary Properties

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

Kepler's laws were far more than mere fits to existing data. They made testable predictions about the future locations of the planets. Those predictions have been borne out to high accuracy every time they have been tested by observation—the hallmark of any credible scientific theory. ∞ *(Sec. 0.5)*

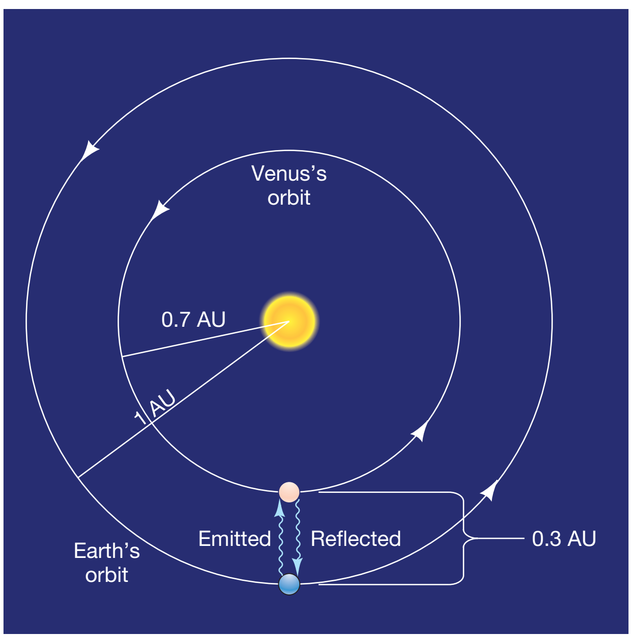
The Dimensions of the Solar System

Kepler's laws allow us to construct a scale model of the solar system, with the correct shapes and *relative* sizes of all the planetary orbits, but they do not tell us the *actual* size of any orbit. Because Kepler's measurements were based on triangulation using Earth's orbit as a baseline, his distances were expressed relative to the size of that orbit—the astronomical unit—which was not itself determined.

Our model of the solar system would be analogous to a road map of the United States showing the *relative* positions of cities and towns but lacking the all-important scale marker indicating distances in kilometers or miles. For example, we would know that Kansas City is about three times farther from New York than it is from Chicago, but we would not know the actual mileage between any two points on the map. If we could somehow determine the value of the astronomical unit—in kilometers, say—we would be able to add the vital scale marker to our map and compute the exact distances between the Sun and each of the planets.

The modern method for deriving the absolute scale of the solar system uses a technique called *radar ranging*. The word **radar** is an acronym for **ra**dio **d**etection **a**nd **r**anging. Radio waves are transmitted toward an astronomical body, such as a planet. Their returning echo indicates the body's direction and distance, in absolute terms—in other words, in kilometers rather than in astronomical units. Multiplying the round-trip travel time of the radar signal (the time elapsed between transmission of the signal and reception of the echo) by the speed of light (300,000 km/s, which is also the speed of radio waves), we obtain twice the distance to the planet.

We cannot use radar ranging to measure the distance to the Sun directly, because radio signals are absorbed at the solar surface and are not reflected back to Earth. Instead, the planet Venus, whose orbit brings it closest to Earth, is the most common target for this technique. Figure 1.14 is an idealized diagram of the



◀ **FIGURE 1.14 Astronomical Unit INTERACTIVE** The wavy blue lines represent the paths along which radar signals are transmitted toward Venus and received back at Earth when Venus is at its minimum distance from Earth. Because the radius of Earth's orbit is 1 AU and that of Venus is about 0.7 AU, the one-way distance covered by the signal is 0.3 AU. Thus, we can calibrate the astronomical unit in kilometers.

Sun–Earth–Venus orbital geometry. Neglecting for simplicity the small eccentricities of the two planets' orbits, we see from Table 1.1 that the distance from Venus to the Sun is roughly 0.7 AU. Hence (from Figure 1.14), the distance from Earth to Venus at closest approach is approximately 0.3 AU. Radar signals bounced off Venus at that instant return to Earth in about 300 seconds, indicating that Venus lies 300,000 km/s $\times$ 300 s $\div$ 2 (dividing by 2 for a one-way trip) = 45,000,000 km from Earth. Since 0.3 AU is 45,000,000 km, it follows that 1 AU is 45,000,000 km/0.3, or 150,000,000 km.

Through precise radar ranging, the astronomical unit is now known to be 149,597,870 km. In this text, we will round this value off to 1.5×10^8 km. Having determined the value of the astronomical unit, we can re-express the sizes of the other planetary orbits in more familiar units, such as miles or kilometers. The entire scale of the solar system can then be calibrated to high precision.

DATA POINTS

Kepler's Laws

Almost half of all students had difficulty applying Kepler's laws to the orbits of objects in the solar system. Remember:

- According to Kepler's second law ("equal areas"), a planet moves fastest in its orbit when it is closest to the Sun.
- Kepler's third law tells us that planets on larger orbits take longer to complete one trip around the Sun. The orbital period increases faster than the size of the orbit—doubling the size increases the period by a factor of $2\sqrt{2}$, or approximately 2.8.

1.4 Newton's Laws

Kepler's three laws, which so simplified the solar system, were discovered *empirically*. In other words, they resulted solely from the analysis of observational data, rather than being derived from a theory or mathematical model. Indeed, Copernicus, Galileo, and Kepler had no real understanding of *why* the planets orbit the Sun. Only by considering something more fundamental can we truly comprehend planetary motion. The critical test of any complete scientific theory is its ability to explain physical phenomena, not simply describe them.

The Laws of Motion

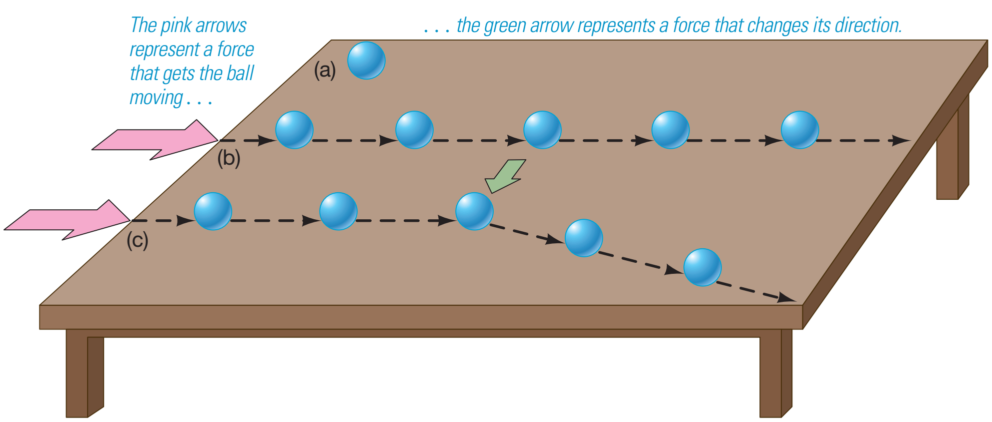
In the 17th century, the British physicist and mathematician Isaac Newton (Figure 1.15) developed a deeper understanding of the way all objects move and interact with one another. Newton's theories form the basis for what today is known as **Newtonian mechanics.** Three basic laws of motion, the law of universal gravitation, and a little calculus (which Newton also developed) are sufficient to explain virtually all of the complex dynamic behavior we see throughout the universe.

Figure 1.16 illustrates *Newton's first law of motion,* which states:

> I. An object at rest remains at rest, and a moving object continues to move forever in a straight line with constant speed, unless some external **force** changes their state of motion.

An example of an external force would be the force exerted by, say, a brick wall when a rolling ball glances off it, or the force exerted on a pitched ball by a baseball bat. In either case, a force changes the original motion of the object. The

▲ FIGURE 1.15 **Isaac Newton (1642–1727)** *(S. Terry)*



◄ FIGURE 1.16 **Newton's First Law** An object at rest will remain at rest (a) until some force acts on it. When a force (represented by the red arrow) does act (b), the object will remain in that state of uniform motion until another force acts on it. When a second force (green arrow) acts in a direction different from the first force (c), the object changes its direction of motion.

tendency of an object to keep moving at the same speed and in the same direction unless acted upon by a force is known as **inertia.** A familiar measure of an object's inertia is its **mass**—loosely speaking, the total amount of matter the object contains. The greater an object's mass, the more inertia it has and the greater is the force needed to change its motion.

Newton's first law contrasts sharply with the view of Aristotle, who maintained (incorrectly) that the natural state of an object was to be at *rest*—most probably an opinion based on Aristotle's observations of the effect of friction. To simplify our discussion, we will neglect friction—the force that slows balls rolling along the ground, blocks sliding across tabletops, and baseballs moving through the air. In any case, this is not an issue for the planets, as there is no appreciable friction in outer space.

The rate of change of the velocity of an object—speeding up, slowing down, or simply changing direction—is called its **acceleration.** *Newton's second law* states:

> II. The acceleration of an object is directly proportional to the net applied force and inversely proportional to the object's mass.

In other words, the greater the force acting on the object, or the smaller the mass of the object, the greater its acceleration. Thus, if two objects are pulled with the same force, the more massive one accelerates less. If two identical objects are pulled with different forces, the one experiencing the greater force accelerates more.

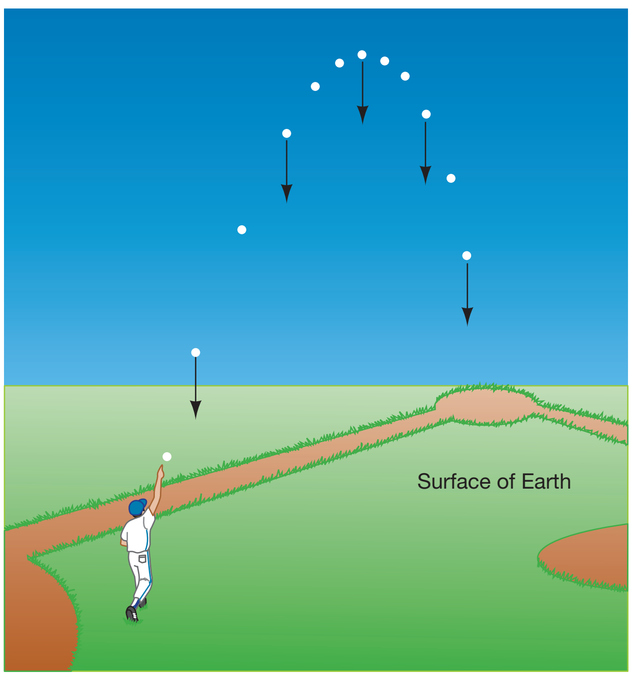
Finally, *Newton's third law* tells us that forces always occur in pairs:

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

If body A exerts a force on body B, then body B necessarily exerts a force on body A that is equal in magnitude but oppositely directed.

Gravity

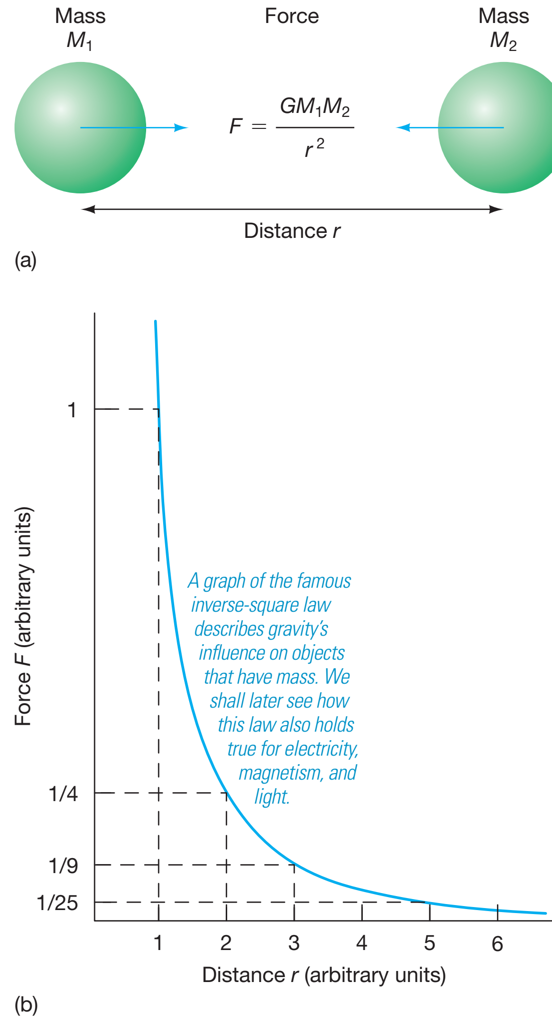
Forces can act either *instantaneously* or *continuously*. The force from a baseball bat that hits a home run can reasonably be thought of as instantaneous. A good example of a continuous force is the one that prevents the baseball from zooming off into space—**gravity,** the phenomenon that started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



▲ FIGURE 1.17 **Gravity** A ball thrown up from the surface of a massive object, such as a planet, is pulled continuously down (arrows) by the gravity of that planet—and, conversely, the gravity of the ball continuously pulls the planet (although very, very little).

Consider a baseball thrown upward from Earth's surface, as illustrated in Figure 1.17. In accordance with Newton's first law, the downward force of Earth's gravity steadily modifies the baseball's velocity, slowing its initial upward motion and eventually causing the ball to fall back to the ground. Of course, the baseball, having some mass of its own, also exerts a gravitational pull on Earth. By Newton's third law, this force is equal in magnitude to the weight of the ball (the weight of an object is a measure of the force with which Earth attracts that object), but oppositely directed. By Newton's second law, however, Earth has a much greater effect on the light baseball than the baseball has on the much more massive Earth. The ball and Earth each feel the same gravitational force, but Earth's *acceleration* as a result of this force is much smaller and can be safely ignored.

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



▶ **FIGURE 1.18 Gravitational Force** (a) The gravitational force between two bodies is proportional to the mass of each and is inversely proportional to the square of the distance between them. (b) Inverse-square forces weaken rapidly with distance from their source, never quite reaching zero no matter how far away.

Studying the motions of the planets reveals a second aspect of the gravitational force. At locations equidistant from the Sun's center, the gravitational force has the same strength and is always directed toward the Sun. Furthermore, detailed calculation of the planets' accelerations as they orbit the Sun reveals that the strength of the Sun's gravitational pull decreases in proportion to the *square* of the distance from the Sun. (Newton is said to have first realized this fact by comparing the accelerations not of the planets, but of the Moon and an apple falling to the ground—the basic reasoning is the same in either case.) The force of gravity is said to obey an **inverse-square law** (Figure 1.18a).

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

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

As shown in Figure 1.18(b), inverse-square forces decrease rapidly with distance from their source. For example, tripling the distance makes the force $3^2 = 9$ times weaker, while multiplying the distance by five results in a force that is $5^2 = 25$ times weaker. Despite this rapid decrease, the force never quite reaches zero. The gravitational pull of an object having some mass can never be completely extinguished.

INTERACTIVE Center of Mass of a Binary Star

CONCEPT CHECK

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

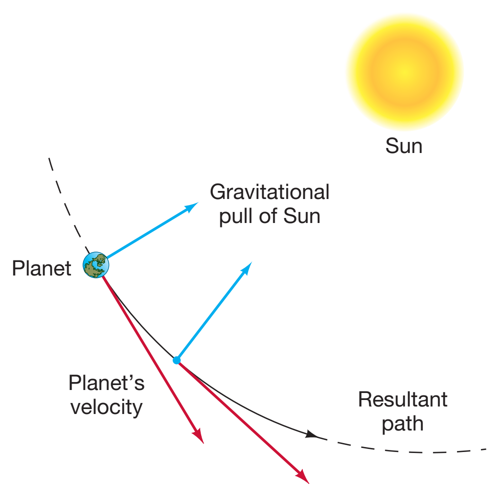
Orbital Motion

The mutual gravitational attraction of the Sun and the planets, as expressed by Newton's law of gravity, is responsible for the observed planetary orbits. As depicted in Figure 1.19, this gravitational force continuously pulls each planet toward the Sun, deflecting its forward motion into a curved orbital path. In the solar system, at this very moment, Earth is moving under the combined influence of these two effects: the competition between gravity and inertia. Because the Sun is much more massive than any of the planets, it dominates the interaction. We might say that the Sun "controls" the planets, not the other way around.

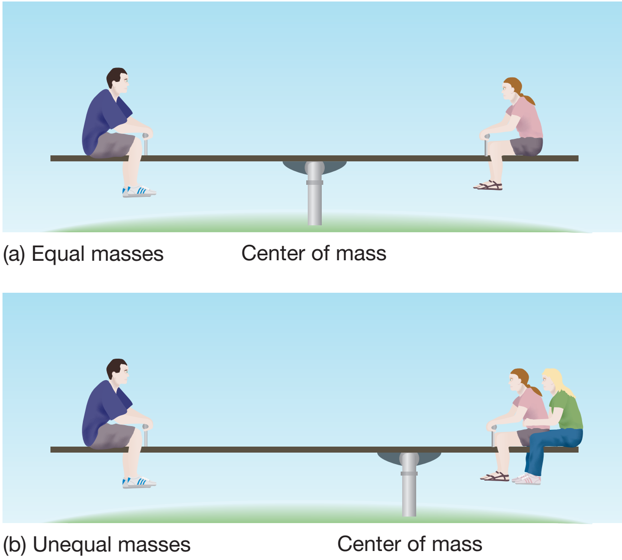
The planet–Sun interaction sketched here is analogous to what occurs when you whirl a rock at the end of a string above your head. The Sun's gravitational pull is your hand and the string, and the planet is the rock at the end of that string. The tension in the string provides the force necessary for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

Kepler's Laws Reconsidered

Newton's laws of motion and his law of universal gravitation provided a theoretical explanation for Kepler's empirical laws of planetary motion. Just as Kepler modified the Copernican model by introducing ellipses in place of circles, so too did Newton make corrections to Kepler's first and third laws. Because the Sun and a planet feel



▶ **FIGURE 1.19 Sun's Gravity** The Sun's inward pull of gravity on a planet competes with the planet's tendency to continue moving in a straight line. These two effects combine, causing the planet to move smoothly along an intermediate path, which continuously "falls around" the Sun.



▲ **FIGURE 1.20 Center of Mass** (a) The center of mass of two bodies of equal mass lies midway between them. (b) As the mass of one body increases, the center of mass moves toward it. Experienced seesawers know that when both sides are balanced, the center of mass is at the pivot point.

ANIMATION / VIDEO
Gravity Demonstration on the Moon

equal and opposite gravitational forces (by Newton's third law), the Sun must also move (by Newton's first law) due to the planet's gravitational pull. As a result, the planet does not orbit the exact center of the Sun but, instead, both the planet and the Sun orbit their common **center of mass**—the "average" position of the matter comprising the two bodies (see Figure 1.20)—and Kepler's first law becomes:

I. The orbit of a planet around the Sun is an ellipse having the center of mass of the planet–Sun system at one focus.

As illustrated in Figure 1.20, the center of mass of a system consisting of two objects of comparable mass does not lie within either object. For identical masses orbiting one another (Figure 1.21a), the orbits are identical ellipses with a common focus located midway between the two objects. For unequal masses (Figure 1.21b), the elliptical orbits still share a focus and have the same eccentricity, but the more massive object moves more slowly and on a tighter orbit. (Note that Kepler's second law continues to apply without modification to each orbit separately, but the rates at which the two orbits sweep out area are different.)

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

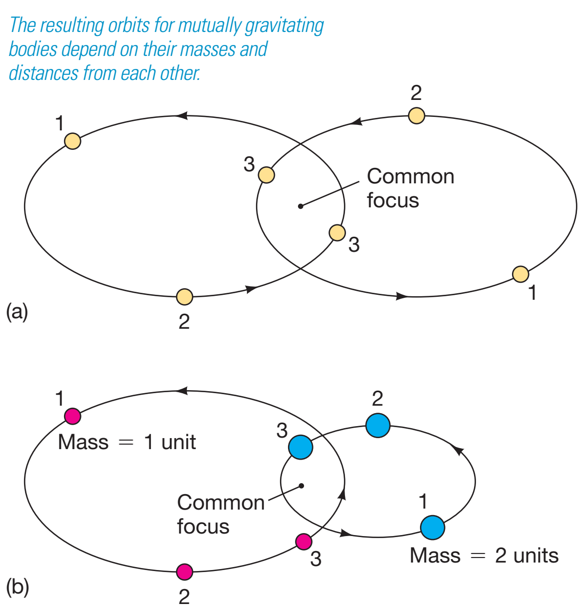
$$P^2 \text{ (in Earth years)} = \frac{a^3 \text{ (in astronomical units)}}{M_{\text{total}} \text{ (in solar units)}},$$

where M_{total} is the *combined* mass of the two objects, expressed in terms of the mass of the Sun. Notice that this restatement of Kepler's third law preserves the proportionality between P^2 and a^3, but now the proportionality also includes M_{total} so it is *not* quite the same for all the planets. The Sun's mass is so great, however, that the differences in M_{total} among the various combinations of the Sun and the other planets are almost unnoticeable. Therefore, Kepler's third law, as originally stated, is a very good approximation.

This modified form of Kepler's third law is true in all circumstances, inside or *outside* the solar system. Most importantly, it provides a means of measuring mass *anywhere* in the universe, so long as we can determine the orbital properties—separation and period—of the bodies involved. In fact, this is how *all* masses are measured in astronomy. When we need to know an object's mass, we always look for its gravitational influence on something else. This principle applies to planets, stars, galaxies, even clusters of galaxies—very different objects but all subject to the same fundamental physical laws. Newton's laws extend our intellectual reach far beyond the tiny fraction of the universe we can actually visit or touch.

The Circle of Scientific Progress

The progression from the complex Ptolemaic model of the universe to the elegant simplicity of Newton's laws is a case study in the scientific method. ***(Sec.0.5)*** Copernicus made a radical conceptual leap away from the Ptolemaic view, gaining much in insight but little in predictive power. Kepler made critical changes to



◀ **FIGURE 1.21 Orbits** (a) The orbits of two bodies with equal masses, under the influence of their mutual gravity, are identical ellipses with a common focus. The pairs of numbers (e.g., the two 2s in each orbit) indicate the positions of the two bodies at three different times. (b) The orbits of two bodies, one twice as massive as the other, are again elliptical and with the same eccentricity, but according to Newton's laws, the more massive body moves more slowly and in a smaller orbit.

the Copernican picture and gained both accuracy and predictive power, but still fell short of a true physical explanation of planetary motion within the solar system, or of orbital motion in general. Eventually, Newton showed how all known planetary motion could be explained in detail by the application of four simple, fundamental laws—the three laws of motion and the law of gravity. The process was slow, with many starts and stops and a few wrong turns, but it worked!

In a sense, the development of Newton's laws and their application to planetary motion represent the end of the first "loop" around the schematic diagram shown in Figure 0.22. The practical and conceptual questions raised by ancient observations of retrograde motion were finally resolved, and new predictions, themselves amenable to observational testing, became possible. But Newton's laws went much further. Unlike the essentially descriptive models of Ptolemy, Copernicus, and Kepler, Newtonian mechanics is not limited to the motions of planets. They apply to moons, comets, spacecraft, stars, and even the most distant galaxies, extending the range of our scientific inquiries across the observable universe.

Newton's laws are still being tested today. Every time a comet appears in the night sky right on schedule or a spacecraft reaches the end of a billion-kilometer journey within meters of its target and seconds of the predicted arrival time, our confidence in the laws is further strengthened.

Yet even Newton's laws are just an approximation to reality. They break down in extreme circumstances—although this fact was only realized in the early 20th century, when Albert Einstein's theories of relativity (Chapter 13) again revolutionized our view of gravity and the universe. The modern conception of an expanding universe dominated on the largest scales by non-gravitational forces (Chapter 17) differs radically from Newton's conception of the cosmos, but it too is the result of the same basic scientific methodology followed by Galileo and Newton.

PROCESS OF SCIENCE CHECK

Describe some ways in which Newtonian mechanics superseded Kepler's laws as a model of the solar system.

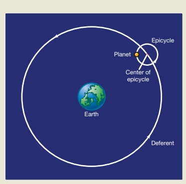
THE BIG QUESTION

Newtonian mechanics and the law of gravity work well for small masses and low velocities, and hence for almost every application on or near Earth. But in the early 20th century, Albert Einstein overthrew these ideas with a better one—relativity theory, which deals with fast-moving, often massive objects in curved space. Now, in the 21st century, scientists are beginning to grapple with the notion that other, still unknown, forces may dominate the universe on the largest scales. Will relativity in turn be replaced by a new paradigm? No one knows, but the scientific method is designed to help us find out.

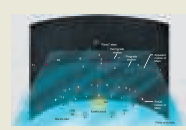
CHAPTER REVIEW

SUMMARY

LO1 **Geocentric** (p. 28) models of the universe, such as the **Ptolemaic model** (p. 29), have the Sun, Moon, and planets all orbiting Earth. They explain **retrograde motion** (p. 31) as a real backward motion of a planet as it moves along its epicyclic path.

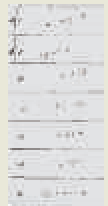


LO2 The **heliocentric** (p. 31) view of the solar system, due to Aristarchus and later Copernicus, holds that Earth, like all the other planets, orbits the Sun. This model explains both retrograde motion as Earth overtakes other planets in its orbit and the observed brightness variations of the planets. The

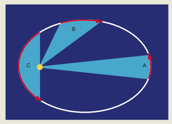


realization that the solar system is Sun centered, not Earth centered, is known as the **Copernican revolution** (p. 31).

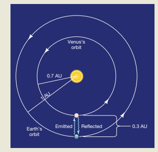
LO3 Copernicus suggested that if the planets orbited the Sun, rather than Earth, this would provide a simpler explanation of their observed motion. Galileo Galilei was the first experimental scientist. His telescopic observations of the Sun, Moon, and planets provided experimental evidence against the geocentric theory and supporting Copernicus's heliocentric model. Johannes Kepler constructed a set of three simple laws describing the motions of the planets around the Sun, explaining Tycho Brahe's detailed observational data.



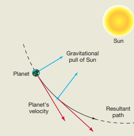
LO4 Kepler's three **laws of planetary motion** (p. 34) state that (1) planetary orbits are **ellipses** (p. 34) having the Sun as one **focus** (p. 34), (2) a planet moves faster as its orbit takes it closer to the Sun, and (3) the orbital **semimajor axis** (p. 34) is simply related to the planet's orbital **period** (p. 35).



LO5 The average distance from Earth to the Sun is one **astronomical unit** (p. 35), today precisely determined by bouncing **radar** (p. 36) signals off the planet Venus. Once this is known, the distances to all other planets can be inferred from Kepler's laws.



LO6 To change a body's velocity, a **force** (p. 34) must be applied. The rate of change of velocity, called the **acceleration** (p. 38), is equal to the applied force divided by the body's mass. **Gravity** (p. 38) attracts the planets to the Sun. Every object having any mass exerts a **gravitational force** (p. 38) on all other objects, and the strength of this force decreases with distance according to an **inverse-square law** (p. 39).



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

REVIEW AND DISCUSSION

1. **LO1** Describe the strengths and weaknesses of the geocentric model of the universe.
2. **POS** The benefit of our current knowledge lets us see flaws in the Ptolemaic model of the universe. What is its basic flaw?
3. What was the great contribution of Copernicus to our knowledge of the solar system?
4. **LO2** How did the heliocentric model explain planetary motions and brightness variations?
5. **LO3** **POS** How did Galileo help confirm the views of Copernicus?
6. Why is Galileo often thought of as the first experimental scientist?
7. **LO4** Briefly describe Kepler's three laws of planetary motion.
8. **LO3** How did Tycho Brahe contribute to Kepler's laws?
9. **POS** What does it mean to say Kepler's laws are empirical?
10. **LO5** If radio waves cannot be reflected from the Sun, how can radar be used to find the distance from Earth to the Sun?
11. List the two modifications made by Newton to Kepler's laws.
12. Why do we say that a baseball falls toward Earth, and not Earth toward the baseball?
13. Why would a baseball thrown from the surface of the Moon go higher than one thrown with the same velocity from Earth's surface?
14. **LO6** According to Newton, why does Earth orbit the Sun?
15. What would happen to Earth if the Sun's gravity were suddenly "turned off"?

CONCEPTUAL SELF-TEST: TRUE OR FALSE?/MULTIPLE CHOICE

1. Aristotle proposed that all planets revolve around the Sun. (T/F)
2. During retrograde motion, planets actually stop and move backward in space. (T/F)
3. The heliocentric model of the universe holds that Earth is at the center and everything else moves around it. (T/F)
4. Copernicus's theories gained widespread scientific acceptance during his lifetime. (T/F)
5. Galileo's observations of the sky were made with the naked eye. (T/F)
6. The speed of a planet orbiting the Sun is independent of the planet's position in its orbit. (T/F)
7. Kepler's laws hold only for the six planets known in his time. (T/F)
8. You throw a baseball to someone; before the ball is caught, it is temporarily in orbit around Earth's center. (T/F)
9. A major flaw in Copernicus's model was that it still had (a) the Sun at the center; (b) Earth at the center; (c) retrograde loops; (d) circular orbits.

10. VIS An accurate sketch of Mars's orbit around the Sun would show (a) the Sun far off center; (b) an oval twice as long as it is wide; (c) a nearly perfect circle; (d) phases.

11. A calculation of how long it takes a planet to orbit the Sun would be most closely related to Kepler's (a) first law of orbital shapes; (b) second law of orbital speeds; (c) third law of planetary distances; (d) first law of inertia.

12. An asteroid with an orbit lying entirely inside Earth's (a) has an orbital semimajor axis of less than 1 AU; (b) has a longer orbital period than Earth's; (c) moves more slowly than Earth; (d) has a highly eccentric orbit.

13. If Earth's orbit around the Sun were to double in size, the new "year" would be (a) less than 2; (b) 2; (c) more than 2 current Earth years.

14. VIS As shown in Figure 1.8 (Venus Phases), Galileo's observations demonstrated that Venus must be (a) orbiting Earth; (b) orbiting the Sun; (c) larger than Earth; (d) similar to the Moon.

15. VIS Figure 1.17 (Gravity), showing the motion of a ball near Earth's surface, depicts how gravity (a) increases with altitude; (b) causes the ball to accelerate downward; (c) causes the ball to accelerate upward; (d) has no effect on the ball.

PROBLEMS

The number of squares preceding each problem indicates its approximate level of difficulty.

1. ■■ Tycho's observations were accurate to about 1 arc minute (1′). To what distance does this correspond at the distance of (a) the Moon, (b) the Sun, (c) Saturn at closest approach? *(∞Problem 0.8)*

2. ■ How long would a radar signal take to complete a round-trip between Earth and Mars when the two planets are 0.7 AU apart?

3. ■■ Seen from Earth, through what angle will Mars appear to move relative to the stars over the course of 24 hours when the two planets are at closest approach? Assume that Earth and Mars move on circular orbits of radii 1.0 AU and 1.5 AU, respectively, in the same plane. Will the apparent motion be prograde or retrograde?

4. ■■ An asteroid has a perihelion distance of 2.0 AU and an aphelion distance of 4.0 AU. Calculate its orbital semimajor axis, eccentricity, and period (see Figure 1.12).

5. ■■ Halley's Comet has a perihelion distance of 0.6 AU and an orbital period of 76 years. What is its aphelion distance from the Sun?

6. ■■ Using the data in Table 1.1, calculate how much farther Mercury is from the Sun at aphelion than at perihelion.

7. ■■■ Jupiter's moon Callisto orbits the planet at a distance of 1.88 million kilometer. Callisto's orbital period about Jupiter is 16.7 days. What is the mass of Jupiter? [Assume that Callisto's mass is negligible compared with that of Jupiter, and use the modified version of Kepler's third law (Section 1.4).]

8. ■■ The acceleration due to gravity at Earth's surface is 9.80 m/s^2. What is the acceleration at altitudes of (a) 100 km? (b) 1000 km? (c) 10,000 km? Take Earth's radius to be 6400 km.

9. ■ Use Newton's law of gravity to calculate the force of gravity between you and Earth. Convert your answer, which will be in newtons, to pounds using the conversion 4.45 N = 1 pound. What do you normally call this force?

10. ■■ The Moon's mass is 7.4×10^{22} kg, and its radius is 1700 km. What would be the period and the speed of a spacecraft moving in a circular orbit just above the lunar surface?

ACTIVITIES

Collaborative

1. You have been asked to arbitrate a dispute between a tour bus company and a nearby Native American tribe concerning a recently discovered ancient medicine wheel. Using sketches as necessary, compose a document describing what a medicine wheel is designed to do astronomically, and summarize the pros and cons of letting the public have unrestricted access to the site.

2. Select what you believe to be Galileo's single most important astronomical observation, state why you think it was most important, and explain using sketches what he observed.

Individual

3. Look in an almanac for the dates of opposition of Mars, Jupiter, and Saturn. At opposition, these planets are at their closest points to Earth and are at their largest and brightest in the night sky. Observe these planets. How long before opposition does each planet's retrograde motion begin? How long afterward does it end?

4. Use a small telescope to replicate Galileo's observations of Jupiter's largest moons. Note the brightness and location of the moons relative to Jupiter. If you watch over a period of several nights, draw what you see; the moons' positions will change as they orbit the planet.

5. Draw an ellipse (see Figure 1.11). You'll need two pins, a piece of string, and a pencil. Tie the string in a loop and place around the pins. Place the pencil inside the loop and run it around the inside of the string, holding the loop taut. The two pins will be at the foci of the ellipse. What is the eccentricity of the ellipse you have drawn? How does its shape change as you vary the distance between the pins?

2

Light and Matter

The Inner Workings of the Cosmos

Astronomical objects are more than just things of beauty in the night sky. Planets, stars, and galaxies are of vital significance if we are to understand fully the big picture—the grand design of the universe. Every object is a source of information about the universe—its temperature, its chemical composition, its state of motion, its past history. The starlight we see tonight began its journey to Earth decades, centuries, even millennia ago. The faint rays from the most distant galaxies have taken billions of years to reach us. The stars and galaxies in the night sky show us not just the far away, but also the long ago. In this chapter, we begin our study of how astronomers extract information from the light emitted by astronomical objects. The observational and theoretical techniques that enable researchers to determine the nature of distant atoms by the way they emit and absorb light are the indispensable foundation of modern astronomy.

THE BIG PICTURE

The human eye sees just a tiny fraction of the radiation that pervades the universe. A much larger cosmos lies unseen beyond the visible spectrum. Space is filled with many different kinds of invisible radiation, ranging from radio waves to gamma rays. Detailed spectroscopic study of this broad range of visible and invisible information is the primary way in which astronomers study stars and other distant objects.

◄ This remarkable composite image of the nearby galaxy M106 was created by combining observations made in the radio (purple), infrared (red), visible (yellow/white), and X-ray (blue) parts of the spectrum. In the visible and infrared, M106 appears to be a rather normal disk galaxy, much like millions of others observed throughout the universe (see Chapter 15). But at radio and X-ray wavelengths, an entirely different picture emerges. The data show huge "bubbles" of superheated gas apparently blasted out of the disk by intense jets of radiation emanating from a supermassive black hole at the galaxy's center. These observations illustrate a key mechanism by which galaxies are thought to evolve, as well as the importance of multiwavelength observations in our understanding of the workings of the cosmos. *(Chandra X-Ray Observatory)*

LEARNING OUTCOMES

Studying this chapter will enable you to:

- **LO1** Describe the nature of electromagnetic radiation, and tell how that radiation transfers energy and information through interstellar space.
- **LO2** List the major regions of the electromagnetic spectrum, and arrange them in order of wavelength, frequency, or photon energy.
- **LO3** Explain how we can determine an object's temperature by observing the radiation it emits.
- **LO4** Describe the characteristics of continuous, emission, and absorption spectra and the conditions under which each is produced.
- **LO5** Specify the basic components of the atom, and describe our modern conception of atomic and molecular structure.
- **LO6** Explain how electron transitions within atoms produce unique emission and absorption spectra and how an object's composition can be determined from its spectrum.
- **LO7** Describe how the relative motion of an object can be determined from shifts in the wavelengths or frequencies of its spectral lines.

2.1 Information from the Skies

Figure 2.1 shows our nearest large galactic neighbor, which lies in the constellation Andromeda. On a dark, clear night, far from cities or other sources of light, the Andromeda galaxy, as it is generally called, can be seen with the naked eye as a faint, fuzzy patch on the sky, comparable in diameter to the full Moon. Yet the fact that it is visible from Earth belies this galaxy's enormous distance from us. It lies roughly 2.5 million light-years away. An object at such a distance is truly inaccessible in any realistic human sense.

Light and Radiation

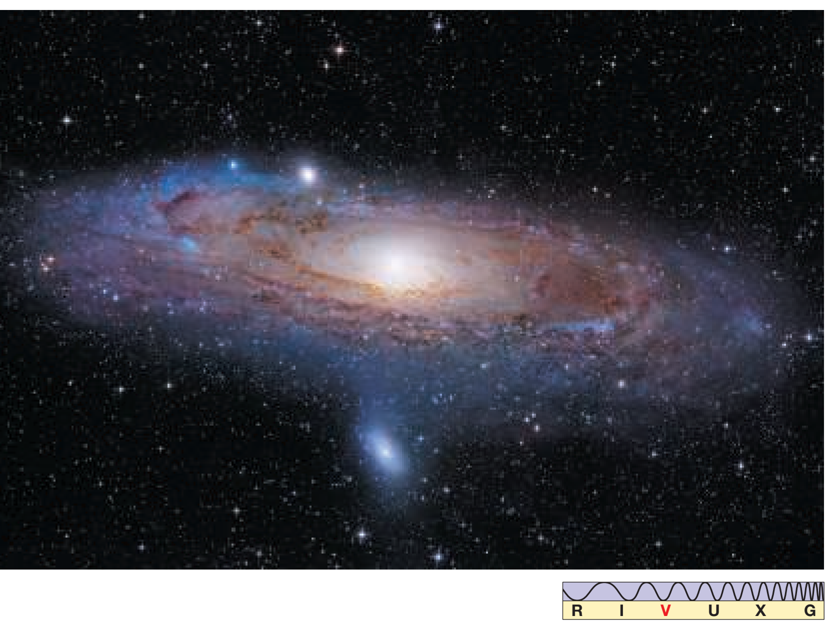
How do astronomers know anything about objects far from Earth? The answer is that we use the laws of physics, as we know them here on Earth, to interpret the light, or **electromagnetic radiation** emitted by these objects. *Radiation* is any way in which energy is transmitted through space from one point to another without the need for any physical connection between those two locations. The term *electromagnetic* refers to the fact that the energy in a beam of light is actually carried in the form of rapidly changing *electric* and *magnetic* fields, as discussed in Section 2.2. Virtually all we know about the universe beyond Earth's atmosphere has been learned from analysis of electromagnetic radiation received from afar.

Visible light is the particular type of electromagnetic radiation to which the human eye happens to be sensitive. But, just as there are sound waves that humans can't hear, there is also *invisible* electromagnetic radiation, which goes completely undetected by our eyes. **Radio, infrared,** and **ultraviolet** waves, as well as **X-rays** and **gamma rays,** all fall into this category. Recognize that, despite the different names, these terms really all refer to the same thing. The names are just historical accidents, reflecting the fact that it took many years for scientists to realize that these apparently very different types of radiation are in reality one and the same physical phenomenon. Throughout this text, we will use the general terms *light* and *electromagnetic radiation* more or less interchangeably.

Wave Motion

All types of electromagnetic radiation travel through space in the form of **waves.** Simply stated, a wave is a way in which energy is transferred from place to place without physical movement of material from one location to another. In wave motion, the energy is carried by a *disturbance* of some sort that occurs in a distinctive, repeating pattern. Ripples on the surface of a pond, sound waves in air, and electromagnetic waves in space, despite their many obvious differences, all share this basic defining property.

As a familiar example, imagine a twig floating in a pond (Figure 2.2). A pebble thrown into the pond at some distance from the twig disturbs the surface of the water, setting it into up-and-down motion. This disturbance propagates outward from the point of impact in the form of waves. When the waves reach the twig, some of the pebble's energy is transferred to it, causing the twig to bob up and down. In this way, both energy and *information*—the fact that the pebble entered the water—are transferred from where the pebble landed to the location of the twig. We could tell just by



◄ **FIGURE 2.1 Andromeda Galaxy** The pancake-shaped Andromeda galaxy is about 2.5 million light-years away and contains a few hundred billion stars. *(R. Gendler)* observing the twig that a pebble (or some small object) had entered the water. With a little additional physics, we could even estimate the pebble's energy.

A wave is *not* a physical object. No water traveled from the point of impact of the pebble to the twig; at any location on the surface, the water surface simply moved up and down as the wave passed. What, then, *does* move across the pond surface? The answer is that the wave is the *pattern* of up-and-down motion, and it is this pattern that is transmitted from one point to the next as the disturbance moves across the water.

Figure 2.3 shows how wave properties are quantified. The **wave period** is the number of seconds needed for the wave to repeat itself at some point in space. The **wavelength** is the number of meters needed for the wave to repeat itself at a given moment in time. It can be measured as the distance between two adjacent wave *crests,* two adjacent wave *troughs,* or any other two similar points on adjacent wave cycles (for example, the points marked "×" in Figure 2.3). The maximum departure of the wave from the undisturbed state—still air, say, or a flat pond surface—is called its **amplitude.** The number of wave crests passing any given point per unit time is called the wave's **frequency.** If a wave of a given wavelength moves at high speed, then many crests pass by per second and the frequency is high. Conversely, if the same wave moves slowly, then its frequency is low. The frequency of a wave is just one divided by the wave's period:

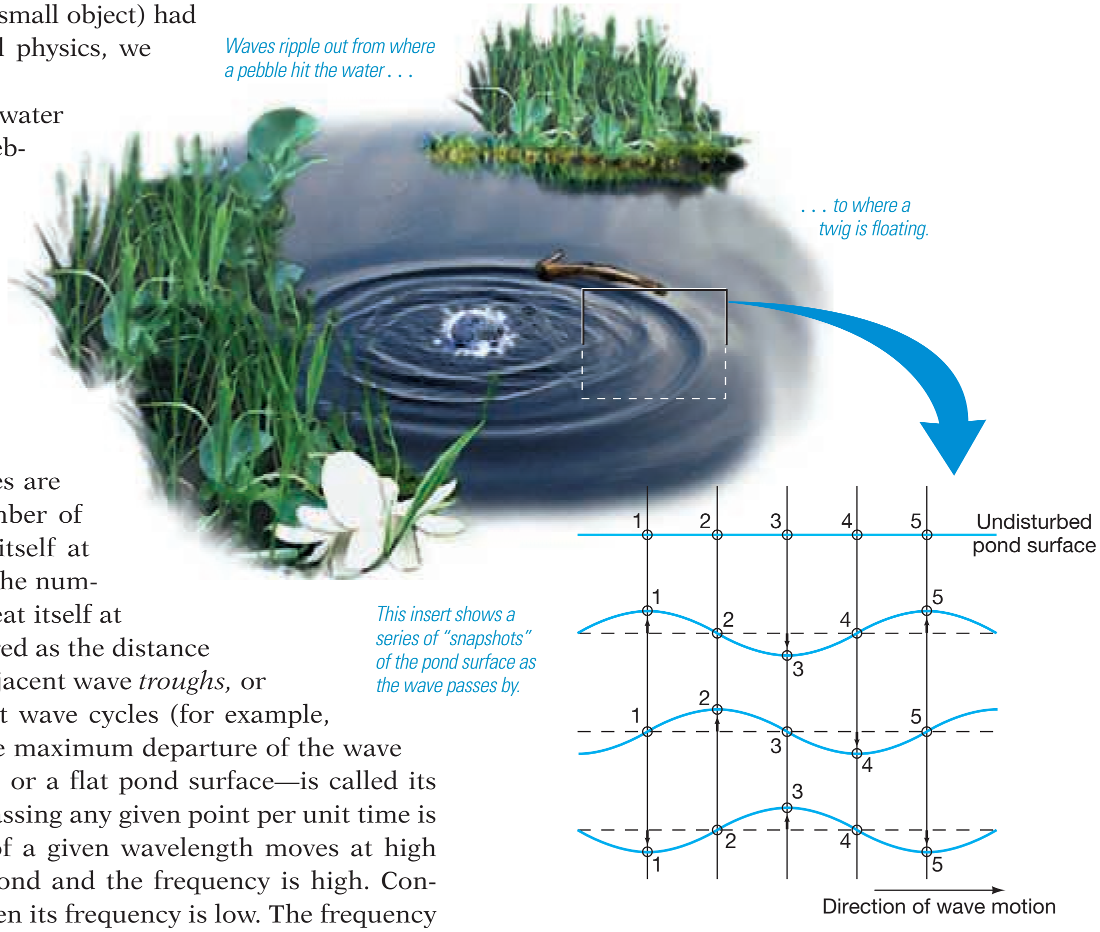
$$\text{frequency} = \frac{1}{\text{period}}.$$

Since frequency counts events per unit time, it is expressed in units of inverse time (cycles per second), called hertz (Hz) in honor of the 19th-century German scientist Heinrich Hertz, who studied the properties of radio waves. For example, a wave with a period of 5 seconds (5 s) has a frequency of (1/5) cycles/s = 0.2 Hz, meaning that one wave crest passes a given point in space every 5 seconds.

A wave moves a distance equal to one wavelength in one wave period. The product of wavelength and frequency therefore equals the *wave velocity:*

$$\text{wavelength} \times \text{frequency} = \text{velocity}.$$

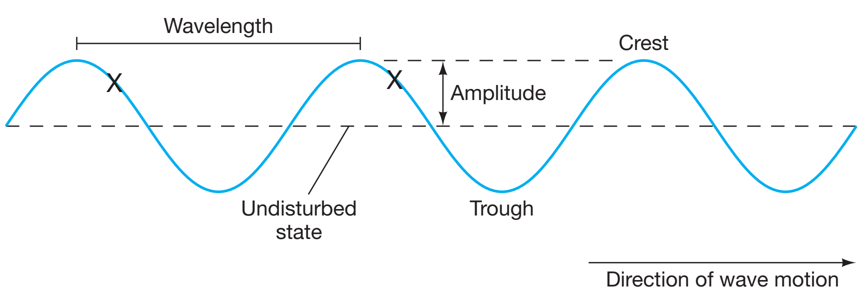
Thus, if the wave in our earlier example had a wavelength of 0.5 m, its velocity is (0.5 m) × (0.2 Hz) = 0.1 m/s. Wavelength and wave frequency are *inversely* related—doubling one halves the other.



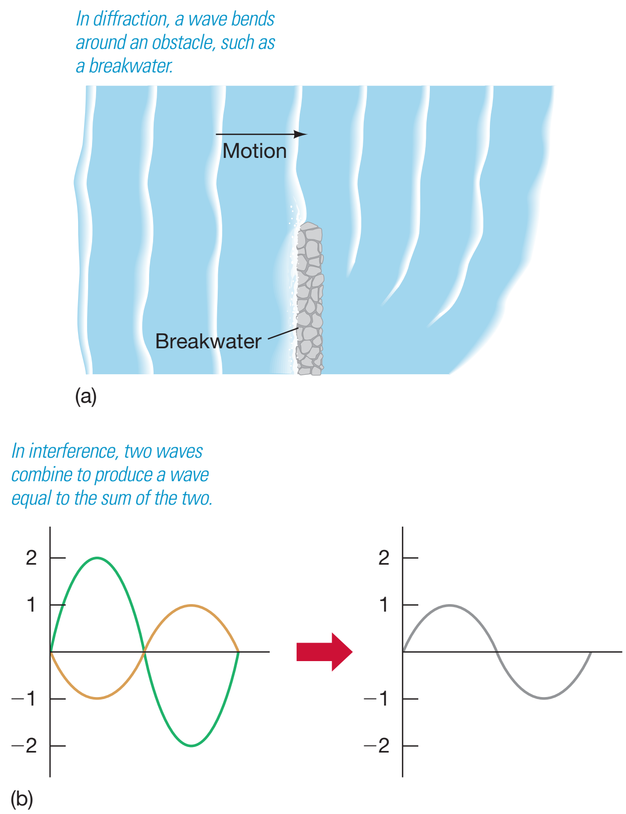
▲ **FIGURE 2.2 Water Wave INTERACTIVE** The passage of a wave across a pond causes the surface of the water to bob up and down, but there is no movement of water from one part of the pond to another.

CONCEPT CHECK

What is a wave? What four basic properties describe a wave, and what relationships, if any, exist among them?



◀ **FIGURE 2.3 Wave Properties INTERACTIVE** A typical wave has a direction of motion, wavelength, and amplitude. In one wave period, the entire pattern shown here moves one wavelength to the right.



▲ **FIGURE 2.4 Wave Behavior** Diffraction (a) and interference (b) are two basic types of behavior shared by all waves, including electromagnetic radiation.

2.2 Waves in What?

Scientists know that radiation travels as a wave because light displays characteristic behavior common to *all* kinds of wave motion. For example, light waves tend to "bend around corners," just like sound waves or ocean waves passing a breakwater (Figure 2.4a). This is called **diffraction.** In addition, the crests and troughs of waves coming from different sources can reinforce or partly cancel one another (Figure 2.4b). This is known as **interference.** We are not normally aware of this behavior in the case of electromagnetic radiation because the effects are generally too small to be noticeable in everyday life. However, they are easily measured in the laboratory and are very important considerations when designing and building telescopes, as we will see in Chapter 3. Their discovery early in the 19th century provided strong evidence in favor of the theory that light moves as a wave.

Waves of radiation differ in one fundamental respect from water waves, sound waves, or any other waves that travel through a material medium—radiation needs *no* medium. When light travels from a distant cosmic object, it moves through the vacuum of space. Sound waves, by contrast, cannot do this, despite what you hear in sci-fi movies! If we were to remove all the air from a room, conversation would be impossible because sound waves cannot exist without air or some other physical medium to support them. Communication by flashlight or radio, however, would be entirely feasible.

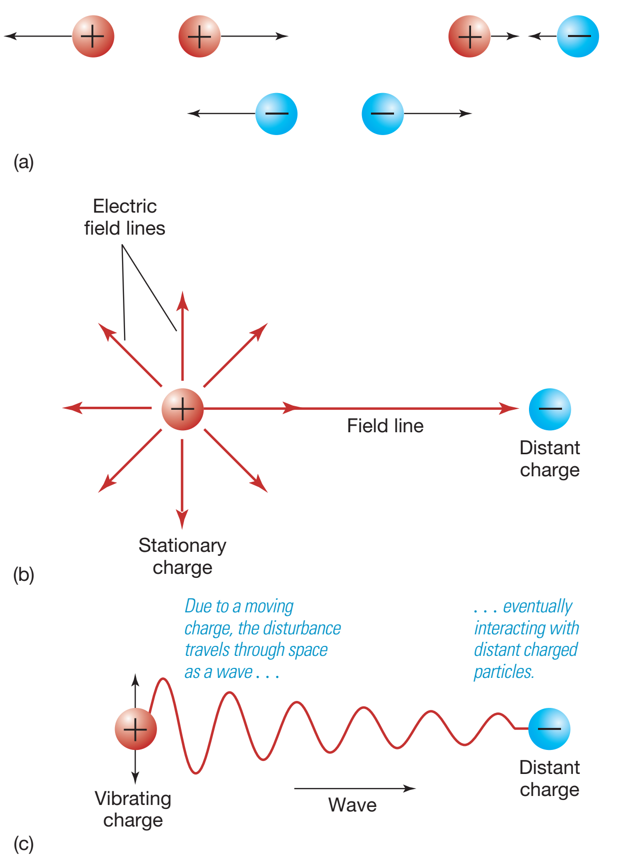
The ability of light to travel through empty space was once a great mystery. The idea that radiation could move as a wave through nothing at all seemed to violate common sense, yet it is now a cornerstone of modern physics.

Interactions Between Charged Particles

To understand more about the nature of light, consider an *electrically charged* particle, such as an **electron** or a **proton.** Electrons and protons are elementary particles—fundamental components of matter—that carry the basic unit of charge. Electrons are said to carry a *negative* charge, while protons carry an equal and opposite *positive* charge. Just as a massive object exerts a gravitational force on any other massive object, an electrically charged particle exerts an *electrical* force on every other charged particle in the universe. ∞ *(Sec. 1.4)* Unlike gravity, however, which is always attractive, electrical forces can be either attractive or repulsive. Particles having like charges (both negative or both positive) repel one another; particles having unlike charges attract (Figure 2.5a).

Extending outward in all directions from our charged particle is an **electric field,** which determines the electric force exerted by the particle on other charged particles (Figure 2.5b). The strength of the electric field, like that of the gravitational field, decreases with increasing distance from the source according to an inverse-square law—doubling the distance reduces the strength of the field by a factor of 4. ∞ *(Sec. 1.4)* By means of the electric field, the particle's presence is "felt" by other charged particles, near and far.

Now suppose our particle begins to vibrate, perhaps because it becomes heated or collides with some other particle. Its changing position causes its associated electric field to change, and this changing field in turn causes the electrical force exerted on other charges to vary (Figure 2.5c). If we measure the changes in the forces on these other charges, we learn about our original particle. Thus,



◀ **FIGURE 2.5 Charged Particles** (a) Particles carrying like electrical charges repel one another; particles with unlike charges attract. (b) A charged particle is surrounded by an electric field, which determines the particle's influence on other charged particles. (c) If a charged particle begins to vibrate, its electric field changes.

information about our particle's motion is transmitted through space via a changing electric field. This *disturbance* in the particle's electric field travels through space as a wave.

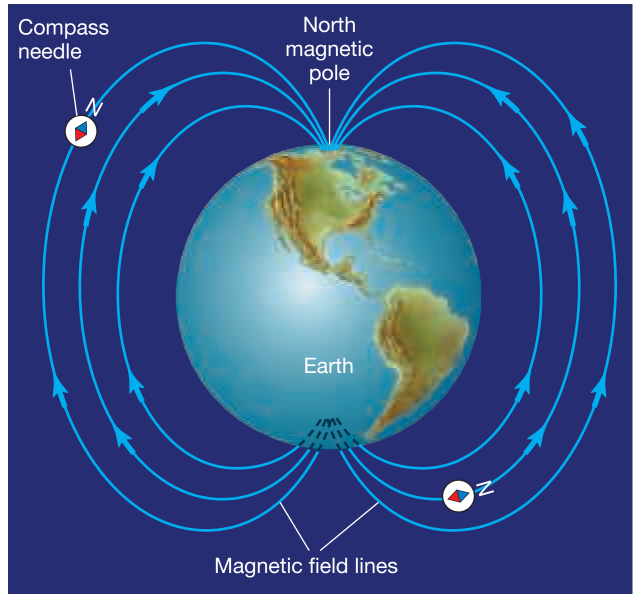
Electromagnetism

The laws of physics tell us that a **magnetic field** must accompany every changing electric field. Magnetic fields govern the influence of *magnetized* objects on one another, much as electric fields govern interactions between charged particles. The fact that one end of a compass needle always points to magnetic north is the result of the interaction between the magnetized needle and Earth's magnetic field (Figure 2.6). Magnetic fields also exert forces on moving electric charges (that is, electric currents)—electric meters and motors rely on this basic fact. Conversely, moving charges create magnetic fields (the electromagnets found in loudspeakers and electric motors are familiar examples).

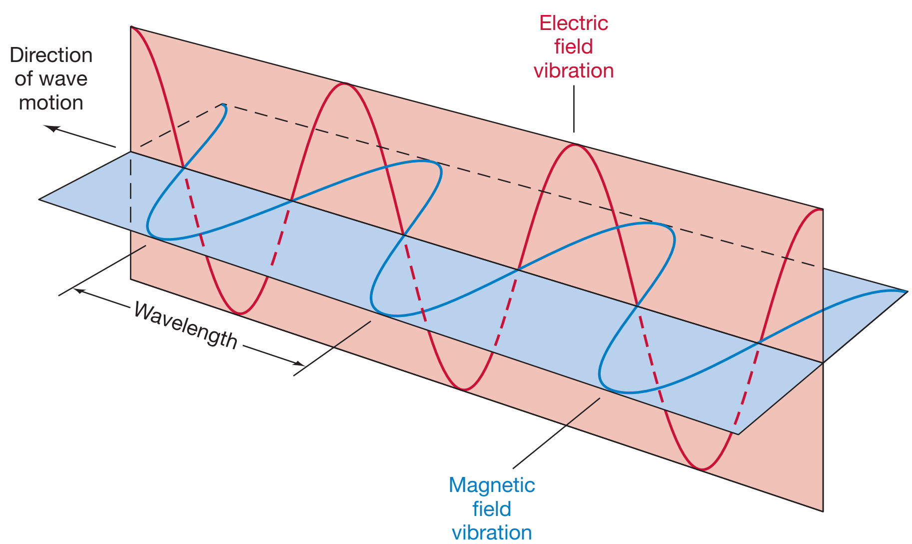
Electric and magnetic fields are inextricably linked to one another. A change in either one *necessarily* creates the other. For this reason, the disturbance produced by our moving charge actually consists of oscillating electric *and* magnetic fields, always oriented perpendicular to one another and moving together through space (Figure 2.7). These fields do not exist as independent entities. Rather, they are different aspects of a single physical phenomenon: **electromagnetism.** Together they constitute an *electromagnetic wave* that carries energy and information from one part of the universe to another.

Now consider a distant cosmic object—a star. It is made up of charged particles, mainly protons and electrons, in constant motion. As these charged contents move around, their electric fields change, and electromagnetic waves are produced. These waves travel outward into space, and eventually some reach Earth. Other charged particles, either in the molecules in our eyes or in our experimental apparatus (a telescope or radio receiver, for example), respond to the electromagnetic field changes by vibrating in tune with the received radiation. This response is how we "see" the radiation—with our eyes or with our detectors.

How fast does an electromagnetic wave travel? Both theory and experiment tell us that all electromagnetic waves move at a very specific speed—the **speed of light** (always denoted by the letter c). Its value is 299,792.458 km/s in a vacuum (and somewhat less in material substances, such as air or water). In this text, we round this value off to $c = 3.00 \times 10^5$ km/s. This is an extremely high speed. In the time needed to snap your fingers—about a tenth of a second—light can travel three quarters of the way around our planet! According to the theory of relativity (see *More Precisely 13-1*), the speed of light is the fastest speed possible.



▲ **FIGURE 2.6 Magnetism** Earth's magnetic field interacts with a magnetic compass needle, causing the needle to become aligned with the field—that is, to point toward Earth's north (magnetic) pole.



◀ **FIGURE 2.7 Electromagnetic Wave** Electric and magnetic fields vibrate perpendicular to each other. Together they form an electromagnetic wave that moves through space at the speed of light.

2.3 The Electromagnetic Spectrum

White light is a mixture of colors, which we conventionally divide into six major hues—red, orange, yellow, green, blue, and violet. As shown in Figure 2.8, we can separate a beam of white light into a rainbow of these basic colors—called a *spectrum* (plural: spectra)—by passing it through a prism. This experiment was first reported by Isaac Newton more than 300 years ago. In principle, the original beam of white light could be recovered by passing the spectrum through a second prism to recombine the colored beams.

Components of Visible Light

What determines the color of a beam of light? The answer is its frequency (or, equivalently, its wavelength). We see different colors because our eyes react differently to electromagnetic waves of different frequencies. Red light has a frequency of roughly 4.3×10^{14} Hz, corresponding to a wavelength of about 7.0×10^{-7} m. Violet light, at the other end of the visible range, has nearly double the frequency—7.5×10^{14} Hz—and just over half the wavelength—4.0×10^{-7} m. The other colors we see have frequencies and wavelengths intermediate between these two extremes.

Because the wavelength of visible light is so small, scientists often use a unit called the *nanometer* (nm) when describing it (see Appendix 2). A nanometer is one-billionth of a meter, or 10^{-9} m. An older unit called the *angstrom* (1Å = 10^{-10} m = 0.1 nm) is also widely used by many astronomers and atomic physicists. Thus, the visible spectrum covers the wavelength range from 400 to 700 nm. The radiation to which our eyes are most sensitive has a wavelength near the middle of this range, at about 550 nm, in the yellow-green region of the spectrum.

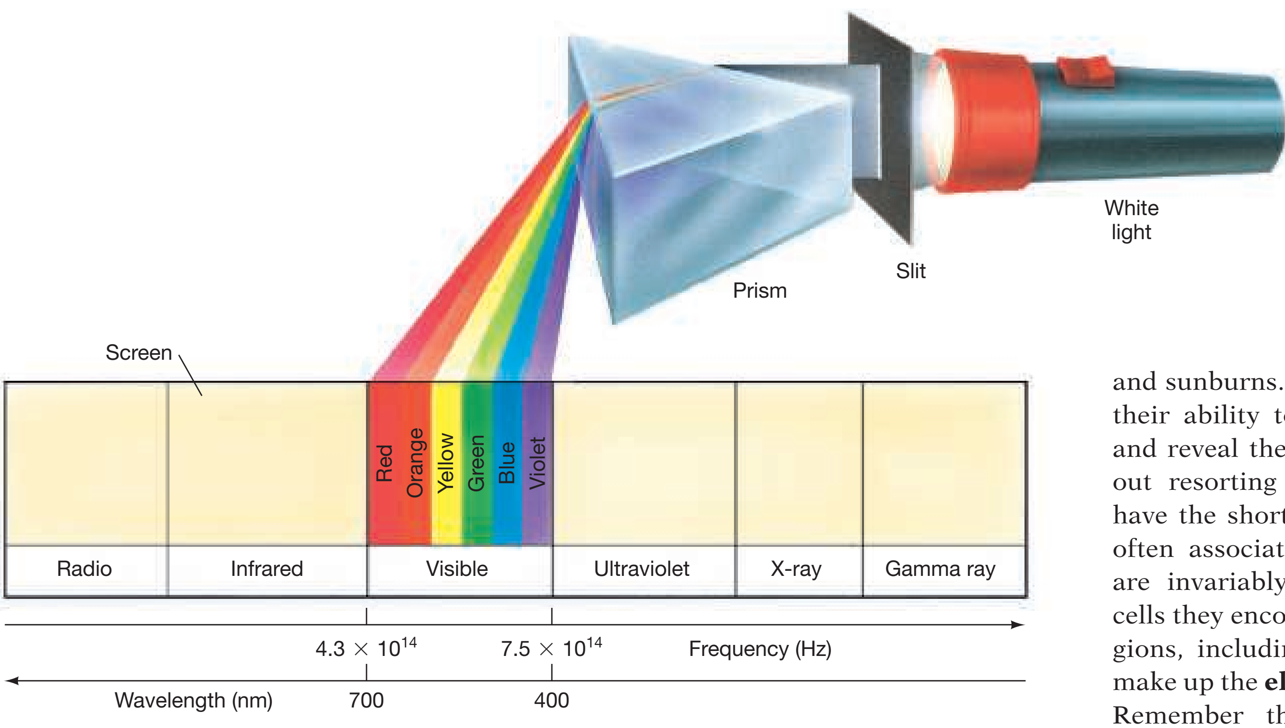
CONCEPT CHECK

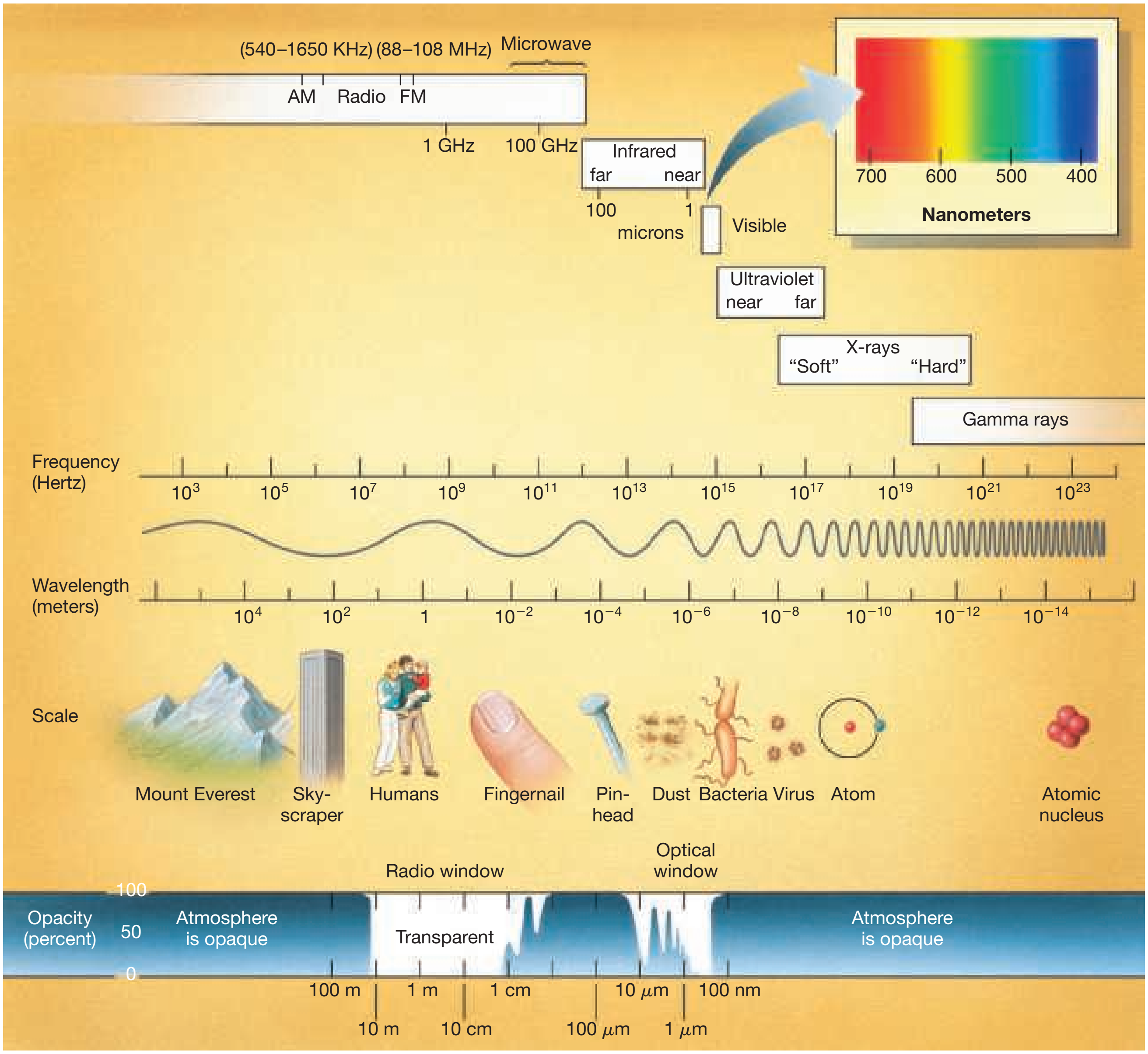
What is light? List some similarities and differences between light waves and waves on water or in air.

The Full Range of Radiation

Figure 2.9 plots the entire range of electromagnetic radiation. To the low-frequency, long-wavelength side of visible light lies radio and infrared radiation. Radio frequencies include radar, microwave radiation, and the familiar AM, FM, and TV bands. We perceive infrared radiation as heat. To the high-frequency, short-wavelength side of visible light lies ultraviolet, X-ray, and gamma-ray radiation. Ultraviolet radiation, lying just beyond the violet end of the visible spectrum, is responsible for suntans and sunburns. X-rays are best known for their ability to penetrate human tissue and reveal the state of our insides without resorting to surgery. Gamma rays have the shortest wavelengths. They are often associated with radioactivity and are invariably damaging to any living cells they encounter. All these spectral regions, including the visible, collectively make up the **electromagnetic spectrum.** Remember that despite their greatly

▼ **FIGURE 2.8 Visible Spectrum** When passed through a prism, white light splits into its component colors, spanning red to violet in the visible part of the electromagnetic spectrum. The slit narrows the beam of radiation. The "rainbow" of colors projected on the screen is just a series of different-colored images of the slit.





▲ **FIGURE 2.9 Electromagnetic Spectrum** INTERACTIVE
The entire electromagnetic spectrum, running from long-wavelength, low-frequency radio waves to short-wavelength, high-frequency gamma rays. Note how small the visible portion of the spectrum is.

differing wavelengths and the very different roles they play in everyday life on Earth, all types of electromagnetic radiation are basically the same and all move at the same speed—the speed of light c.

Note that wave frequency (in hertz) in Figure 2.9 increases from left to right, while wavelength (in meters) increases from right to left. Scientists often disagree on the "correct" way to display wavelengths and frequencies in diagrams of this type, and it is common for astronomers working in different parts of the spectrum to adopt opposite conventions. Throughout this book we will consistently display frequency increasing toward the *right*.

The wavelength and frequency scales in Figure 2.9 do not increase by equal increments of 10. Instead, successive values on the horizontal axis increase by *factors* of 10—each successive value is 10 times greater than its neighbor. This type of scale (called a *logarithmic* scale) is often used in science to condense a very large range of data into a manageable size. We will use such scales frequently throughout this book.

Many objects emit only a tiny fraction of their total energy in the visible range. A wealth of knowledge can be gained by studying the invisible regions of the electromagnetic spectrum. To remind you of this important fact and to identify the region of the electromagnetic spectrum in which a particular observation was made, we have attached a spectrum icon—an idealized version of the wavelength scale in Figure 2.9—to every astronomical image presented in this text.

Only a small fraction of the radiation arriving at our planet from space actually reaches Earth's surface because of the *opacity* of Earth's atmosphere. **Opacity** is the extent to which radiation is blocked by the material through which it is passing. The more opaque an object is, the less radiation gets through. For example, a pane of glass has low opacity (i.e., is *transparent*) to visible light, while a sheet of paper or the air on a foggy day has high opacity. Earth's atmospheric opacity is plotted along the bottom of Figure 2.9. Where the shading is greatest, no radiation can get in or out. Where there is no shading at all, our atmosphere is almost totally transparent.

Note that there are just a few *windows* (the unshaded regions) at well-defined locations in the electromagnetic spectrum, where Earth's atmosphere is transparent. In much of the radio and all of the visible portion of the spectrum, the opacity is low, and we can study the universe at those wavelengths from ground level. In parts of the infrared range, the atmosphere is partially

2.1 MORE PRECISELY

The Kelvin Temperature Scale

The atoms and molecules that make up any piece of matter are in constant random motion. This motion represents a form of energy known as *thermal energy*. The quantity we call temperature is a direct measure of this internal motion: the higher an object's temperature, the faster the random motion of its constituent particles. More precisely, the temperature of a piece of matter specifies the average thermal energy of the particles it contains.

The temperature scale probably most familiar to you, the Fahrenheit scale, is now a peculiarity of American society. Most of the rest of the world uses the Celsius temperature scale, in which water freezes at 0 degrees (0°C) and boils at 100 degrees (100°C), as illustrated in the accompanying figure.

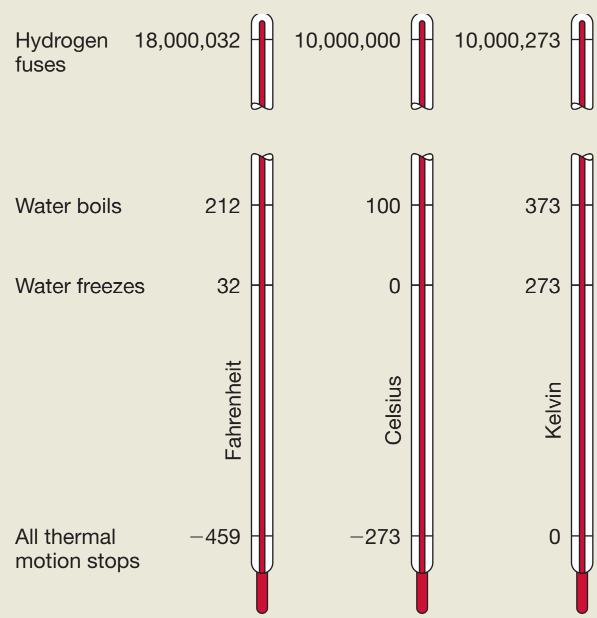
There are, of course, temperatures below the freezing point of water. Temperatures can in principle reach as low as –273.15°C (although we know of no matter anywhere in the universe that is actually this cold); this is the temperature at which, theoretically, all atomic and molecular motion effectively ceases. It is convenient to construct a temperature scale based on this lowest possible temperature, which is called *absolute zero*. Scientists commonly use such a scale, called the Kelvin scale in honor of the 19th-century British physicist Lord Kelvin. Since it takes absolute zero as its starting point, the Kelvin scale differs from the Celsius scale by 273.15°. In this book, we round off the decimal places and simply use the relationship

$$\text{kelvins} = \text{degrees Celsius} + 273.$$

Thus,

- Thermal motion of atoms and molecules ceases at 0 kelvins (0 K).
- Water freezes at 273 kelvins (273 K).
- Water boils at 373 kelvins (373 K).

Note, by the way, that the unit is "kelvins," or "K," not "degrees kelvin" or "°K."



transparent, so we can make some infrared observations from the ground. Over the rest of the spectrum, however, the atmosphere is opaque. As a result, most infrared, and all ultraviolet, X-ray, and gamma-ray observations, can be made only from high-flying balloons or (more commonly) above the atmosphere, from orbiting satellites (see Section 3.5).

CONCEPT CHECK

In what sense are radio waves, visible light, and X-rays one and the same phenomenon?

2.4 Thermal Radiation

All macroscopic objects—fires, ice cubes, people, stars—emit radiation at all times. They radiate because the microscopic charged particles in them are in constant random motion, and whenever charges change their state of motion, electromagnetic radiation is emitted. The **temperature** of an object is a direct measure of the amount of microscopic motion within it (see *More Precisely 2-1*). The hotter the object, the higher its temperature, the faster its constituent particles move and the more energy they radiate.

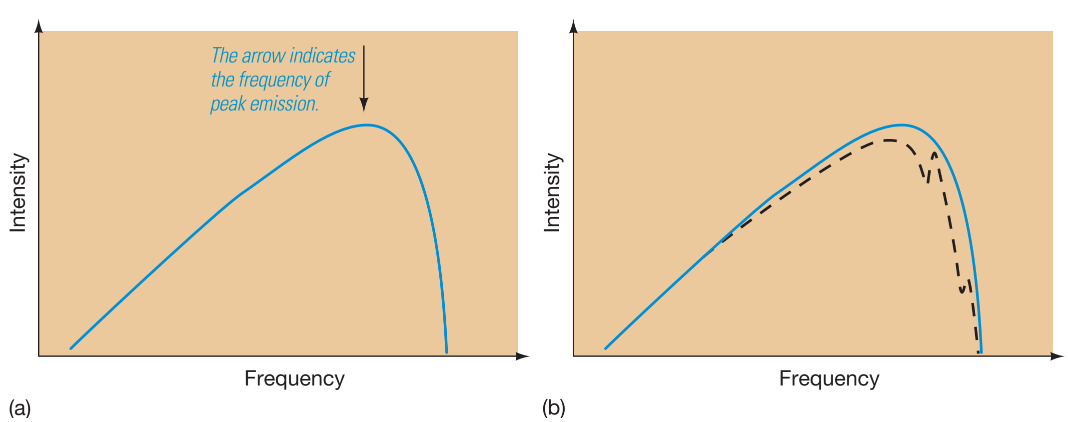
The Blackbody Spectrum

Intensity is a term often used to specify the amount or strength of radiation at any point in space. Like frequency and wavelength, intensity is a basic property of electromagnetic radiation. No natural object emits all of its radiation at just one frequency. Instead, the energy is often spread out over a range of frequencies. By studying the way in which the intensity of this radiation is distributed across the electromagnetic spectrum, we can learn much about the object's properties.

Figure 2.10 (a) illustrates schematically the distribution of radiation emitted by any object. Note that the curve peaks at a single, well-defined frequency (marked) and falls off to lesser values above and below that frequency. However, the curve is not symmetrical about the peak—the falloff is more rapid on the high-frequency side of the peak than it is toward lower frequencies. This overall shape is characteristic of the electromagnetic radiation emitted by *any* object, regardless of its size, shape, composition, or temperature.

The curve drawn in Figure 2.10(a) refers to a mathematical idealization known as a *blackbody*—an object that absorbs all radiation falling upon it. In a steady state (that is, if the temperature remains constant), a blackbody must reemit the same amount of energy as it absorbs. The **blackbody curve** shown in the figure describes the distribution of that reemitted radiation. No real object absorbs or radiates as a perfect blackbody. For example, the Sun's actual emission is shown in Figure 2.10(b). However, in many cases the blackbody curve is a very good approximation to reality, and the properties of blackbodies provide important insights into the behavior of real objects, including stars.

MA SELF-GUIDED TUTORIAL
Continuous Spectra and Blackbody Radiation



◀ **FIGURE 2.10 Blackbody Curves, Ideal vs. Reality** The blackbody curve represents the spread of the intensity of radiation emitted across the electromagnetic spectrum. Note the contrast between the perfect "textbook" case (a) and a real graph (dashed) of the Sun's emission (b). The difference is due to absorption in the atmospheres of the Sun and Earth.

The Radiation Laws

As illustrated in Figure 2.11, the entire blackbody curve shifts toward higher frequencies (shorter wavelengths) and greater intensities as an object's temperature increases. Even so, the *shape* of the curve remains the same. This shifting of radiation's peak frequency with temperature is familiar to us all. Very hot glowing objects, such as lightbulb filaments or stars, emit visible light because their blackbody curves peak in or near the visible range. Cooler objects, such as warm rocks or household radiators, produce invisible radiation—they are warm to the touch but are not glowing hot to the eye. These objects emit most of their radiation in the lower-frequency infrared portion of the electromagnetic spectrum.

There is a very simple connection between the frequency or wavelength at which most radiation is emitted and the absolute temperature (that is, temperature measured in kelvins—see *More Precisely 2-1*) of the emitting object: The peak frequency is *directly proportional* to the temperature. This relationship, known as **Wien's law** after Wilhelm Wien, the German scientist who formulated it in 1897, is usually expressed as:

$$\text{wavelength of peak emission} \propto \frac{1}{\text{temperature}}.$$

The symbol "$\propto$" just means "is proportional to." Wien's law tells us that the hotter the object, the bluer its radiation. For example, an object with a temperature of 6000 K (Figure 2.11c) emits most of its energy in the visible part of the spectrum, with a peak wavelength of 480 nm. At 600 K (Figure 2.11b), the object's emission would peak at 4800 nm, well into the infrared. At a temperature of 60,000 K (Figure 2.11d), the peak would move all the way through the visible range to a wavelength of 48 nm, in the ultraviolet.

It is also a matter of everyday experience that as the temperature of an object increases, the *total* amount of energy it radiates (summed over all frequencies) increases rapidly. For example, the heat given off by an electric heater increases sharply as the heater warms up and begins to emit visible light. In fact, the total amount of energy radiated per unit time is proportional to the *fourth power* of an object's temperature:

$$\text{total energy radiated per second} \propto \text{temperature}^4.$$

This relationship is called **Stefan's law,** after the 19th-century Austrian physicist Josef Stefan. It implies that the energy emitted by a body rises dramatically as the body's temperature increases. Doubling the temperature, for example, causes the total energy radiated to increase by a factor of 16. The radiation laws are presented in more detail in *More Precisely 2-2*.

MA ANIMATION/VIDEO
Solar Eclipse Viewed from Space, in X-rays

MA ANIMATION/VIDEO
Shoemaker-Levy 9 Impact at 2.15 Microns

MA ANIMATION/VIDEO
Multispectral View of Orion Nebula

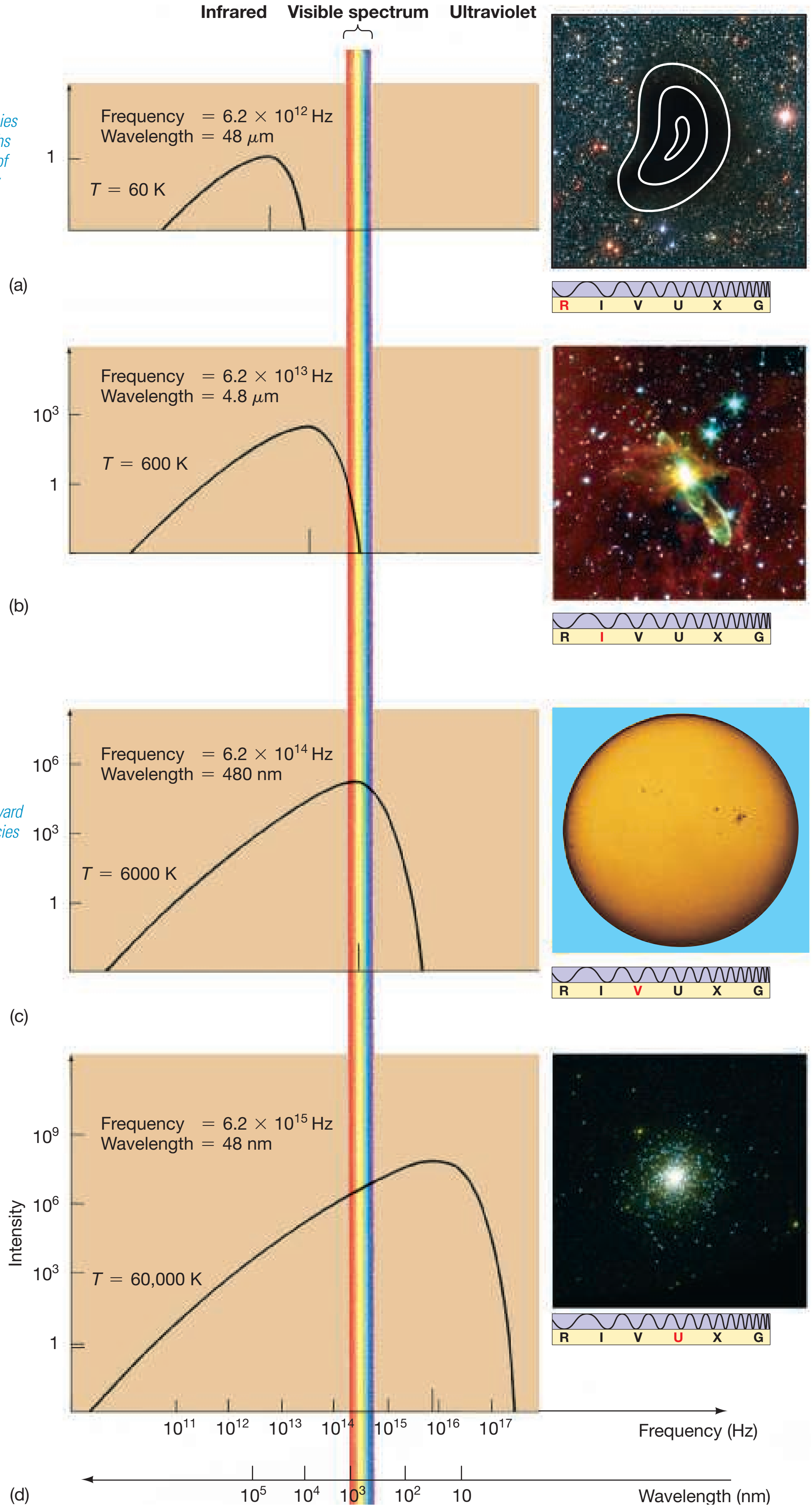
MA ANIMATION/VIDEO
Earth Aurora in X-rays

Astronomical Applications

Astronomers use blackbody curves as thermometers to determine the temperatures of distant objects. For example, study of the solar spectrum makes it possible to measure the temperature of the Sun's surface. Observations of the electromagnetic radiation from the Sun at many frequencies yield a curve shaped somewhat like that shown in Figure 2.10. The Sun's curve peaks in the visible part of the electromagnetic spectrum. The Sun also emits a lot of infrared and a little ultraviolet radiation. Applying Wien's law to the blackbody curve that best fits the solar spectrum, we find that the temperature of the Sun's surface is approximately 6000 K (Figure 2.11c). A more precise measurement, based on the detailed solar spectrum (Section 2.6), yields a temperature of 5800 K.

Other cosmic objects have surfaces very much cooler or hotter than the Sun's, emitting most of their radiation in invisible parts of the spectrum. For example, *These frequencies and wavelengths mark the peak of each blackbody curve.*

Notice how the curves shift toward higher frequencies with increasing temperature.



◂ **FIGURE 2.11 Blackbody Curves**
INTERACTIVE Comparison of blackbody curves for four cosmic objects. (a) A cool, dark galactic cloud called Barnard 68. At a temperature of 60 K, it emits mostly radio radiation, shown here as overlaid contours. (b) A dim, young star (shown white in the inset photograph) called Herbig-Haro 46. The star's atmosphere, at 600 K, radiates mainly in the infrared. (c) The Sun's surface, at approximately 6000 K, is brightest in the visible region of the electromagnetic spectrum. (d) Some very hot, bright stars in a cluster called Messier 2, as observed by an orbiting space telescope above Earth's atmosphere. At a temperature of 60,000 K, these stars radiate strongly in the ultraviolet. *(ESO; AURA; NASA; Kennedy Space Center)*

2.2 MORE PRECISELY

More on the Radiation Laws

Wien's law relates the temperature T of an object to the wavelength λ_{max} at which the object's blackbody radiation spectrum peaks. (The Greek letter λ—lambda—is conventionally used to denote wavelength.) Mathematically, if we measure T in kelvins, we find that

$$\lambda_{max} = \frac{0.29 \text{ cm}}{T}.$$

Thus, at 6000 K (the approximate surface temperature of the Sun), the wavelength of maximum intensity is 0.29/6000 cm, or 480 nm, corresponding to the yellow-green part of the visible spectrum. A cooler star with a temperature of 3000 K has a peak wavelength of 970 nm, just longward of the red end of the visible spectrum, in the near infrared. The blackbody curve of a star with a temperature of 12,000 K peaks at 242 nm, in the near ultraviolet, and so on.

We can also give Stefan's law a more precise mathematical formulation. With T again measured in kelvins, the total amount of energy emitted per square meter of surface per second (a quantity known as the *energy flux F*) is given by

$$\underbrace{F}_{\text{energy per unit area}} = \underbrace{\sigma}_{\text{constant}} \underbrace{T^4}_{\text{temperature to the fourth power}}.$$

This equation is usually referred to as the *Stefan-Boltzmann* equation. (Stefan's student, Ludwig Boltzmann, was an Austrian physicist who played a central role in the development of the laws of thermodynamics during the late 19th and early 20th centuries.) The constant σ (the Greek letter sigma) is known as the Stefan-Boltzmann constant. In SI units, the Stefan-Boltzmann constant has the value $\sigma = 5.67 \times 10^{-8}$ W/m^2 K^4.

Thus, red-hot metal in a furnace, at a temperature of 3500 K, radiates energy at a rate of about 850 W for every square centimeter of its surface area. Doubling its temperature to 7000 K (so that it becomes yellow to white hot, by Wien's law) increases the energy emitted by a factor of 16 (four "doublings"), to 13.6 *kilo*watts (kW) (13,600 W) per square centimeter.

Finally, note that the law relates to energy emitted *per unit area*. The flame of a blowtorch is considerably hotter than a bonfire, but the bonfire emits far more energy in total, because it is much larger.

Thus, in computing the total energy emitted from a hot object, both the object's temperature and its surface area must be taken into account. This fact is of great importance in determining the "energy budget" of planets and stars, as we will see in later chapters.

the relatively cool surface of a very young star might measure 600 K and emit mostly infrared radiation (Figure 2.11b). Cooler still is the interstellar gas cloud from which the star formed. At a temperature of 60 K, such a cloud would emit mainly long-wavelength radiation in the radio and infrared parts of the spectrum (Figure 2.11a). The brightest stars, by contrast, have surface temperatures as high as 60,000 K and, hence, emit mostly ultraviolet radiation (Figure 2.11d).

CONCEPT CHECK

Describe, in terms of the radiation laws, how the appearance of an incandescent lightbulb changes as you turn a dimmer switch to increase its brightness from "off" to "maximum."

2.5 Spectroscopy

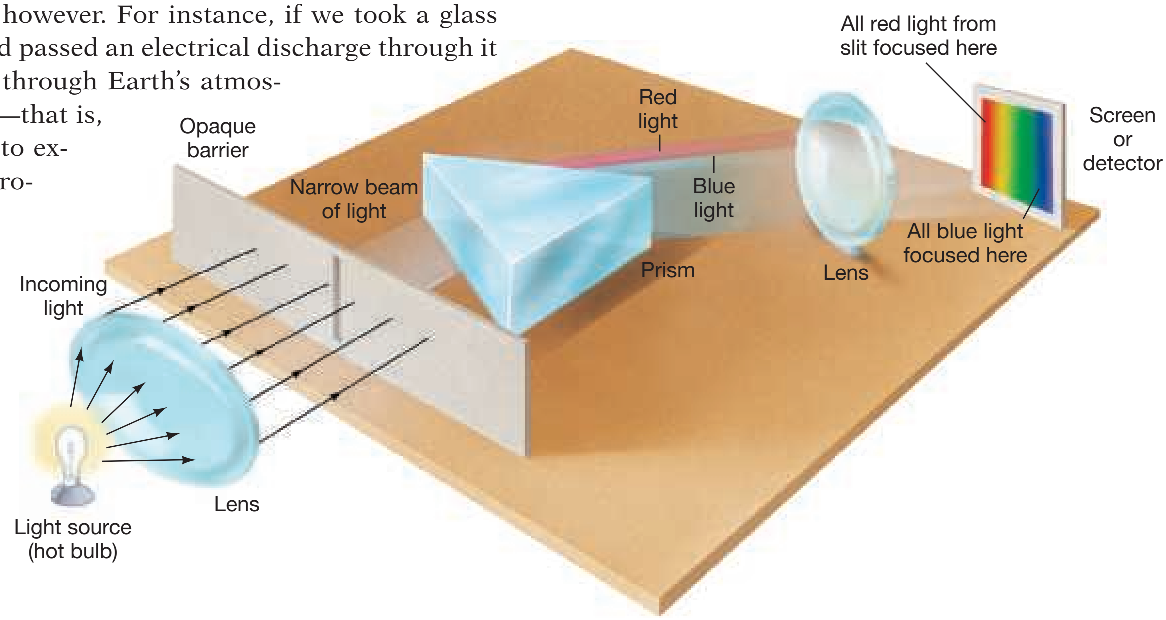
Radiation can be analyzed with an instrument known as a **spectroscope.** In its most basic form, this device consists of an opaque barrier with a slit in it (to form a narrow beam of light), a prism (to split the beam into its component colors), and either a detector or a screen (to allow the user to view the resulting spectrum). Figure 2.12 shows such an arrangement.

Emission Lines

The spectra encountered in the previous section are examples of **continuous spectra.** A lightbulb, for instance, emits radiation of all wavelengths (but mostly in the visible and near-infrared ranges), with an intensity distribution that is well described by the blackbody curve corresponding to the bulb's temperature. Viewed through a spectroscope, the spectrum of the light from the bulb would show the familiar rainbow running from red to violet without interruption, as presented in Figure 2.12.

Not all spectra are continuous, however. For instance, if we took a glass jar containing pure hydrogen gas and passed an electrical discharge through it (a little like a lightning bolt arcing through Earth's atmosphere), the gas would begin to glow—that is, it would emit radiation. If we were to examine that radiation with our spectroscope, we would find that its spectrum consisted of only a few bright lines on an otherwise dark background, quite unlike the continuous spectrum of the lightbulb. Figure 2.13 shows this schematically (the lenses have been removed for clarity), and a more detailed rendering of the spectrum of hydrogen appears in the top panel of Figure 2.14. The light produced by the hydrogen in this experiment does *not* consist of all possible colors but instead includes only a few narrow, well-defined **emission lines**, narrow "slices" of the continuous spectrum. The black background represents all the wavelengths *not* emitted by hydrogen.

After some experimentation, we would also find that although we could alter the intensity of the lines (for example, by changing the amount of hydrogen in the jar or the strength of the electrical discharge), we could not alter their color (in other words, their frequency or wavelength). The particular pattern of spectral emission lines shown in Figure 2.13 is a property of the element hydrogen—whenever we perform this experiment, the same characteristic **emission spectrum** is the result. Other elements yield different emission spectra. Depending on which element is involved, the pattern of lines can be fairly simple or very complex. Always, though, it is *unique* to that element. The emission spectrum of a gas thus provides a "fingerprint" that allows scientists to deduce its presence by spectroscopic means. An analogy is a bar code that specifies uniquely the cost of a supermarket item. Examples of the emission spectra of some common substances are shown in Figure 2.14.



▲ **FIGURE 2.12 Spectroscope** A simple spectroscope allows a narrow beam of light to pass through a thin slit and then into a prism where it is split into its component colors. A lens then focuses the light into a sharp image that is either projected onto a screen, as shown here, or analyzed as it strikes the detector.

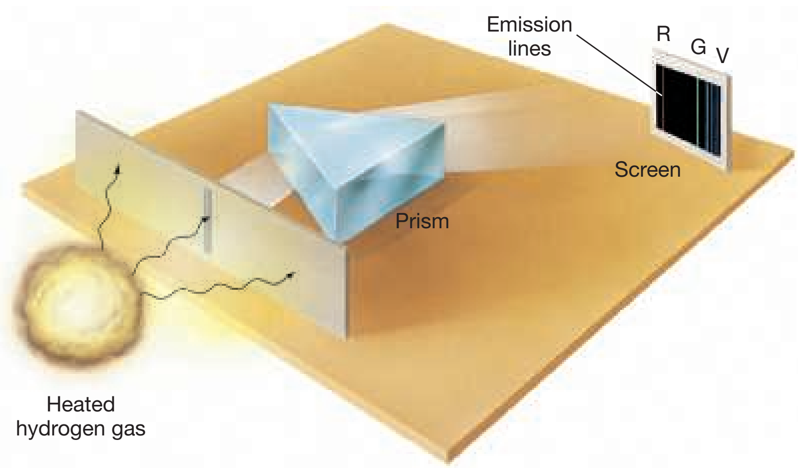
MA SELF-GUIDED TUTORIAL
Emission Spectra

CONCEPT CHECK

What are absorption and emission lines? What do they tell us about the properties of the gas producing them?

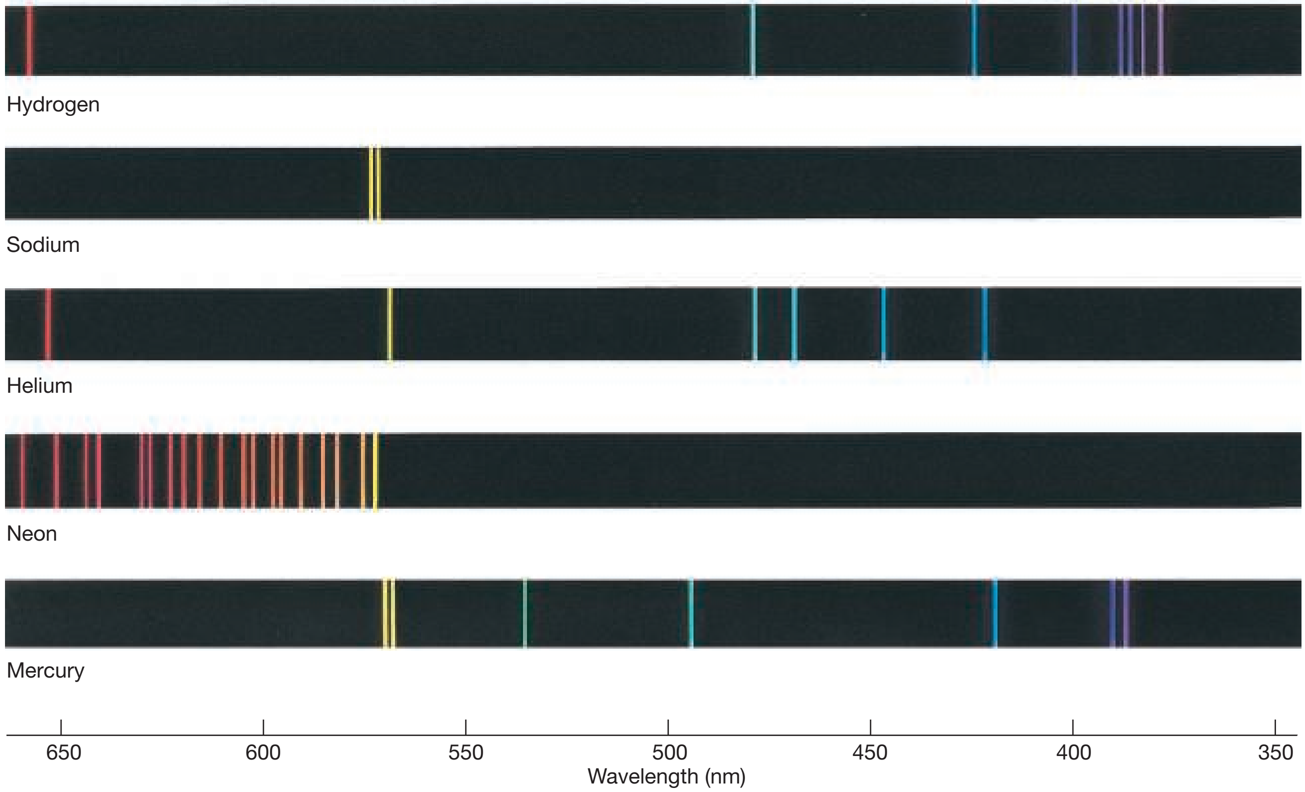
Absorption Lines

When sunlight is split by a prism, at first glance it appears to produce a continuous spectrum. However, closer scrutiny shows that the solar spectrum is interrupted by a large number of narrow dark lines, as shown in Figure 2.15. These lines represent wavelengths of light that have been removed (absorbed) by gases present either in the outer layers of the Sun or in Earth's atmosphere. These gaps in the spectrum are called **absorption lines**. The absorption lines in the solar spectrum are referred to collectively as *Fraunhofer lines*, after the 19th-century German physicist Joseph Fraunhofer, who measured and cataloged more than 600 of them.



▶ **FIGURE 2.13 Emission Spectrum INTERACTIVE** Instead of a continuous spectrum, the light from excited (heated) hydrogen gas consists of a series of distinct spectral lines. (For simplicity, the focusing lens has been omitted.)

Spectra are like supermarket bar codes that uniquely specify the type and cost of a product.

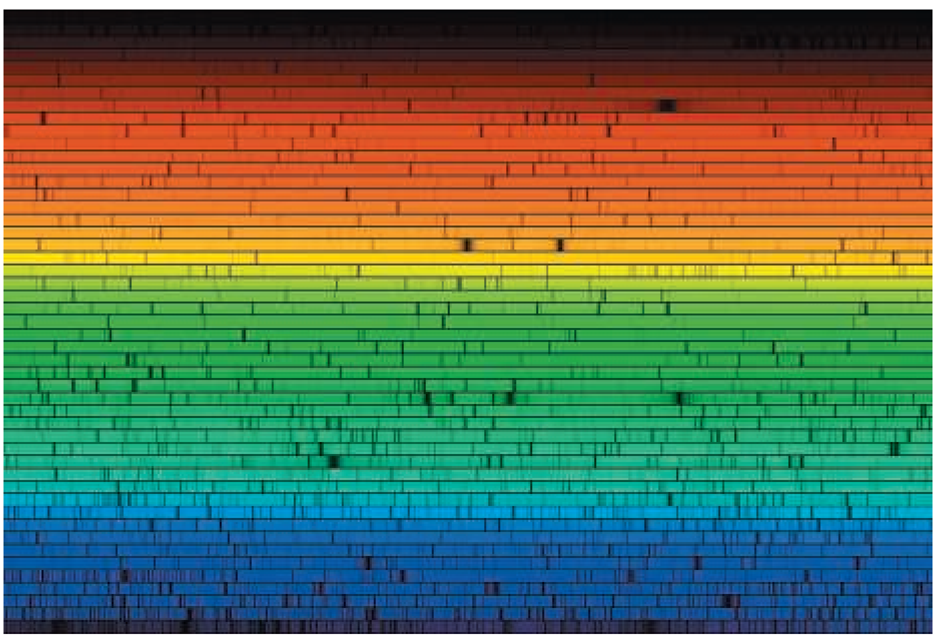


▲ **FIGURE 2.14 Elemental Emission** The emission spectra of some well-known elements. Note that wavelengths shorter than 400 nm, shown here in shades of purple, are in the ultraviolet part of the spectrum and thus invisible to the human eye. *(Wabash Instrument Corporation)*

At around the time solar absorption lines were discovered, scientists found that absorption lines could also be produced in the laboratory by passing a beam of light from a continuous source through a cool gas, as shown in Figure 2.16. They quickly observed a connection between emission and absorption lines: The absorption lines associated with a given gas occur at precisely the *same* wavelengths as the emission lines produced when the gas is heated. Both sets of lines therefore contain the *same* information about the composition of the gas.

The study of the ways in which matter emits and absorbs radiation is called **spectroscopy.** The observed relationships between the three types of spectra—continuous, emission line, and absorption line—are illustrated in Figure 2.17 and may be summarized as follows:

The scale of this spectrum extends from long wavelengths in red . . .

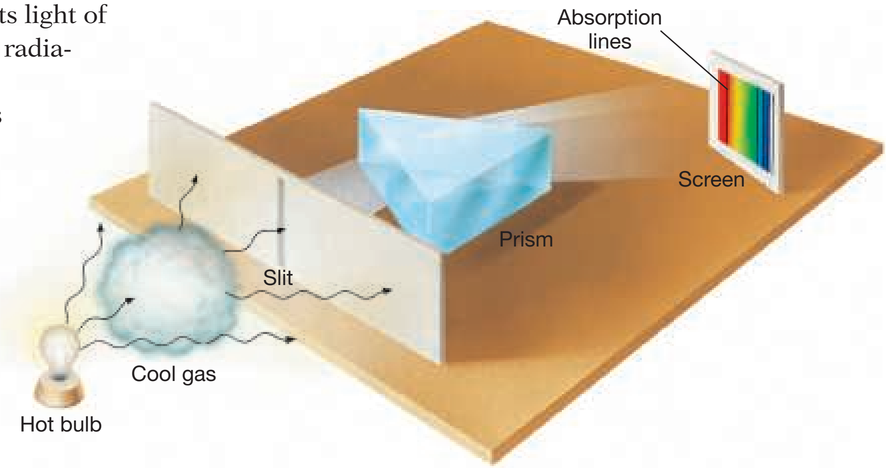


. . . to short wavelengths in blue.

◀ **FIGURE 2.15 Solar Spectrum** The Sun's visible spectrum shows hundreds of dark absorption lines superimposed on a bright continuous spectrum. This high-resolution spectrum is displayed in a series of 48 horizontal strips stacked vertically; each strip covers a small portion of the entire spectrum from left to right. If the strips were placed side by side, the full spectrum would be some 6 meters (20 feet) across! (AURA)

1. A luminous solid or liquid, or a sufficiently dense gas, emits light of all wavelengths and so produces a continuous spectrum of radiation (Figure 2.12).
2. A low-density hot gas emits light whose spectrum consists of a series of bright emission lines. These lines are characteristic of the chemical composition of the gas (Figure 2.13).
3. A low-density cool gas absorbs certain wavelengths from a continuous spectrum, leaving dark absorption lines in their place, superimposed on the continuous spectrum. These lines are characteristic of the composition of the intervening gas. They occur at precisely the same wavelengths as the emission lines produced by the gas at higher temperatures (Figure 2.16).

These rules are collectively known as **Kirchhoff's laws,** after the German physicist Gustav Kirchhoff, who published them in 1859.



▲ **FIGURE 2.16 Absorption Spectrum INTERACTIVE** When a cool gas is placed between a source of continuous radiation (such as a hot lightbulb) and the detector/screen, the resulting color spectrum is crossed by a series of dark absorption lines. These lines are formed when the intervening cool gas absorbs certain wavelengths (colors) from the original beam of light. The absorption lines appear at precisely the same wavelengths as the emission lines that would be produced if the gas were heated to high temperatures (see Figure 2.13).

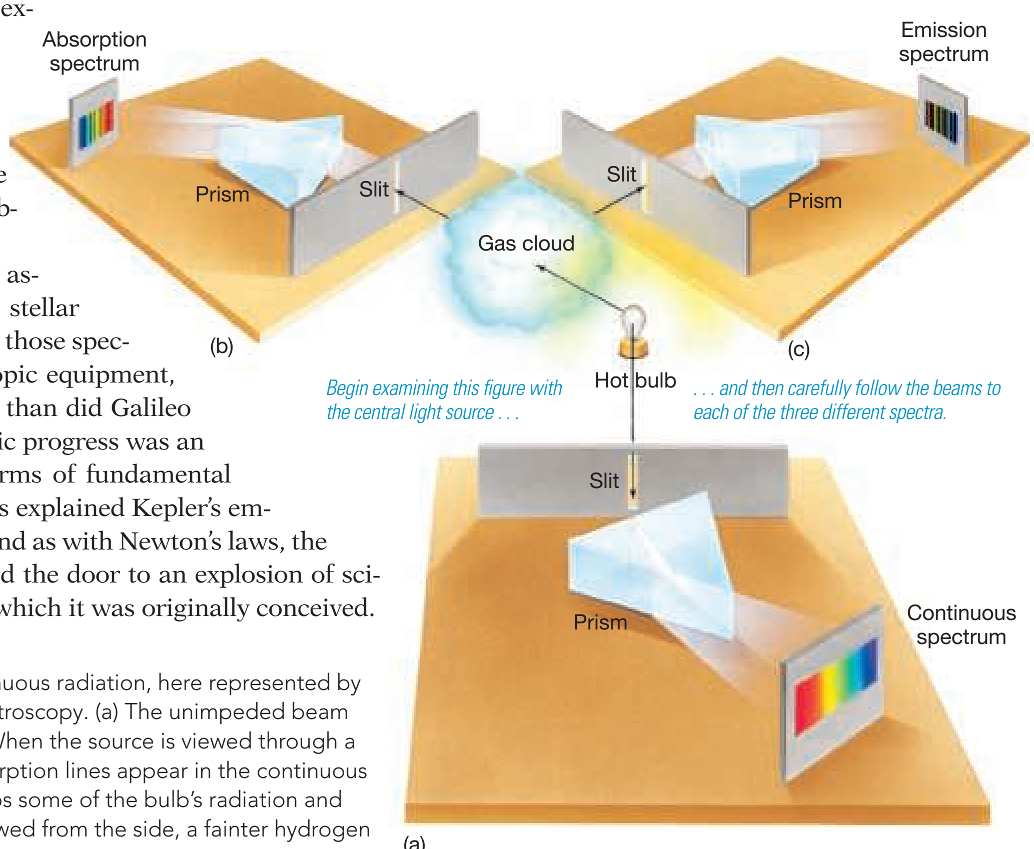
MA SELF-GUIDED TUTORIAL
Absorption Spectra

Astronomical Applications

Once astronomers realized that spectral lines were indicators of chemical composition, they set about identifying the observed lines in the Sun's spectrum. Almost all of the lines observed from extraterrestrial sources could be attributed to known elements. For example, many of the Fraunhofer lines in sunlight are associated with the element iron. However, some unfamiliar lines also appeared in the solar spectrum. In 1868 astronomers realized that those lines must correspond to a previously unknown element. It was given the name helium, after the Greek word *helios*, meaning "Sun." Only in 1895 was helium discovered on Earth.

The development of spectroscopy is another example of the scientific method in action. ∞ *(Sec. 0.5)* As technology evolved and experimental measurement techniques improved, scientists realized that spectra were unique fingerprints of matter. They then went on to use this knowledge as a means of determining the composition of objects that were otherwise impossible to reach.

Yet for all the information that 19th-century astronomers could extract from observations of stellar spectra, they still lacked a theory explaining *how* those spectra arose. Despite their sophisticated spectroscopic equipment, they knew little more about the physics of stars than did Galileo or Newton. The next step in the circle of scientific progress was an explanation of Kirchhoff's empirical laws in terms of fundamental physical principles, just as Newtonian mechanics explained Kepler's empirical laws of planetary motion. ∞ *(Sec. 1.4)* And as with Newton's laws, the new theory—called *quantum mechanics*—opened the door to an explosion of scientific understanding far beyond the context in which it was originally conceived.



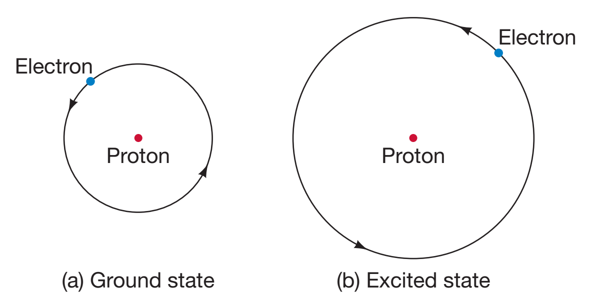
▶ **FIGURE 2.17 Kirchhoff's Laws** A source of continuous radiation, here represented by a lightbulb, is used to illustrate Kirchhoff's laws of spectroscopy. (a) The unimpeded beam shows the familiar continuous spectrum of colors. (b) When the source is viewed through a cloud of hydrogen gas, a series of dark hydrogen absorption lines appear in the continuous spectrum. These lines are formed when the gas absorbs some of the bulb's radiation and reemits it in random directions. (c) When the gas is viewed from the side, a fainter hydrogen emission spectrum is seen, consisting of reemitted radiation.

DATA POINTS

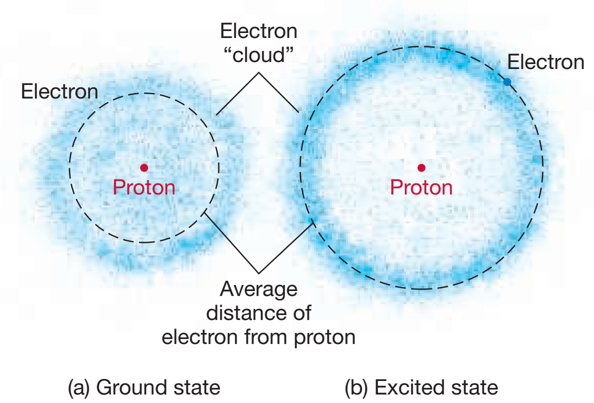
Atomic Structure and Spectroscopy

Fifty-seven percent of students had problems connecting atomic structure to an atom's emission and absorption of energy. Remember the following:

- Electrons in atoms can occupy only certain orbits, with precisely defined energies; the allowed energies increase as we move outward from the nucleus.
- When an electron moves from one orbit to another, the law of conservation of energy says that the change must be accompanied by the emission (if the electron drops from a high-energy orbit to a lower one) or absorption (low to high) of a photon of radiation.
- The energy of the photon is exactly equal to the change in orbital energy. High-energy photons have shorter wavelength (higher frequency).



▲ **FIGURE 2.18 Classical Atom** An early-20th-century conception of the hydrogen atom—the Bohr model—pictured its electron orbiting the central proton in a well-defined orbit, much like a planet orbiting the Sun. Two electron orbits of different energies are shown: (a) the ground state and (b) an excited state.



▲ **FIGURE 2.19 Modern Atom** The modern view of the hydrogen atom sees the electron as a "cloud" surrounding the nucleus.

2.6 Formation of Spectral Lines

By the start of the 20th century, physicists knew that light sometimes behaves in a manner that cannot be explained by the wave theory of radiation. Absorption and emission lines are produced only at certain, very specific wavelengths. This would not be the case if light behaved only as a continuous wave and matter always obeyed the laws of Newtonian mechanics. Clearly, when light interacts with matter on very small scales, it does so not in a smooth, continuous way but in a discontinuous, stepwise manner. The challenge was to explain this unexpected behavior. The solution revolutionized our view of nature and now forms the foundation not just for physics and astronomy, but for all of modern science.

Atomic Structure

To explain the formation of spectral lines, we must understand not just the nature of light but also something of the structure of **atoms**—the microscopic building blocks of matter. Let's start with the simplest atom, hydrogen, which consists of a single negatively charged electron orbiting a positively charged proton. The proton forms the central **nucleus** (plural: nuclei) of the atom. Because the positive charge on the proton exactly cancels the negative charge on the electron, the hydrogen atom as a whole is electrically neutral. If an atom absorbs some energy in the form of radiation, that energy must cause some internal change. And if the atom emits energy, it must come from somewhere within the atom. The energy absorbed or emitted by the atom is associated with changes in the motion of the orbiting electron.

In 1913, Danish physicist Niels Bohr developed a model of the atom that provided the first explanation of hydrogen's observed spectral lines. His work earned him the 1922 Nobel Prize in Physics. The essential features of the **Bohr model** of the atom are as follows. First, there is a state of lowest energy—the **ground state**—which represents the "normal" condition of the electron as it orbits the nucleus. Second, there is a maximum energy that the electron can have and still be part of the atom. If the electron acquires more than that maximum energy, it is no longer bound to the nucleus, and the atom is said to be *ionized*. An atom having fewer (or more) than its normal complement of electrons, and, hence, a net electrical charge, is called an **ion.** Third, and most important (and also least intuitive), between those two energy levels, the electron can exist only in certain sharply defined energy states, often referred to as *orbitals*.

An atom is said to be in an **excited state** when an electron occupies an orbital other than the ground state. The electron then lies at a greater than normal distance from its parent nucleus, and the atom has a greater than normal amount of energy. The excited state with the lowest energy (that is, the one closest to the ground state) is called the *first excited state*, that with the second-lowest energy the *second excited state*, and so on.

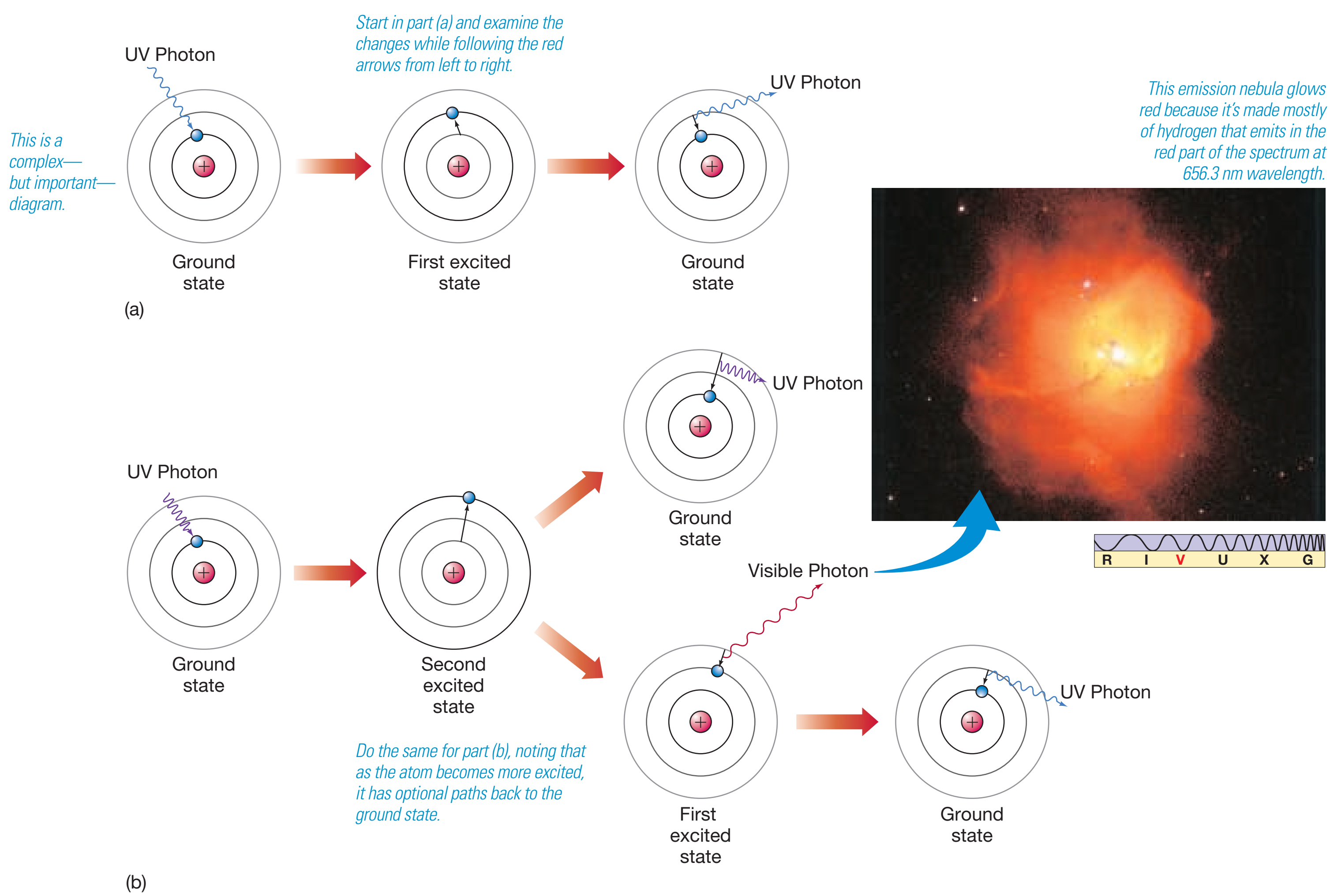
In Bohr's model, each electron orbital was pictured as having a specific radius, like a planetary orbit in the solar system, as shown in Figure 2.18. The modern view is not so simple. Although each orbital *does* have a precise energy, the electron is now envisioned as being smeared out in an *electron cloud* surrounding the nucleus, as illustrated in Figure 2.19. It is common to speak of the average distance from the cloud to the nucleus as the radius of the electron's orbital. When a hydrogen atom is in its ground state, the radius of the orbital is about 0.05 nm. As the orbital energy increases, the radius increases, too. For clarity, Figures 2.20 and 2.21 below use solid lines to represent electron orbitals, but bear in mind that the fuzziness in Figure 2.19 is a more accurate depiction of reality.

An atom can become excited by absorbing some light energy from a source of electromagnetic radiation or by colliding with some other particle—another atom, for example. However, the atom cannot stay in that state forever. After about 10^{-8} s, it returns to its ground state.

The Particle Nature of Radiation

Here is the crucial point that links atoms to radiation and allows us to interpret atomic spectra. Because electrons may exist only in orbitals having specific energies, atoms can absorb only specific amounts of energy as their electrons are boosted into excited states. Likewise, atoms can emit only specific amounts of energy as their electrons fall back to lower energy states. Thus, the amount of light energy absorbed or emitted in these processes *must correspond precisely to the energy difference between two orbitals*. This requires that light must be absorbed and emitted in the form of little "packets" of electromagnetic radiation, each carrying a very specific amount of energy. We call these packets **photons.** A photon is, in effect, a "particle" of electromagnetic radiation.

The idea that light sometimes behaves not as a continuous wave but as a stream of particles was first suggested by Albert Einstein in 1905. By then, experimental evidence clearly indicated that, on microscopic scales, electromagnetic radiation often displayed particle properties. Scientists understood that the notion of radiation as a wave was incomplete, but they did not know how to reconcile its



▲ **FIGURE 2.20 Atomic Excitation** INTERACTIVE (a) Absorption of an ultraviolet (UV) photon (left) by a hydrogen atom causes the momentary excitation of the atom into its first excited state (center). Eventually, the atom returns to its ground state (right), in the process emitting a photon having exactly the same energy as the original photon. (b) Absorption of a higher-energy UV photon may boost the atom into a higher excited state, from which there are several possible paths back to the ground state. At the top, the electron falls immediately back to the ground state, emitting a photon identical to the one it absorbed. At the bottom, the electron initially falls into the first excited state, producing visible radiation of wavelength 656.3 nm—the characteristic red glow of excited hydrogen. (*Inset:* NASA)

ANIMATION/VIDEO
Classical Hydrogen Atom I

ANIMATION/VIDEO
Classical Hydrogen Atom II

two seemingly contradictory natures. Einstein's great breakthrough (for which he won the 1919 physics Nobel Prize) came when he realized that all of the puzzling experiments could be explained by a simple, but critically important, connection between the particle and wave aspects of light. He found that the energy contained within a photon had to be proportional to the frequency of the radiation:

$$\text{photon energy} \propto \text{radiation frequency}.$$

Thus, for example, a "red" photon having a frequency of 4×10^{14} Hz (corresponding to a wavelength of about 750 nm) has 4/7 the energy of a "blue" photon, of frequency of 7×10^{14} Hz. Because it connects the *energy* of a photon with the *color* of the light it represents, this relationship is the final piece in the puzzle of how to understand the spectra we see.

Environmental conditions ultimately determine which description—wave or stream of particles—better fits the behavior of electromagnetic radiation. As a general rule of thumb, in the macroscopic realm of everyday experience, radiation is more usefully described as a wave, and in the microscopic domain of atoms, it is best characterized as a stream of particles.

CONCEPT CHECK

In what ways do electron orbits in the Bohr atom differ from planetary orbits around the Sun?

The Spectrum of Hydrogen

Figure 2.20 illustrates the absorption and emission of photons by a hydrogen atom. In part (a), the atom absorbs a photon of radiation and makes a transition from the ground state to the first excited state, then emits a photon of precisely the same energy and drops back to the ground state. The energy difference between the two states corresponds to an ultraviolet photon of wavelength 121.6 nm.

Figure 2.20(b) depicts the absorption of a more energetic (higher frequency, shorter wavelength) ultraviolet photon, this one having a wavelength of 102.6 nm, causing the atom to jump to the *second* excited state. From that state, the electron may return to the ground state via either one of two alternate paths:

ANIMATION/VIDEO
Photon Emission

1. It can proceed directly back to the ground state, in the process emitting an ultraviolet 102.6-nm photon identical to the one that excited the atom in the first place.
2. Alternatively, it can *cascade* down one orbital at a time, emitting *two* photons: one having an energy equal to the difference between the second and first excited states and the other having an energy equal to the difference between the first excited state and the ground state.

The second step in the cascade produces a 121.6-nm ultraviolet photon, just as in Figure 2.20(a). However, the first part of the cascade—the one from the second to the first excited state—produces a photon of wavelength 656.3 nm, which is in the visible part of the electromagnetic spectrum. This photon is seen as red light. An individual atom—if one could be isolated—would emit a momentary red flash. The inset in Figure 2.20 shows an astronomical object whose red color is the result of precisely this process.

Absorption of still more energy can boost the electron to even higher orbitals within the atom. As the excited electron cascades back down to the ground state, the atom may emit many photons, each with a different energy and, hence, a different color. In this case, the resulting spectrum shows many distinct spectral lines. For hydrogen, all transitions ending at the ground state produce ultraviolet photons. However, downward transitions ending at the *first* excited state give rise to spectral lines in or near the visible portion of the electromagnetic spectrum (Figure 2.14). Because they form the most easily observable part of the hydrogen spectrum and were the first to be discovered, these lines (also known as *Balmer lines*) are often referred to simply as the "hydrogen series" and are denoted by the letter H. Individual transitions are labeled with Greek letters, in order of increasing energy (decreasing wavelength): The Hα (H alpha) line corresponds to the transition from the second to the first excited state and has a wavelength of 656.3 nm (red); Hβ (H beta; third to first) has wavelength 486.1 nm (green); Hγ (H gamma; fourth to first) has wavelength 434.1 nm (blue); and so on.

Kirchhoff's Laws Explained

Let's reconsider our earlier discussion of emission and absorption lines in terms of the model just presented. In Figure 2.17(b) a beam of radiation shines through a cloud of gas. The beam contains photons of all energies, but most of them do not interact with the gas because the gas can absorb only photons having precisely the right energy to cause an electron to jump from one orbital to another. Photons having energies that cannot produce such a jump pass through the gas unhindered. Photons having the right energies are absorbed, excite the gas, and are removed from the beam. This is the cause of the dark absorption lines in the spectrum. These lines are direct indicators of the energy differences between orbitals in the atoms making up the gas.

The excited gas atoms rapidly return to their original states, each emitting one or more photons in the process. Most of these reemitted photons leave at angles that do *not* take them through the slit and on to the detector. A second detector looking at the cloud from the side (Figure 2.17c) would record the reemitted energy as an emission spectrum. (This is what we are seeing in the inset to Figure 2.20.) Like the absorption spectrum, the emission spectrum is characteristic of the gas, not of the original beam.

The case of a *continuous* spectrum in Figure 2.17(c) is shown for emitted photons escaping from the bulb without further interaction with matter. Actually, the situation in a denser source of radiation (a thick gas cloud or in a liquid or solid body) is more complex. There, a photon is likely to interact with atoms, free electrons, and ions in the body many times before finally escaping, exchanging some energy with the matter at each encounter. The net result is that the emitted radiation displays a continuous spectrum, in accordance with Kirchhoff's first law. The spectrum is approximately that of a blackbody with the same temperature as the source.

More Complex Spectra

All hydrogen atoms have the same structure—a single electron orbiting a single proton—but, of course, there are many other kinds of atoms, each having a unique internal structure. The number of protons in the nucleus of an atom determines which **element** the atom represents. That is, just as all hydrogen atoms have a single proton, all oxygen atoms have 8 protons, all iron atoms have 26 protons, and so on.

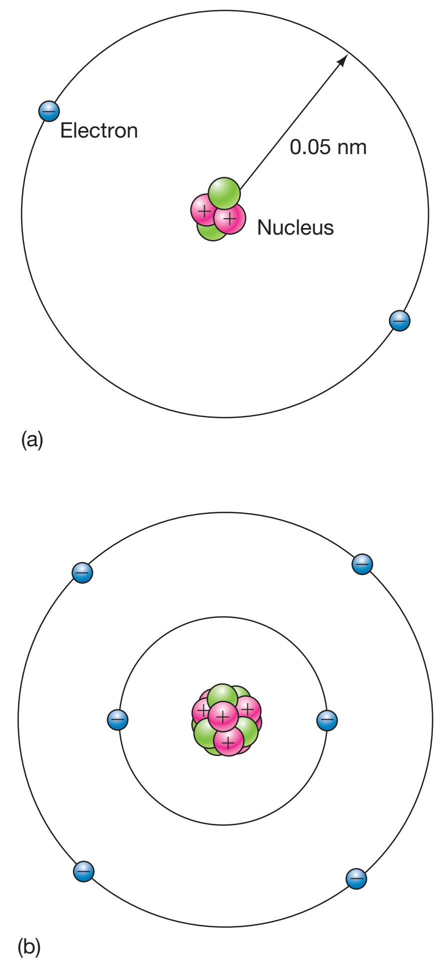
The next simplest element after hydrogen is helium. Its nucleus is made up of two protons and two **neutrons** (another elementary particle with a slightly larger mass than a proton, but carrying no electrical charge). Two electrons orbit the nucleus. As with hydrogen and all other atoms, the "normal" condition for helium is to be electrically neutral, with the negative charge of the orbiting electrons exactly canceling the positive charge of the nucleus (Figure 2.21a).

More complex atoms contain more protons (and neutrons) in the nucleus and have correspondingly more orbiting electrons. For example, an atom of carbon (Figure 2.21b) consists of six electrons orbiting a nucleus containing six protons and six neutrons. As we progress to heavier and heavier elements, the number of orbiting electrons increases, and consequently the number of possible electronic transitions rises rapidly. The number increases further as the temperature increases and atoms become excited or even ionized. The result is that very complicated spectra can be produced. The complexity of atomic spectra generally reflects the complexity of the source atoms.

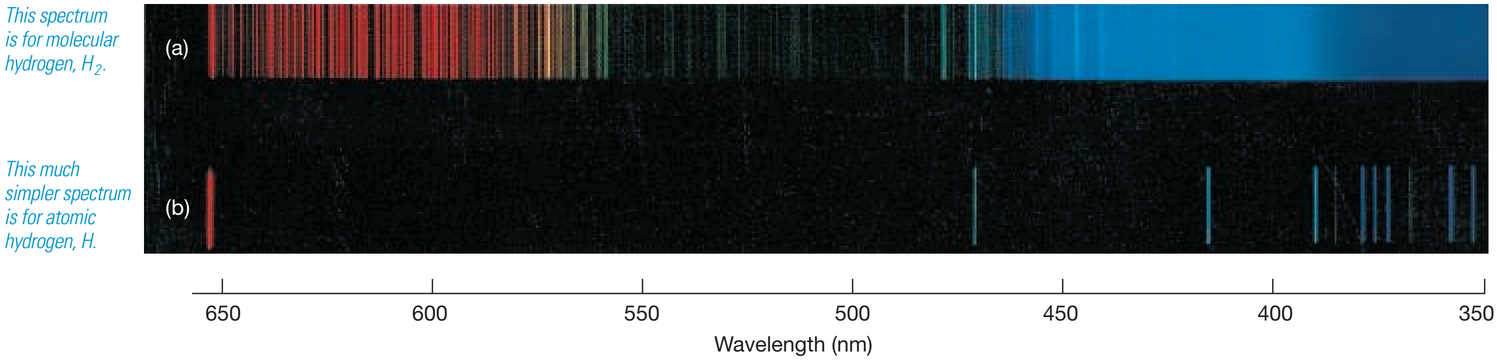
Even more complex spectra are produced by **molecules.** A molecule is a tightly bound group of atoms held together by interactions among their orbiting

PROCESS OF SCIENCE CHECK

In what ways was the wave theory of radiation unable to account for detailed observations of atomic spectra? Describe some key aspects of the theory of quantum mechanics, and explain how the new theory explains spectral lines.



▲ FIGURE 2.21 **Helium and Carbon** (a) A helium atom in its ground state has two electrons within the lowest-energy orbital around a nucleus containing two protons and two neutrons. (b) A carbon atom in its ground state has six electrons orbiting around a six-proton, six-neutron nucleus—two of the electrons in an inner orbital and the other four at a greater distance from the center.



▲ **FIGURE 2.22 Hydrogen Spectra** The emission spectrum of molecular hydrogen (a) differs greatly from that of simpler atomic hydrogen (b). (Bausch & Lomb Inc.)

electrons—interactions called *chemical bonds*. Much like atoms, molecules can exist only in certain well-defined energy states, and they produce emission or absorption spectral lines when they make a transition from one state to another. Because molecules are more complex than atoms, the rules of molecular physics are also much more complex. Nevertheless, as with atomic spectral lines, painstaking experimental work over many decades has determined the precise frequencies at which millions of molecules emit and absorb radiation. These lines are molecular fingerprints, just like their atomic counterparts, enabling researchers to identify and study one kind of molecule to the exclusion of all others.

Molecular lines usually bear little resemblance to the spectral lines associated with their component atoms. For example, Figure 2.22(a) shows the emission spectrum of the simplest molecule known—molecular hydrogen. Notice how different it is from the spectrum of atomic hydrogen shown in part (b).

CONCEPT CHECK

How does the structure of an atom determine the atom's emission and absorption spectra?

2.7 The Doppler Effect

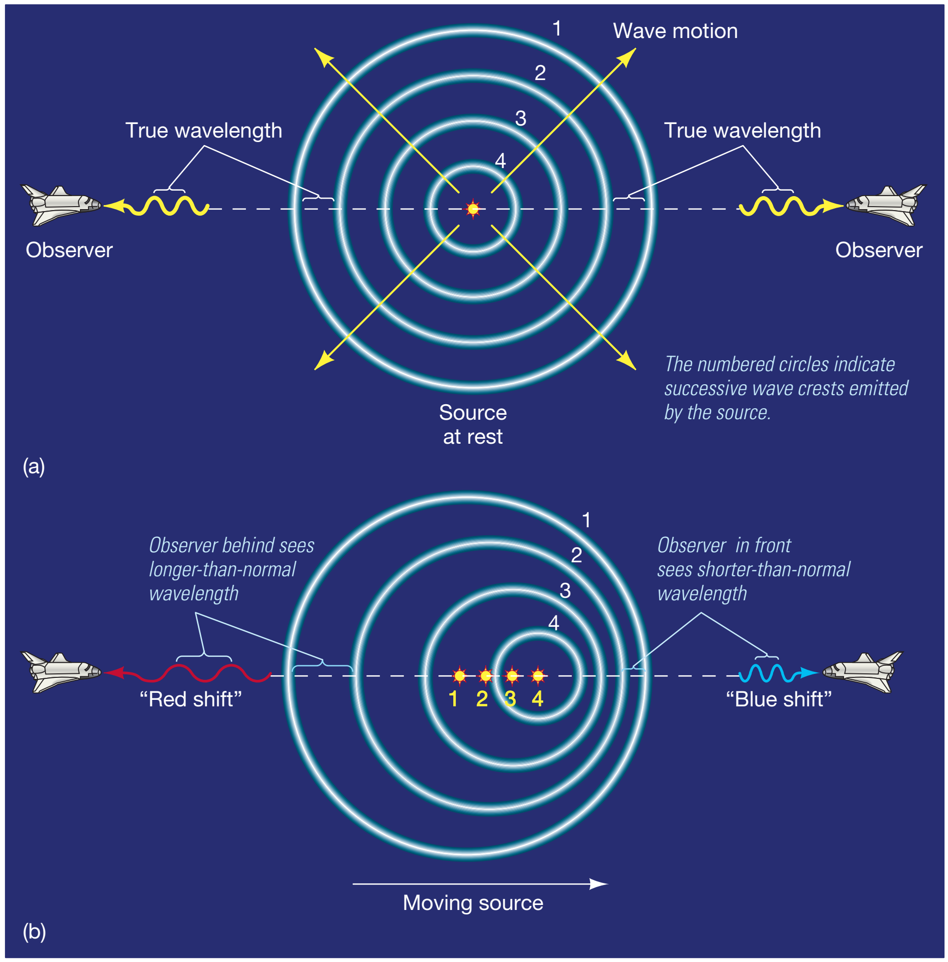
Most of us have had the experience of hearing the pitch of a train whistle change from high shrill (high frequency, short wavelength) to low blare (low frequency, long wavelength) as the train approaches and then recedes. This motion-induced change in the observed frequency of a wave is known as the **Doppler effect,** in honor of Christian Doppler, the 19th-century Austrian physicist who first explained it. Applied to cosmic sources of electromagnetic radiation, it has become one of the most important observational tools in all of 20th-century astronomy. Here's how it works.

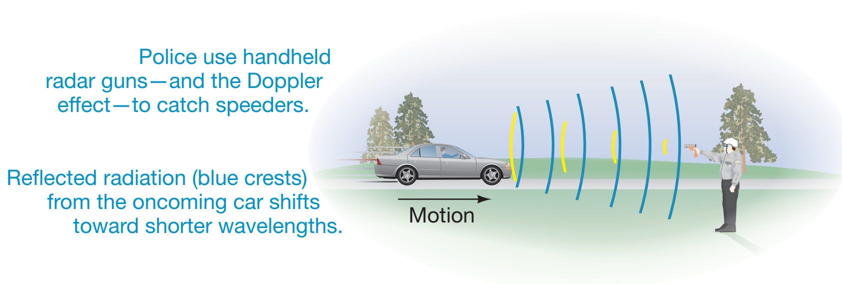
Imagine a wave moving from the place where it is generated toward an observer who is not moving with respect to the wave source (Figure 2.23a). By noting the distances between successive wave crests, the observer can determine the wavelength of the emitted wave. Now suppose that the wave source begins to move (Figure 2.23b). Because the source moves between the times of emission of one wave crest and the next, wave crests in the direction of motion of the source are seen to be *closer together* than normal, while crests behind the source are more widely spaced. Thus, an observer in front of the source measures a *shorter* wavelength than normal, while one behind sees a *longer* wavelength.

The greater the relative speed of source and observer, the greater the observed shift. In terms of the net velocity of *recession* between source and observer, the apparent wavelength and frequency (measured by the observer) are related to the true quantities (emitted by the source) by

$$\frac{\text{apparent wavelength}}{\text{true wavelength}} = \frac{\text{true frequency}}{\text{apparent frequency}} = 1 + \frac{\text{recession velocity}}{\text{wave speed}}.$$

A positive recession velocity means that the source and the observer are moving apart; a negative value means that they are approaching. The wave speed is the





▸ **FIGURE 2.23 Doppler Effect INTERACTIVE** (a) Wave motion from a source toward an observer at rest with respect to the source. As seen by the observer, the source is not moving, so the wave crests are just concentric spheres (shown here as circles). (b) Waves from a moving source tend to "pile up" in the direction of motion and be "stretched out" on the other side. As a result, an observer situated in front of the source measures a shorter-than-normal wavelength—a blueshift—while an observer behind the source sees a redshift.

speed of light c in the case of electromagnetic radiation. For most of this text, the recession velocity will be small compared to the speed of light. Only when we come to discuss the properties of black holes (Chapter 13) and the structure of the universe on the largest scales (Chapter 17) will we have to reconsider this formula.

Note that, in the figure, the source is shown in motion. However, the same general statements hold whenever there is any *relative* motion between source and observer. Note also that only motion along the line joining source and observer, known as *radial* motion, appears in the above equation. Motion *transverse* (perpendicular) to the line of sight has no significant effect.

In astronomical jargon, the wave measured by an observer situated in front of a moving source is said to be *blueshifted*, because blue light has a shorter wavelength than red light. Similarly, an observer situated behind the source will measure a longer-than-normal wavelength—the radiation is said to be *redshifted*. This terminology holds even for invisible radiation, for which "red" and "blue" have no meaning. Any shift toward shorter wavelengths is called a blueshift, and any shift toward longer wavelengths is called a redshift.

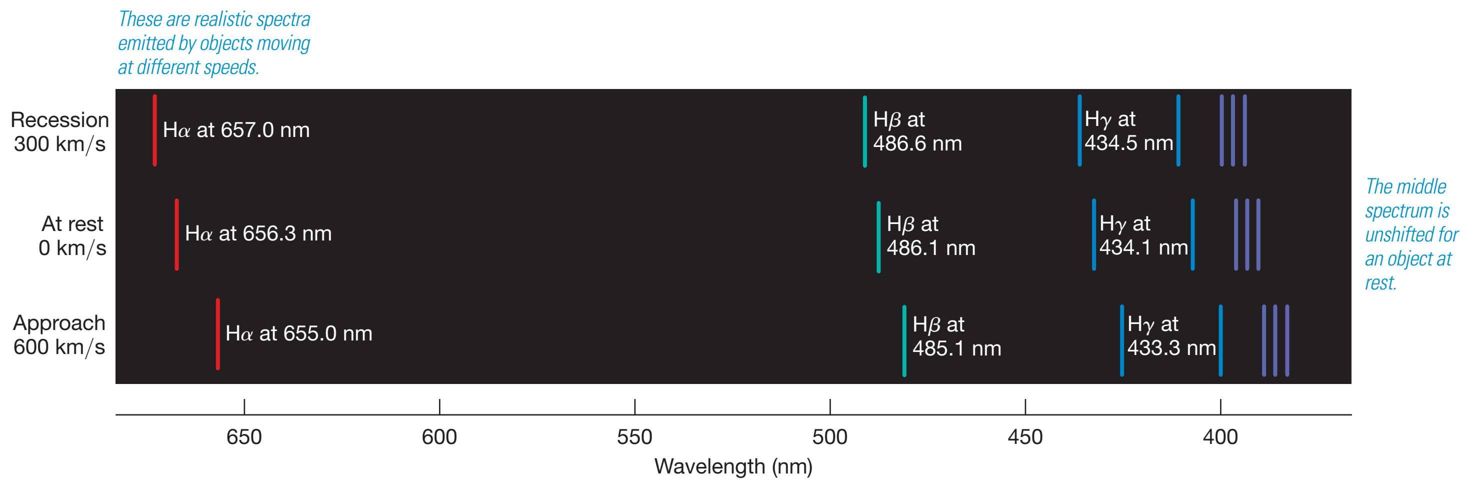
The Doppler effect is not normally noticeable in visible light on Earth—the speed of light is so large that the wavelength change is far too small to be noticeable for everyday terrestrial velocities. However, using spectroscopic techniques, astronomers routinely use the Doppler effect to measure the line-of-sight velocity of cosmic objects by determining the extent to which known spectral lines are shifted to longer or shorter wavelengths. For example, suppose that an astronomer observes the red Hα line in the spectrum of a star to have a wavelength of 657 nm instead of the 656.3 nm measured in the laboratory. (How does she know it is the same line? Because, as illustrated in Figure 2.24, she realizes that *all* the hydrogen lines are shifted by the same fractional amount—the characteristic pattern of lines identifies hydrogen as the source.) Using the above equation, she calculates that the star's radial velocity is $657/656.3 - 1 = 0.0056$ times the speed of light. In other words, the star is receding from Earth at a rate of 320 km/s.

The motions of nearby stars and distant galaxies—even the expansion of the universe itself—have all been measured in this way. Motorists stopped for speeding on the highway have experienced another, much more down-to-earth, application. As illustrated in the inset to Figure 2.23, police radar measures speed by means of the Doppler effect, as do the radar guns used to clock the velocity of a pitcher's fastball or a tennis player's serve.

MA® SELF-GUIDED TUTORIAL
Doppler Effect

CONCEPT CHECK

How might the Doppler effect be used in determining the mass of a distant star?



▲ **FIGURE 2.24** **Doppler Shift** **INTERACTIVE** The Doppler effect shifts the entire spectrum of a moving object to higher or lower frequencies. The spectrum at top shows the redshift of the hydrogen lines from an object moving at a speed of 300 km/s away from the observer; that at bottom shows those same lines blueshifted while the object moves at double that speed toward the observer.

2.8 Spectral-Line Analysis

Astronomers apply the laws of spectroscopy in analyzing radiation from beyond Earth. A nearby star or a distant galaxy takes the place of the lightbulb in our previous examples, an interstellar cloud or a stellar (or even planetary) atmosphere plays the role of the intervening cool gas, and a spectrograph attached to a telescope replaces our simple prism and detector. We list below some of the properties of emitters and absorbers that can be determined by careful analysis of radiation received on (or near) Earth. We will encounter other important examples as our study of the cosmos unfolds.

1. The *composition* of an object is determined by matching its spectral lines with the laboratory spectra of known atoms and molecules.
2. The *temperature* of an object emitting a continuous spectrum can be measured by matching the overall distribution of radiation with a blackbody curve. Temperature may also be determined from detailed studies of spectral lines. In Section 10.3 we will see how stellar temperatures are most accurately measured by spectroscopic means.
3. The (*line-of-sight) velocity* of an object is measured by determining the Doppler shift of its spectral lines.
4. An object's *rotation rate* can be determined by measuring the *broadening* (smearing out over a range of wavelengths) produced by the Doppler effect in emitted or reflected spectral lines.
5. The *pressure* of the gas in the emitting region of an object can be measured by its tendency to broaden spectral lines. The greater the pressure, the broader the line.
6. The *magnetic field* of an object can be inferred from a characteristic splitting it produces in many spectral lines, when a single line divides into two. (This is known as the *Zeeman effect*.)

Given sufficiently sensitive equipment, there is almost no end to the wealth of data contained in starlight. The challenge facing astronomers is to unravel the extent to which each of the above mechanisms, in a complex mix of atoms and molecules, contributes to spectral line profiles, and thereby obtain meaningful information about the source of the lines.

CONCEPT CHECK

Why is it important for astronomers to analyze spectral lines in detail?

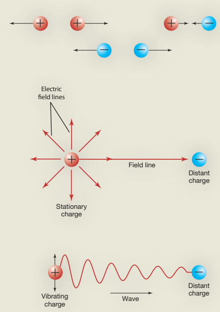
THE BIG QUESTION

Atoms are the basic components of normal matter–the stuff from which stars, planets, and we ourselves are built. In turn, all atoms are made of smaller elementary particles: protons, neutrons, and electrons. But even those particles are not fundamental, for physicists know that protons and neutrons are made of quarks, and many theorists think that quarks and electrons may have even deeper structure. How far does this hierarchy continue, and what new windows on the cosmos will be opened by our understanding of these unknown levels of nature?

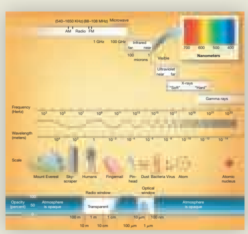
CHAPTER REVIEW

SUMMARY

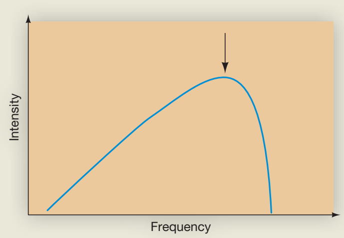
LO1 **Electromagnetic radiation** (p. 46) travels through space in the form of a **wave** (p. 46). Any electrically charged object is surrounded by an **electric field** (p. 48) that determines the force it exerts on other charged objects. When a charged particle moves, information about that motion is transmitted via the particle's changing **electric** and **magnetic fields** (pp. 48, 49). The information travels at the **speed of light** (p. 47) as an electromagnetic wave.



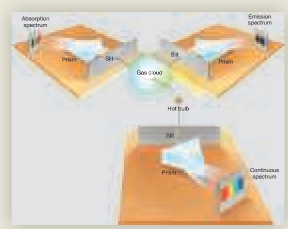
LO2 The **electromagnetic spectrum** (p. 50) consists of (in order of decreasing wavelength, or increasing frequency) **radio waves**, **infrared radiation**, **visible light**, **ultraviolet radiation**, **X-rays**, and **gamma rays** (p. 46). The **opacity** (p. 52) of Earth's atmosphere—the extent to which it absorbs radiation—varies greatly with the wavelength of the radiation. Only radio waves, some infrared wavelengths, and visible light can penetrate the atmosphere and reach the ground.



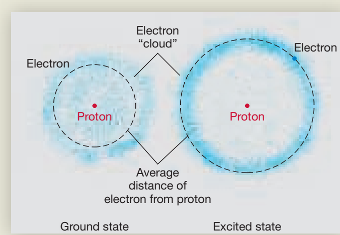
LO3 The **temperature** (p. 53) of an object is a measure of the speed with which its constituent particles move. The **intensity** (p. 53) of radiation emitted by an object has a characteristic distribution, called a **blackbody curve** (p. 53), that depends only on the temperature of the object. **Wien's law** (p. 54) tells us that the wavelength at which the object's radiation peaks is inversely proportional to its temperature. **Stefan's law** (p. 54) states that the total amount of energy radiated is proportional to the fourth power of the temperature.



LO4 Many hot objects emit a **continuous spectrum** (p. 56) of radiation, containing light of all wavelengths. A hot gas may instead produce an **emission spectrum** (p. 57), consisting only of a few well-defined **emission lines** (p. 57) of specific frequencies, or colors. Passing a continuous beam of radiation through cool gas will produce **absorption lines** (p. 57) at precisely the same frequencies as would be present in the gas's emission spectrum.

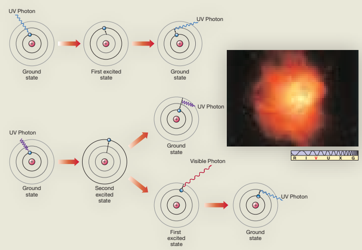


LO5 **Atoms** (p. 60) are made up of negatively charged electrons orbiting a positively charged **nucleus** (p. 60) consisting of positively charged protons and electrically neutral **neutrons** (p. 63). The number of protons determines the type of **element** (p. 63) the atom represents. In the **Bohr model** (p. 60), a hydrogen atom has a minimum-energy **ground state** (p. 60), representing its "normal" condition. When the electron has a higher-than-normal energy, the atom is in an **excited state** (p. 60). For any given atom, only certain,

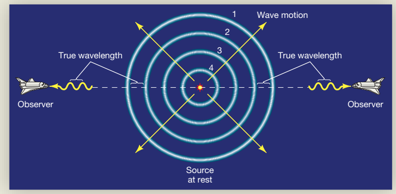


well-defined energies are possible. In the modern view, the electron is envisaged as being spread out in a "cloud" around the nucleus but still having a sharply defined energy.

LO6 When an electron moves from one energy state to another in an atom, the difference in the energy between the states is emitted or absorbed in the form of "packets" of electromagnetic radiation—**photons** (p. 61). Because the energy levels have definite energies, the photons also have definite energies that are characteristic of the type of atom involved. The energy of a photon determines the frequency, and hence the color, of the light emitted or absorbed.



LO7 Our perception of the wavelength of a beam of light can be altered by the source's velocity relative to us. This motion-induced change in the observed frequency of a wave is called the **Doppler effect** (p. 64). Any net motion of the source away from the observer causes a redshift—a shift to lower frequencies—in the received beam. Motion toward the observer causes a blueshift. The extent of the shift is directly proportional to the source's radial velocity relative to the observer.



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

REVIEW AND DISCUSSION

1. Define the following wave properties: period, wavelength, amplitude, frequency.
2. Compare and contrast the gravitational and electric forces.
3. **LO1** Describe how light radiation leaves a star, travels through the vacuum of space, and finally is seen by someone on Earth.
4. **LO2** What do radio waves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays have in common? How do they differ?
5. In what regions of the electromagnetic spectrum is the atmosphere transparent enough to allow observations from the ground?
6. What is a blackbody? Describe the radiation it emits.
7. **POS** If Earth were completely blanketed with clouds and we couldn't see the sky, could we learn about the realm beyond the clouds? What forms of radiation might penetrate the clouds and reach the ground?
8. **LO3** In terms of its blackbody curve, describe what happens as a red-hot glowing coal cools.
9. **LO6 POS** Explain how astronomers might use spectroscopy to determine the composition and temperature of a star.
10. **LO4** What are continuous, emission, and absorption spectra? How are they produced?
11. What is the normal condition for atoms? What is an excited atom? What are orbitals?
12. **LO5** Why do atoms absorb and reemit radiation at characteristic frequencies?
13. **POS** Suppose a luminous cloud of gas is discovered emitting an emission spectrum. What can be learned about the cloud from this observation?
14. What is the Doppler effect, and how does it alter the way in which we perceive radiation?
15. **LO7** How do astronomers use the Doppler effect to determine the velocities of astronomical objects?

CONCEPTUAL SELF-TEST: TRUE OR FALSE?/MULTIPLE CHOICE

1. The wavelength of green light is about the size of an atom. (T/F)
2. Two otherwise identical objects have temperatures of 1000 K and 1200 K, respectively. The object at 1200 K emits roughly twice as much radiation as the object at 1000 K. (T/F)
3. As you drive away from a radio transmitter, the radio signal you receive from the station is shifted to longer wavelengths. (T/F)
4. Imagine an emission spectrum produced by a container of hydrogen gas. Changing the amount of hydrogen in the container will change the colors of the lines in the spectrum. (T/F)
5. In the previous question, changing the gas in the container from hydrogen to helium will change the colors of the lines occurring in the spectrum. (T/F)
6. The energy of a photon is inversely proportional to the wavelength of the radiation. (T/F)
7. An electron moves to a higher energy level in an atom after absorbing a photon of a specific energy. (T/F)
8. Compared with ultraviolet radiation, infrared radiation has a greater (a) wavelength; (b) amplitude; (c) frequency; (d) energy.

9. An X-ray telescope located in Antarctica would not work well because of (a) the extreme cold; (b) the ozone hole; (c) continuous daylight; (d) Earth's atmosphere.
10. A star much cooler than the Sun would appear (a) red; (b) blue; (c) smaller; (d) larger.
11. The blackbody curve of a star moving toward Earth would have its peak shifted (a) to lower intensity; (b) toward higher energies; (c) toward longer wavelengths; (d) toward lower energies.
12. The visible spectrum of sunlight reflected from Saturn's cold moon Titan would be expected to be (a) continuous; (b) an emission spectrum; (c) an absorption spectrum.
13. Astronomers analyze starlight to determine a star's (a) temperature; (b) composition; (c) motion; (d) all of the above.
14. VIS According to Figure 2.11 (Blackbody Curves), an object having a temperature of 1000 K emits mostly (a) infrared light; (b) visible light; (c) ultraviolet light; (d) X-rays.
15. VIS In Figure 2.20 (Atomic Excitation), the total energy of the two photons emitted in the branch at the lower right is (a) greater than, (b) less than, (c) approximately equal to, (d) exactly equal to, the energy of the UV photon absorbed at the left.

PROBLEMS

The number of squares preceding each problem indicates its approximate level of difficulty.

1. ■ A sound wave moving through water has a frequency of 256 Hz and a wavelength of 5.77 m. What is the speed of sound in water?
2. ■ What is the wavelength of a 100-MHz (FM 100) radio signal?
3. ■ What would be the frequency of an electromagnetic wave having a wavelength equal to Earth's diameter (12,800 km)? In what part of the electromagnetic spectrum would such a wave lie?
4. ■■ The blackbody emission spectrum of object A peaks in the ultraviolet region of the electromagnetic spectrum at a wavelength of 200 nm. That of object B peaks in the red region, at 650 nm. Which object is hotter, and, according to Wien's law, how many times hotter is it? According to Stefan's law, how many times more energy per unit area does the hotter body radiate per second?
5. ■ Normal human body temperature is about 37°C. What is this temperature in kelvins? What is the peak wavelength emitted by a person with this temperature? In what part of the spectrum does this lie?
6. ■■ According to the Stefan-Boltzmann law, how much energy is radiated into space per unit time by each square meter of the Sun's surface (see *More Precisely 2-2*)? If the Sun's radius is 696,000 km, what is the total power output of the Sun?
7. ■ By what factor does the energy of a 1-nm X-ray photon exceed that of a 10-MHz radio photon? How many times more energy has a 1-nm gamma ray than a 10-MHz radio photon?
8. ■■ How many different photons (that is, photons of different frequencies) can be emitted as a hydrogen atom in the second excited state falls back, directly or indirectly, to the ground state? What are their wavelengths? What about a hydrogen atom in the third excited state?
9. ■ The Hα line (Section 2.6) of a star is received on Earth at a wavelength of 656 nm. What is the star's radial velocity relative to Earth?
10. ■■■ You are observing a spacecraft moving in a circular orbit of radius 100,000 km around a distant planet. You happen to be located in the plane of the spacecraft's orbit. You find that the spacecraft's radio signal varies periodically in wavelength between 2.99964 m and 3.00036 m. Assuming that the radio is broadcasting at a constant wavelength, what is the mass of the planet?

ACTIVITIES

Collaborative

1. Find a spectrum of the Sun with a wavelength scale on it. Google is a good place to start. Select some absorption lines and determine their wavelengths by interpolation. Now, try to identify the element that produced these lines. Use a reference such as Moore's *A Multiplet Table of Astrophysical Interest*, available on the NASA Astrophysics Data System. Work with the darkest lines before trying the fainter ones. How many elements can you find?
2. Stand near (but not too near!) a train track or busy highway and wait for a train or traffic to pass by. Can you notice the Doppler effect in the pitch of the engine noise or whistle blowing? How does the sound frequency depend on the train's (a) speed and (b) motion toward or away from you? Divide your group into two. One subgroup should time the train's motion and hence calculate approximately its speed. The other (consisting of the more musically inclined!) should estimate the perceived frequency change of the whistle when the train is moving first toward you and then away from you.

Individual

1. Locate the constellation Orion. Its two brightest stars are Betelgeuse and Rigel. Which is hotter? How can you tell? Which of the other stars scattered across the night sky are hot, and which are cool?
2. Obtain a handheld spectroscope, available from your school science lab or online. In the shade, point the spectroscope at a white cloud or white piece of paper that is in direct sunlight. Look for the absorption lines in the Sun's spectrum. Note their wavelength from the scale inside the spectroscope. How many of the lines can you identify by comparing your list with the Fraunhofer lines given in many astronomy reference books or on Wikipedia?

3

Telescopes

The Tools of Astronomy

At its heart, astronomy is an observational science. Painstaking observations of cosmic phenomena almost always precede any clear theoretical understanding of their nature. As a result, our detecting instruments—our telescopes—have evolved to observe as broad a range of wavelengths as possible. Until the middle of the 20th century, telescopes were limited to visible light. Since then, however, technological advances have expanded our view of the universe to all parts of the electromagnetic spectrum. Some telescopes are sited on Earth, others must be placed in space, and designs vary widely from one region of the spectrum to another. Whatever the details of its construction, however, the basic purpose of a telescope is to collect electromagnetic radiation and deliver it to a detector for detailed study.

THE BIG PICTURE

Telescopes are time machines, and astronomers, in a sense, are historians. Telescopes enhance our senses, enabling us to look far out in space—and hence far back in time. They allow us to explore objects at a much farther distance than would be possible with our unaided eyes and to perceive radiation at wavelengths far beyond human vision. Almost everything in this book would be unknown without these powerful and versatile instruments.

◂ Astronomers like to think big, and really big telescopes are now on the drawing board. This artist's conception for the European Southern Observatory shows E-ELT—the European Extremely Large Telescope. Its mirror diameter of nearly 40 m means that E-ELT will combine unrivaled light-gathering power with the ability to examine cosmic objects at unprecedented resolution. This largest telescope in the world will be built on Cerro Armazones, a 3000-m mountaintop in Chile's Atacama Desert. *(ESO/L. Calcada)*

LEARNING OUTCOMES

Studying this chapter will enable you to:

- **LO1** Describe how optical telescopes work, and specify the advantages of reflecting telescopes over refractors.
- **LO2** Explain why larger telescopes gather more light and can make more detailed images.
- **LO3** Describe how Earth's atmosphere limits astronomical observations, and explain how astronomers overcome these limitations.
- **LO4** Outline the advantages and disadvantages of radio astronomy.
- **LO5** Explain how interferometry is used to improve astronomical observations.
- **LO6** Describe the design of infrared, ultraviolet, and high-energy telescopes, and explain why some telescopes must be placed in space.
- **LO7** Explain the importance of making astronomical observations at many different wavelengths across the electromagnetic spectrum.

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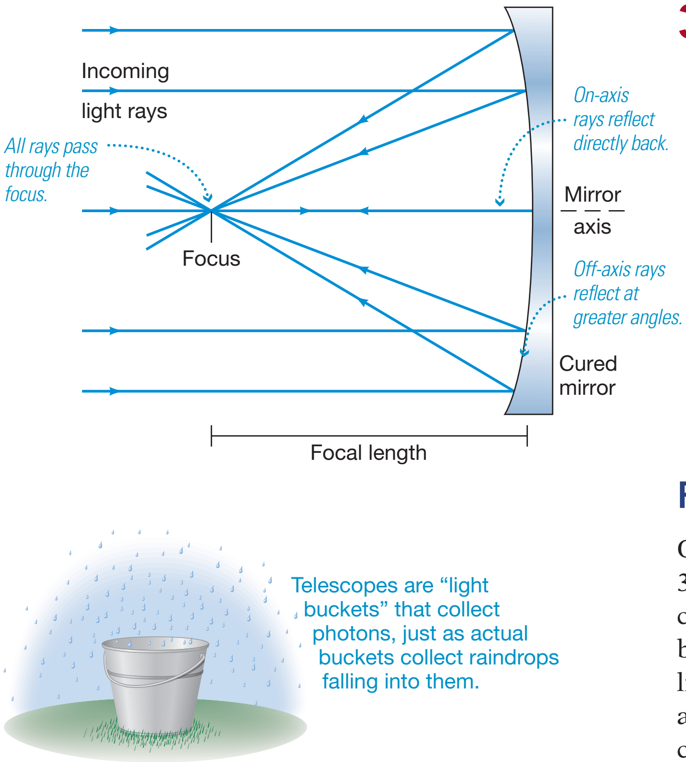


▲ **FIGURE 3.1 Reflecting Mirror** Curved mirrors focus to a single point all rays of light arriving parallel to the mirror axis. The arrows indicate the directions of the incoming and reflected rays.

3.1 Optical Telescopes

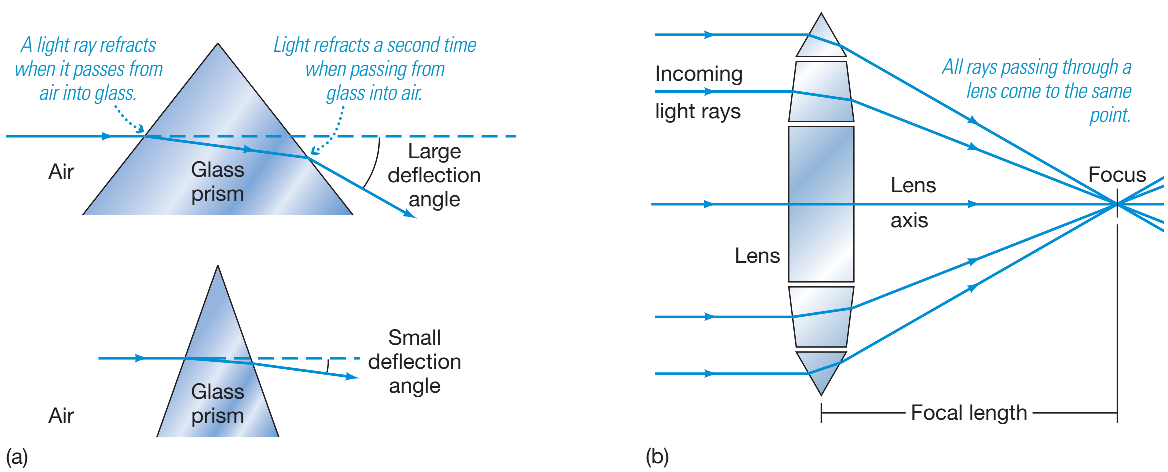
Simply put, a **telescope** is a "light bucket"—a device whose primary function is to capture as much radiation as possible from a given region of the sky and concentrate it into a focused beam for analysis. We begin our study of astronomical hardware with *optical* telescopes, designed to collect wavelengths visible to the human eye. Later, we will look at telescopes designed to capture and analyze radiation in other, *invisible* regions of the electromagnetic spectrum. Throughout this text we will see how advances in our understanding of the universe have always gone hand in hand with technological improvements in both the sensitivity and the spectral range of our detectors. This combination of technology and science is as vital today as it was when Galileo first turned his telescope toward the skies. ∞ *(Sec. 1.2)*

Reflecting and Refracting Telescopes

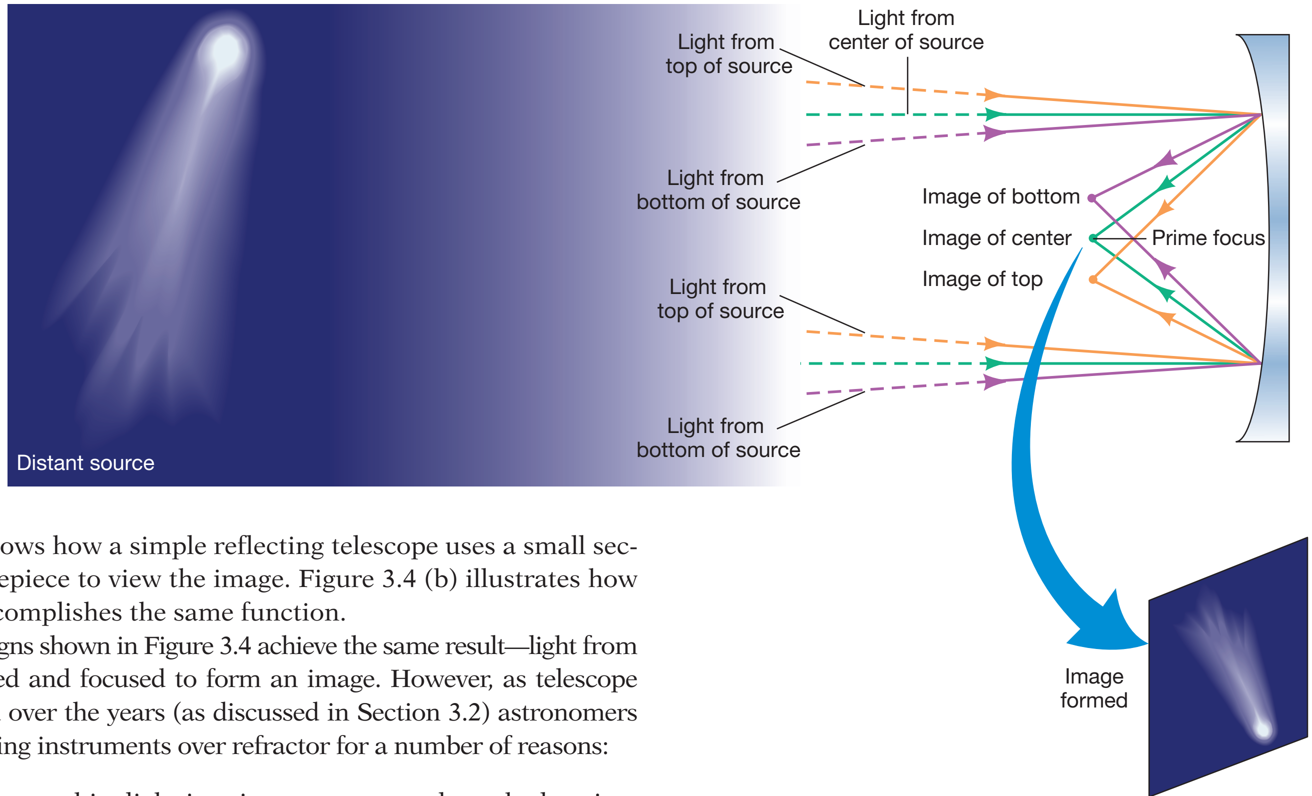
Optical telescopes fall into two basic categories—*reflectors* and *refractors*. Figure 3.1 shows how a **reflecting telescope** uses a curved mirror to gather and concentrate a beam of light. This mirror, usually called the *primary mirror* because telescopes generally contain more than one, is constructed so that all light rays arriving parallel to its axis (the imaginary line through the center of and perpendicular to the mirror) are reflected to pass through a single point, called the *focus*. The distance between the primary mirror and the focus is the *focal length*. In astronomical contexts, the focus of the primary mirror is referred to as the **prime focus.**

A **refracting telescope** uses a lens instead of a mirror to focus the incoming light, relying on refraction rather than reflection to achieve its purpose. **Refraction** is the bending of a beam of light as it passes from one transparent medium (for example, air) into another (such as glass). Figure 3.2 (a) illustrates how a prism can be used to change the direction of a beam of light. As illustrated in Figure 3.2 (b), we can think of a lens as a series of prisms combined in such a way that all light rays striking the lens parallel to the axis are refracted to pass through the focus.

Astronomers often use telescopes to make **images** of their fields of view. Figure 3.3 illustrates how this is accomplished, in this case by the primary mirror in a reflecting telescope. Light from a distant object reaches the telescope as nearly parallel rays. A ray of light entering the instrument parallel to the mirror axis is reflected through the focus. Light from a slightly different direction—that is, at a slight angle to the axis—is focused to a slightly different point. In this way, an image is formed near the focus. Each point in the image corresponds to a different angle in the field of view. Often, a lens known as an *eyepiece* is used to magnify the image before it is viewed by eye or recorded using a



◀ **FIGURE 3.2 Refracting Lens** (a) Refraction by a prism changes the direction of a light ray. (b) A lens can be thought of as a series of prisms.



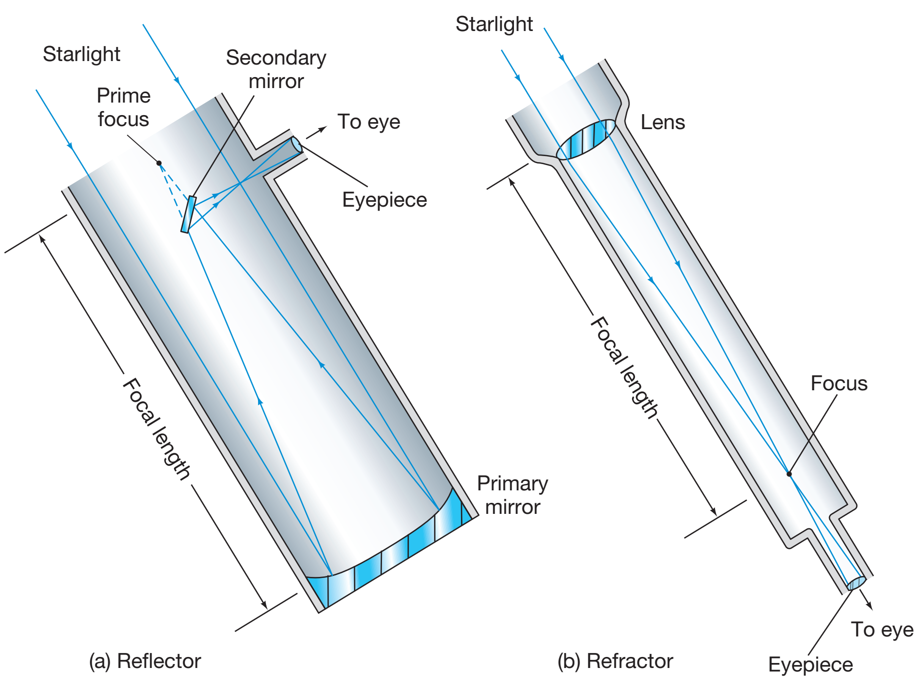
▲ **FIGURE 3.3 Image Formation** An image is formed by a mirror as rays of light coming from different points on a distant object focus to slightly different locations. Notice that the image is inverted (that is, upside down).

camera. Figure 3.4 (a) shows how a simple reflecting telescope uses a small secondary mirror and an eyepiece to view the image. Figure 3.4 (b) illustrates how a refracting telescope accomplishes the same function.

The two telescope designs shown in Figure 3.4 achieve the same result—light from a distant object is captured and focused to form an image. However, as telescope *size* has steadily increased over the years (as discussed in Section 3.2) astronomers have come to favor reflecting instruments over refractor for a number of reasons:

1. Just as a prism separates white light into its component colors, the lens in a refracting telescope focuses red and blue light differently (the blue focus lying closer to the lens). This deficiency is known as *chromatic aberration*. Careful design and choice of materials can largely correct this problem, but it is difficult to eliminate it entirely, and it requires the use of very high-quality glass for the body of the lens. Mirrors do not suffer from this defect.
2. As light passes through the lens, some of it is absorbed by the glass. This absorption is a relatively minor problem for visible radiation, but it can be severe for infrared and ultraviolet observations because glass blocks most of the radiation in those regions of the electromagnetic spectrum. This problem obviously does not affect mirrors.

MA® SELF-GUIDED TUTORIAL
Chromatic Aberration



◀ **FIGURE 3.4 Reflectors and Refractors** Comparison of (a) reflecting and (b) refracting telescopes. Both types are used to gather and focus electromagnetic radiation. The image is viewed with a small magnifying lens called an *eyepiece*.

3. A large lens can be quite heavy. Because it can be supported only around its edge (so as not to block the incoming radiation), the lens tends to deform under its own weight. A mirror does not have this drawback because it can be supported over its entire back surface.
4. A lens has two surfaces that must be accurately machined and polished, which can be a difficult task. A mirror has only one surface.

For these reasons, *all* large modern optical telescopes are reflectors.

Types of Reflecting Telescopes

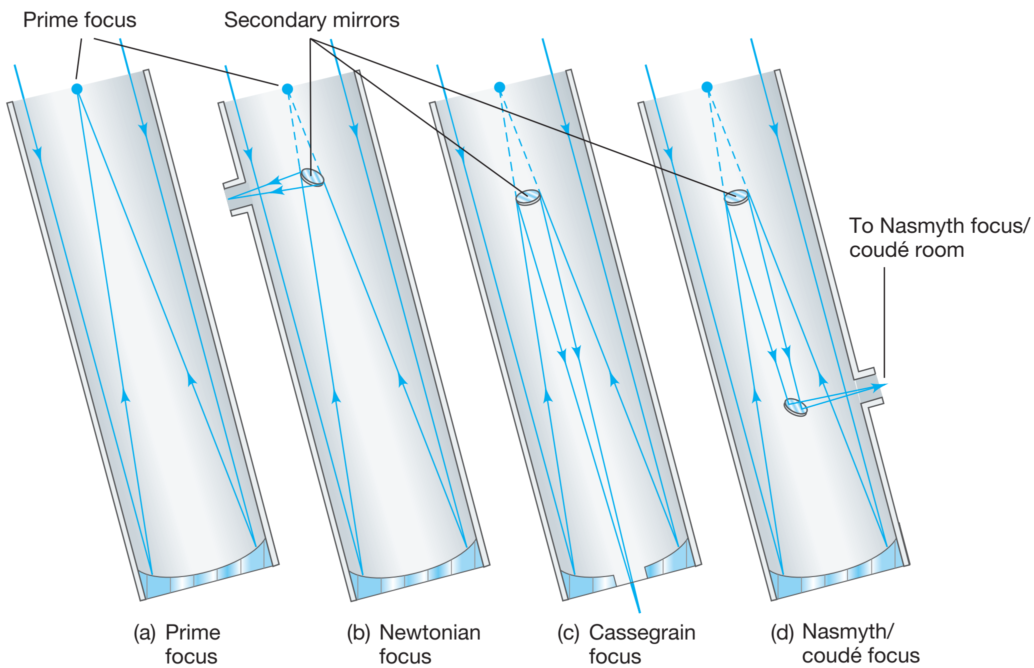
SELF-GUIDED TUTORIAL
Reflecting Telescopes

SELF-GUIDED TUTORIAL
The Optics of a Simple Lens

Figure 3.5 shows some basic reflecting telescope designs. Radiation from a star enters the instrument, passes down the main tube, strikes the primary mirror, and is reflected back toward the prime focus, near the top of the tube. Sometimes astronomers place their recording instruments at the prime focus. However, it can be very inconvenient, or even impossible, to suspend bulky pieces of equipment there. More often, the light is intercepted on its path to the focus by a secondary mirror and redirected to a more convenient location, as in Figure 3.5 (b–d).

In a **Newtonian telescope** (named after Isaac Newton, who invented this design), the light is intercepted by a flat secondary mirror before it reaches the prime focus and deflected 90°, usually to an eyepiece at the side of the instrument (Figure 3.5b). This is a popular design for smaller reflecting telescopes, such as those used by amateur astronomers.

Alternatively, astronomers may choose to work on a rear platform where they can use detecting equipment too heavy or delicate to hoist to the prime focus. In this case, the light reflected by the primary mirror toward the prime focus is intercepted by a convex secondary mirror, which reflects the light back down the tube and through a small hole at the center of the primary mirror (Figure 3.5c). This arrangement is known as a **Cassegrain telescope** (after Guillaume Cassegrain, a French lensmaker). The point behind the primary mirror where the light from the star finally converges is called the *Cassegrain focus*. A well-known example of a Cassegrain telescope is the *Hubble Space Telescope (HST; see Discovery 3-1)*, named for one of America's most notable astronomers, Edwin Hubble. The telescope's detectors all lie directly behind the primary mirror and are capable of making measurements in the optical, infrared, and ultraviolet parts of the spectrum.



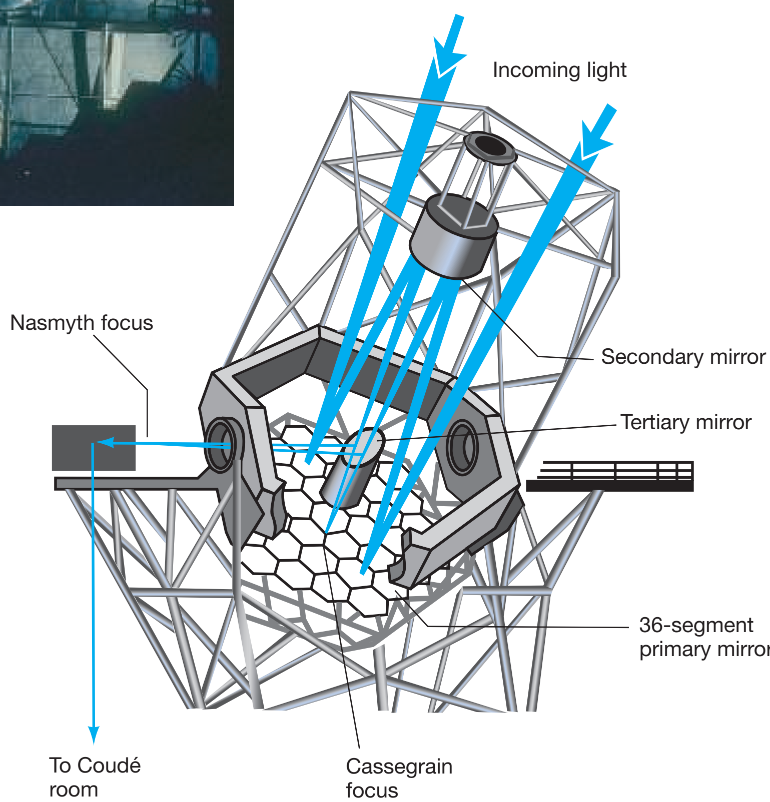
▸ FIGURE 3.5 **Reflecting Telescopes** Four reflecting telescope designs: (a) prime focus, (b) Newtonian focus, (c) Cassegrain focus, and (d) Nasmyth or coudé focus. Each design uses a primary mirror at the bottom of the telescope to capture radiation, which is then directed along different paths for analysis.

A more complex observational configuration requires starlight to be reflected by several mirrors. As in the Cassegrain design, light is first reflected by the primary mirror toward the prime focus and is then reflected back down the tube by a secondary mirror. Next, a third, much smaller, mirror reflects the light out of the telescope, where (depending on the details of the telescope's construction) the beam may be analyzed by a detector mounted alongside, at the *Nasmyth focus,* or it may be directed via a further series of mirrors into an environmentally controlled laboratory known as the *coudé* room (from the French word for "bent"). This laboratory is separate from the telescope itself, enabling astronomers to use very heavy and finely tuned equipment that cannot be placed at any of the other foci (all of which necessarily move with the telescope). The arrangement of mirrors is such that the light path to the coudé room does not change as the telescope tracks objects across the sky.

Figure 3.6 (a) shows the twin 10-m-diameter optical/infrared telescopes of the Keck Observatory on Mauna Kea in Hawaii, operated jointly by the California Institute of Technology and the University of California. The diagram in part (b) illustrates the light paths and some of the foci. Observations may be made at the Cassegrain, Nasmyth, or coudé focus, depending on the needs of the user. As the size of the person in part (c) indicates, this is indeed a very large telescope—in fact, the two mirrors are currently among the very largest on Earth. We will see numerous examples throughout this text of Keck's many important discoveries.

(c)

(a)



(b)

◀ **FIGURE 3.6 Keck Telescope** (a) The two 10-m telescopes of the Keck Observatory atop a dormant volcano in Hawaii, high above the surrounding clouds. (b) Artist's illustration of the telescope; the blue arrows show some of the paths starlight can take within the telescope and some of the locations where instruments may be placed. (c) One of the 10-m mirrors. Note the technician in orange coveralls at center. *(W. M. Keck Observatory)*

3.1 DISCOVERY

The Hubble Space Telescope

The *Hubble Space Telescope (HST)* is the largest, most complex, most sensitive observatory ever deployed in space. At more than $8 billion (including the cost of several missions to service and refurbish the system), it is also the most expensive scientific instrument ever built and operated. Built jointly by NASA and the European Space Agency, *HST* was designed to allow astronomers to probe the universe with at least 10 times finer resolution and with some 30 times greater sensitivity to light than existing Earth-based devices. The first figure shows the telescope being lifted out of the cargo bay of the space shuttle *Discovery* in the spring of 1990.

The accompanying "see-through" illustration displays *HST*'s main features. The telescope's Cassegrain design (Section 3.1) reflects light from its 2.4-m-diameter primary mirror (the large bluish disk at center) back to a smaller, 0.3-m secondary mirror, which sends the light through a small opening in the center of the primary mirror, from where it can be directed to any of several instruments (shown here in various colors at left) arrayed in the aft bay of the spacecraft. The large red objects are sensors that guide the pointing of the telescope, and the huge blue panels collect light from the Sun to power everything onboard. For scale, each of the instruments is about the size of a refrigerator. They were designed to be maintained by NASA astronauts, and indeed most of the telescope's original instruments have been upgraded or replaced since *HST* was launched. The current detectors on the telescope span the visible, near-infrared, and near-ultraviolet regions of the electromagnetic spectrum, from about 100 nm (UV) to 2200 nm (IR).

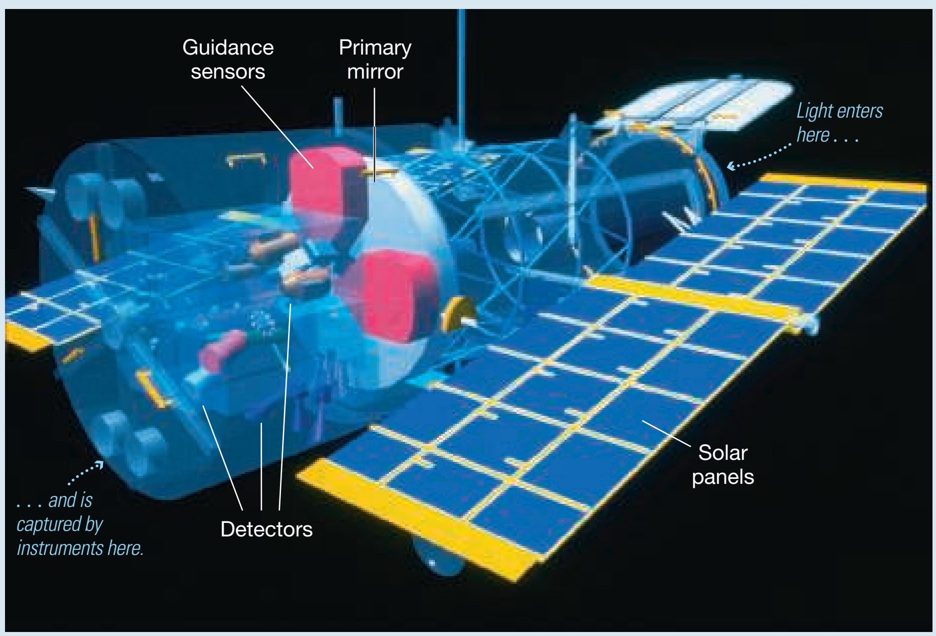
Soon after launch, astronomers discovered that the telescope's primary mirror had been polished to the wrong shape. The mirror is too flat by 2 μm, about 1/50 the width of a human hair, making it impossible to focus light as well as expected. In 1993, shuttle astronauts replaced *Hubble*'s gyroscopes to help the telescope point more accurately, installed sturdier versions of the solar panels that power the telescope's electronics, and—most important—inserted an intricate set of small mirrors to compensate for the faulty primary mirror. *Hubble*'s resolution is now close to the original design specifications, and the telescope has regained much of its lost sensitivity. Additional service missions were performed in 1997, 1999, 2002, and 2009 to replace instruments and repair faulty systems.

A good example of *Hubble*'s scientific capabilities can be seen by comparing the two images of the spiral galaxy M100, shown below.

(NASA)

ANIMATION/VIDEO MA
Hubble Space Telescope in Orbit

ANIMATION/VIDEO MA
Deployment of the *James Webb Space Telescope*



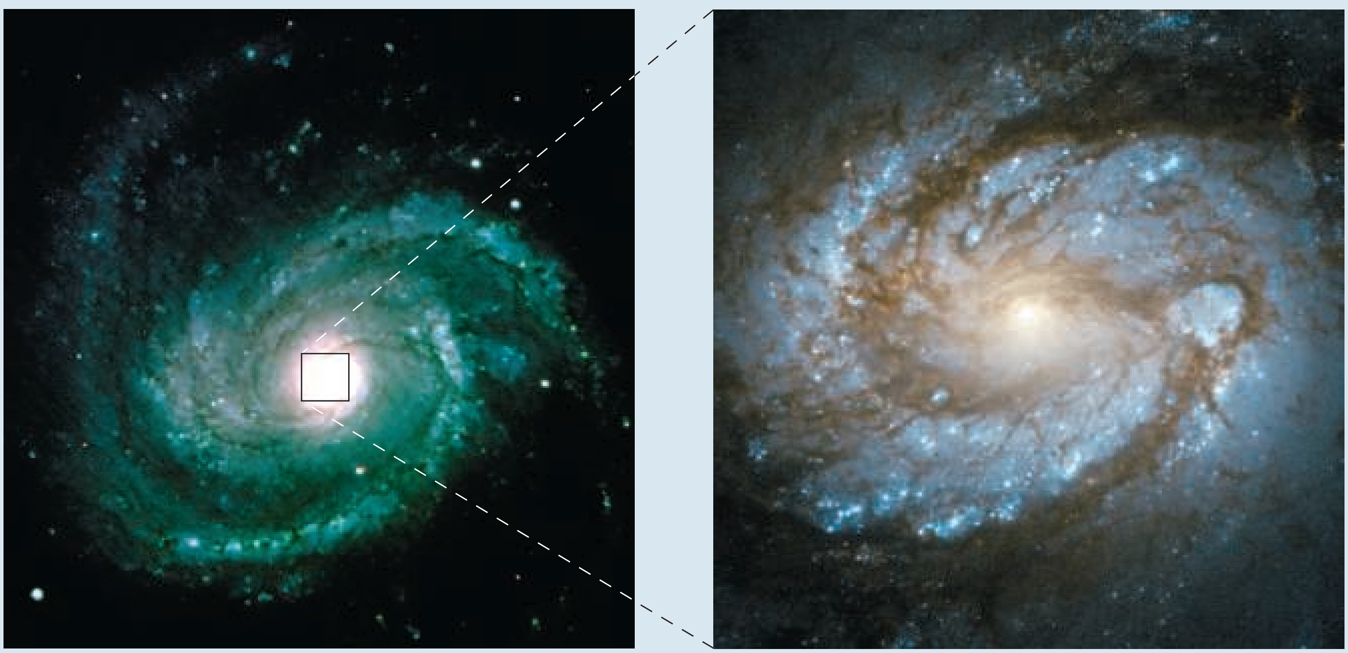
(D. Berry)

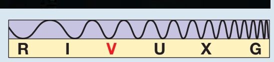
On the left is one of the best ground-based photographs of this beautiful galaxy at the time of launch, showing rich detail and color in its spiral arms. On the right is an exquisitely detailed *HST* image of the galaxy's core, showing great improvements in both resolution and sensitivity. However, its small coverage reminds us that the trade-off for *Hubble*'s highest resolution is a relatively limited field of view.

During its 25 years of operation, *Hubble* has revolutionized our view of the sky, helping to rewrite some theories of the universe along the way. By measuring the properties of stars and supernovae within distant galaxies, it has helped establish the size and the expansion rate of the cosmos and has provided insights into the past and future evolution of the universe. *Hubble* has studied newborn galaxies almost at the limit of the observable universe with unprecedented clarity, allowing astronomers to see the interactions and collisions that may have shaped the evolution of our own Milky Way. Turning its gaze to the hearts of galaxies closer to home, *Hubble* has provided strong evidence for supermassive black holes in their cores. Within our own Galaxy, it has given astronomers stunning new insights into the physics of star formation and the evolution of stellar systems and stars of all sizes, from superluminous giants to objects barely more massive than planets. Finally, in our solar system, *Hubble* has given scientists new views of both the planets and their moons, and of the tiny fragments from which they formed long ago. Many spectacular examples of the telescope's remarkable capabilities appear throughout this book.

With *Hubble* now well into its third decade of highly productive service, NASA's plans for the telescope's successor are well underway. The *James Webb Space Telescope* (*JWST*), named after the administrator who led NASA's *Apollo* program during the 1960s and 1970s, will dwarf *Hubble* in both scale and capability. Sporting a 6.5-m segmented mirror with seven times *Hubble*'s collecting area and containing a formidable array of detectors optimized for use at visible and infrared wavelengths, *JWST* will orbit the Sun some 1.5 million km outside Earth's orbit, far beyond the Moon. NASA plans to launch the telescope in 2018. Its primary mission is to study the formation of the first stars and galaxies, measure the large-scale structure of the universe, and investigate the evolution of planets, stars, and galaxies.

Note that the *JWST* launch schedule likely means an interruption of a few years in space-based astronomical observations at near-optical wavelengths. The 2009 servicing mission extended *Hubble*'s operating lifetime at least into 2015, but few astronomers expect that the telescope will survive until *JWST* becomes fully operational. *HST* was designed to be retrieved by a shuttle and one day returned to Earth for placement in a museum, but the termination of the shuttle program in 2011 now means a much less glamorous end for the mission. Once the satellite is declared nonfunctional, it will be most likely be taken out of orbit by a robot tug and simply dropped into the ocean.





(European Southern Observatory/VLT)

Detectors and Image Processing

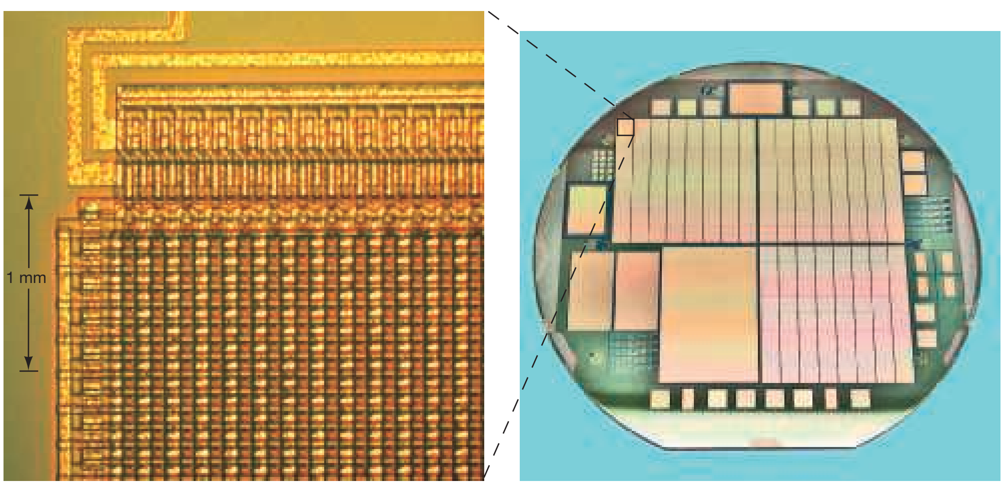
ANIMATION/VIDEO Gemini Control Room

ANIMATION/VIDEO Speckle Imaging

Most modern telescopes use electronic detectors known as **charge-coupled devices,** or **CCDs,** to record and store their data. A CCD (Figure 3.7) consists of a wafer of silicon divided into a two-dimensional grid of many tiny picture elements called *pixels*. When light strikes a pixel, an electric charge builds up on the device. The amount of charge is directly proportional to the number of photons striking each pixel—in other words, to the intensity of the light at that point. The charge buildup is monitored electronically, and a two-dimensional image is obtained (see Figures 3.7c and d). This is the same basic technology used in consumer video and digital cameras. A CCD is typically a few square centimeters in area and may contain several million pixels. As technology continually improves, both the areas of CCDs and the number of pixels they contain are steadily increasing.

CCDs have two important advantages over photographic plates, which were the staple of astronomers for over a century. First, CCDs are much more *efficient* than photographic plates, recording as many as 75 percent of the photons striking them, compared with less than 5 percent for photographic methods. This means that a CCD instrument can image objects 10 to 20 times fainter—or the same object 10 to 20 times faster—than can a photographic plate. Second, CCDs produce a faithful representation of an image in a digital format that can be manipulated by software, stored on disk, or sent across the Internet as needed.

Astronomers use computer processing on digital CCD images to compensate for known instrumental defects and even partly remove unwanted background noise in the signal, allowing them to see features in their data that would otherwise remain hidden. In addition, the computer can often carry out many of the tedious and time-consuming chores that must be performed before an image or spectrum reaches its final "clean" form. Figure 3.8 illustrates how computerized image-processing techniques were used to correct for known instrumental problems in the *Hubble Space Telescope,* allowing much of the planned resolution of the telescope to be recovered even before its repair in 1993.



(a) (b)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	3	3	3	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	3	5	6	5	3	1	0	0	0	0	0	0	0	0	0	0
0	0	0	1	3	6	7	6	3	1	0	0	0	0	0	0	0	0	0	0
0	0	0	1	3	5	6	5	3	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	3	3	3	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
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0	0	0	0	0	0	0	0	0	0	0	1	2	2	2	2	2	1	0	0
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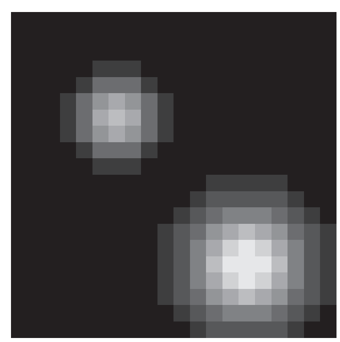
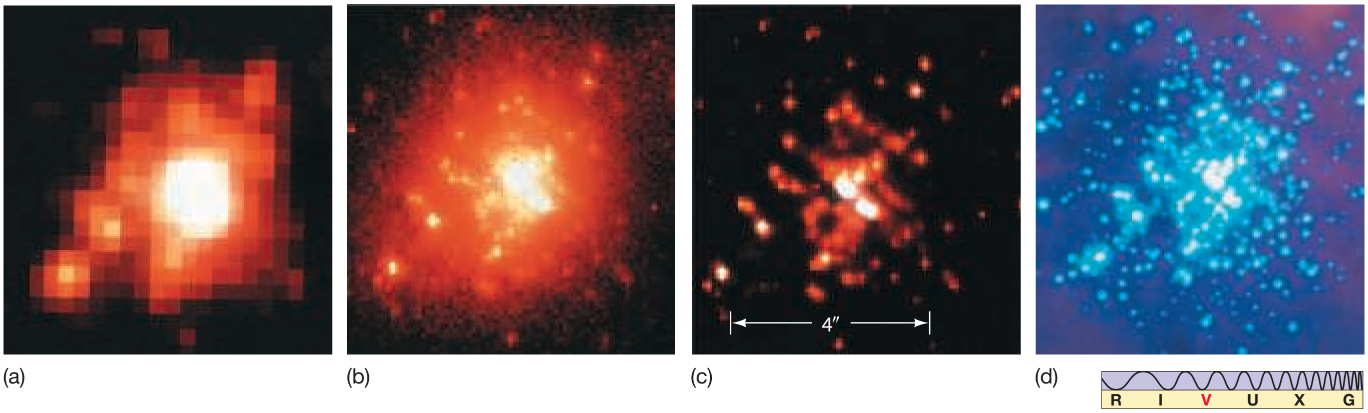
0	0	0	0	0	0	0	0	0	1	2	3	5	6	7	6	5	3	2	1
0	0	0	0	0	0	0	0	0	1	2	4	6	8	9	8	6	4	2	1
0	0	0	0	0	0	0	0	0	1	2	4	7	9	9	9	7	4	2	1
0	0	0	0	0	0	0	0	0	1	2	4	6	8	9	8	6	4	2	1
0	0	0	0	0	0	0	0	0	1	2	3	5	6	7	6	5	3	2	1
0	0	0	0	0	0	0	0	0	0	1	2	3	4	4	4	3	2	1	0
0	0	0	0	0	0	0	0	0	0	0	1	2	2	2	2	2	1	0	0

(c)



(d)

▲ **FIGURE 3.7 CCD Chip** A charge-coupled device (CCD) consists of millions of tiny light-sensitive cells called pixels. Light striking a pixel causes an electrical charge to build up on it. By electronically reading out the charge on each pixel, a computer can reconstruct the pattern of light—the image—falling on the chip. (a) Detail of a CCD array. (b) A CCD chip mounted for use at the focus of a telescope. (c) Typical data from the chip consist of an array of numbers, running from 0 to 9 in this simplified example. Each number represents the intensity of the radiation striking that particular pixel. (d) The resulting image. *(MIT Lincoln Lab; AURA)*



▲ **FIGURE 3.8** **Image processing** (a) Ground-based view of the star cluster R136, a group of stars in the Large Magellanic Cloud (a nearby galaxy). (b) The "raw" image of this same region as seen by the *Hubble Space Telescope* in 1990, before the first repair mission. (c) The same image after computer processing that partly compensated for imperfections in the mirror. (d) The same region as seen by the repaired *HST* in 1994, here observed at a somewhat bluer wavelength. *(AURA/NASA)*

3.2 Telescope Size

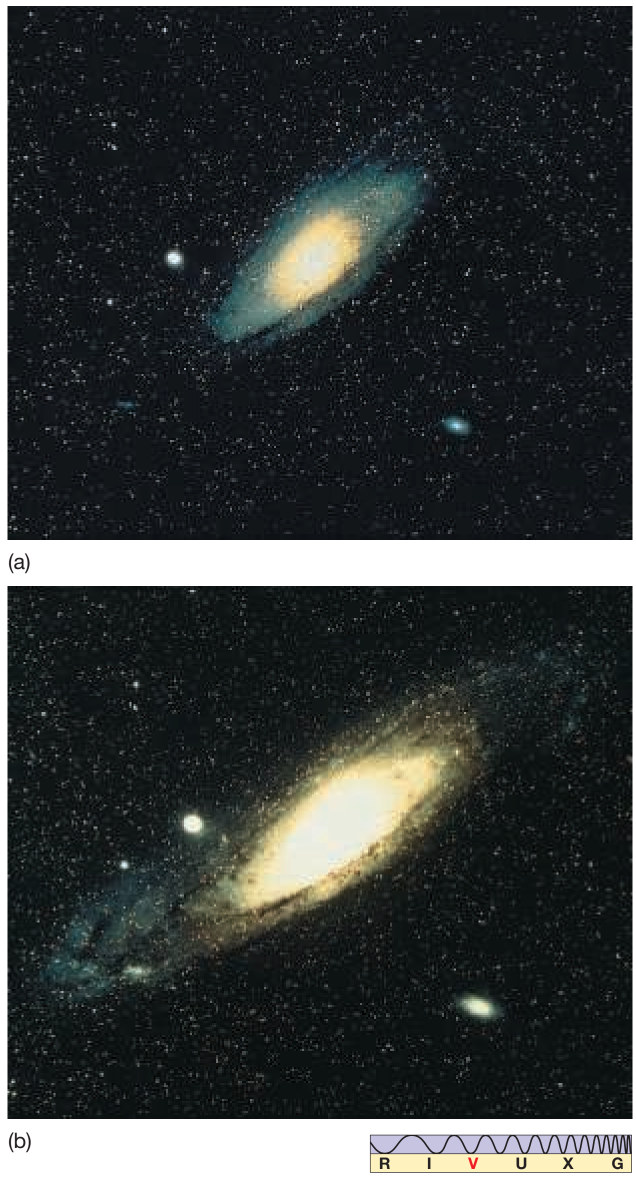
Large telescopes have two main advantages over small ones—*light-gathering power,* the ability to capture light, and *resolving power,* the ability to distinguish fine detail.

Light-Gathering Power

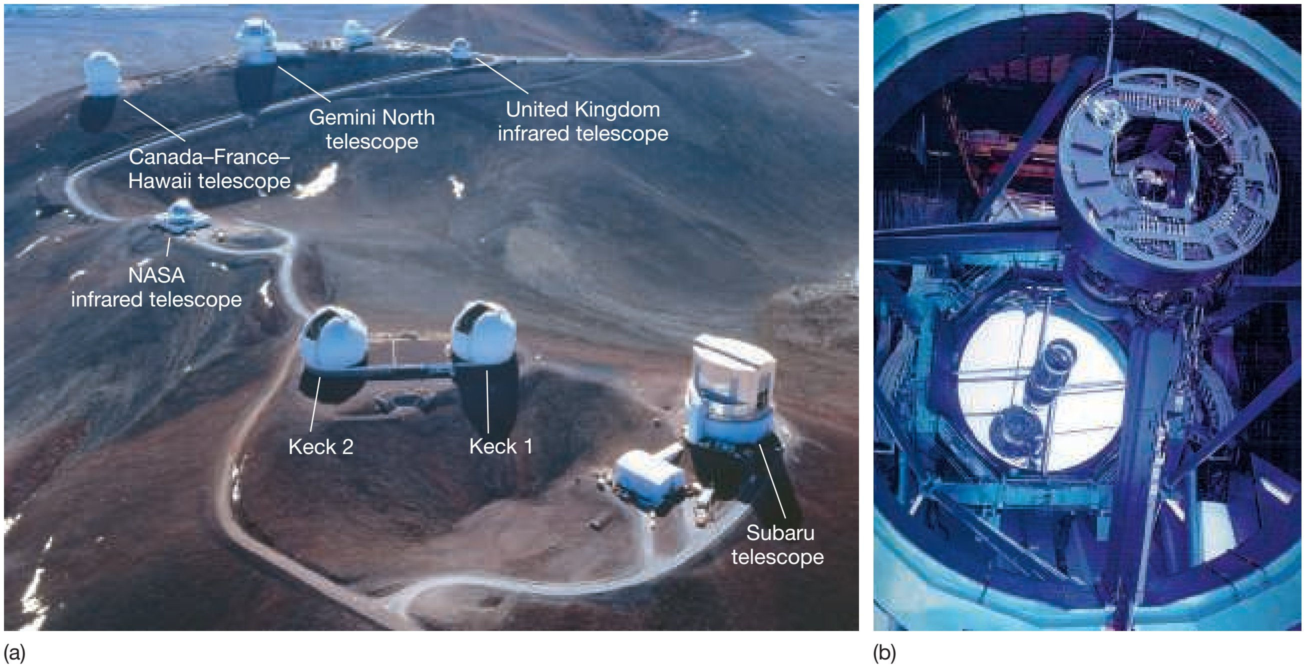
Astronomers spend much of their time observing very distant—and, hence, very *faint*—cosmic sources. In addition, they often want to obtain *spectra,* which entail spreading the incoming light out into its component colors. ∞ *(Sec. 2.5)* In order to make such detailed observations, astronomers must collect as much light as possible for analysis by their detectors.

The two factors determining a telescope's ability to collect light are *exposure time* and *collecting area.* **Exposure time** is simply the time spent gathering light from a source. Doubling the exposure time doubles the total amount of radiation captured. In Chapter 16 we will see an extreme example of a long-exposure image: constructed in 2003 from more than 300 hours of observations of the same small region of the sky, the so-called Hubble Ultra-Deep Field continues to provide astronomers with volumes of information on some of the most distant galaxies in the universe. However, such long exposures are rare. Access to telescopes and the sophisticated instruments attached to them is a precious commodity, and observatories are reluctant to allocate large amounts of time to a single observation.

The second factor controlling a telescope's light-gathering power is **collecting area,** the area capable of intercepting and focusing radiation—the "size of the bucket" (recall Figure 3.1). The larger the telescope's reflecting mirror (or refracting lens), the more light it collects and the easier it is to measure and study an object's radiative properties. The observed brightness of an astronomical object is directly proportional to the area of the telescope's mirror and, hence, to the *square* of the mirror diameter (Figure 3.9). For example, a 5-m telescope produces an image 25 times brighter than a 1-m instrument because a 5-m mirror



▶ **FIGURE 3.9** **Sensitivity** Telescope size affects the image of a cosmic source, in this case the Andromeda galaxy. Both of these photographs had the same exposure time, but image (b) was taken with a telescope twice the size of that used to make image (a). Fainter detail can be seen as the diameter of the telescope mirror increases because larger telescopes are able to collect more photons per unit time. *(Adapted from AURA)*



▸ **FIGURE 3.10 Mauna Kea Observatory** (a) The world's highest ground-based observatory, at Mauna Kea, Hawaii, sits atop a dormant volcano some 4 km above sea level. Among the domes visible here are those housing the Canada–France–Hawaii 3.6-m telescope, the 8.1-m Gemini North instrument, the 2.2-m telescope of the University of Hawaii, the UK's 3.8-m infrared facility, and the twin 10-m Keck telescopes. To the right of the Kecks is the Japanese 8.3-m Subaru telescope. (b) The Subaru mirror. *(R. Wainscoat; NAOJ)*

CONCEPT CHECK

Why do the largest modern telescopes use mirrors to gather and focus light?

has $5^2 = 25$ times the collecting area of a 1-m mirror. We can also think of this relationship in terms of the *time* required for a telescope to collect enough energy to create a recognizable image. A 5-m telescope produces an image 25 times faster than a 1-m device because it gathers energy at a rate 25 times greater. Put another way, a 1-hour time exposure with a 1-m telescope is roughly equivalent to a 2.4-minute (1/25 of an hour) time exposure with a 5-m instrument.

▸ **FIGURE 3.11 VLT Observatory** Located at the Paranal Observatory in Atacama, Chile, the European Southern Observatory's Very Large Telescope (VLT) is the world's largest optical telescope. Four 8.2-m reflecting telescopes are used in tandem to create the effective area of a single 16-m mirror. *(ESO)*

The twin Keck telescopes, shown in Figure 3.6 and in a larger view in Figure 3.10(a), are a case in point. Each telescope combines 36 hexagonal 1.8-m mirrors into the equivalent collecting area of a single 10-m reflector. The high altitude and large size of these telescopes makes them particularly well suited for detailed spectroscopic studies of very faint objects. To the right of the Keck domes in Figure 3.10(a) is the 8.3-m Subaru (the Japanese name for the Pleiades) telescope. Its mirror, shown in Figure 3.10 (b), is one of the largest single mirrors (as opposed to the segmented design used in Keck) yet built. In terms of total available collecting area, the largest telescope system now operating is the European Southern Observatory's Very Large Telescope (VLT), located at Cerro Paranal, in Chile (Figure 3.11). Its four separate 8.2-m mirrors can function as a single instrument of equivalent diameter 16.4 m. Both Keck and the VLT are designed to operate in the optical and near-infrared parts of the electromagnetic spectrum.

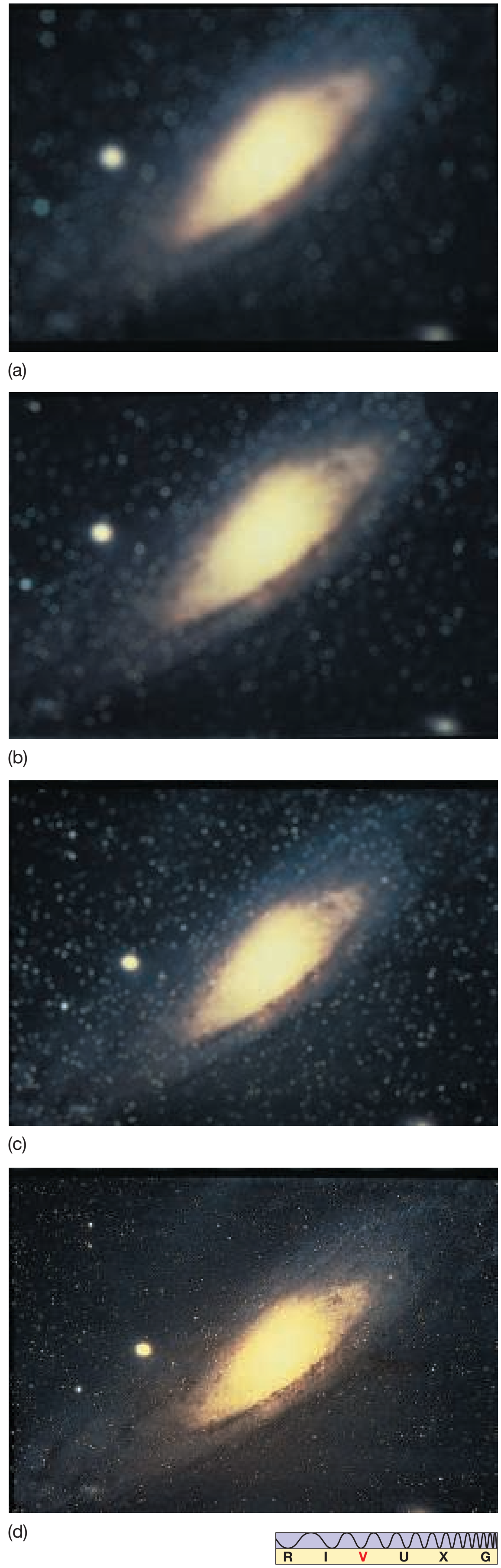
With 10-meter-class telescopes now almost routine, astronomers are turning their attention to the next generation of ground-based systems, the so-called *extremely large telescopes*, with mirrors tens of meters in diameter. All employ multimirror designs and real-time image enhancement technology; the first should come online early in the 2020s. The largest (so far) is the European Extremely Large Telescope, shown in the chapter-opening image on p. 70.

Resolving Power

The second advantage of large telescopes over smaller instruments is their superior **angular resolution.** In general, *resolution* refers to the ability of any device, such as a camera or a telescope, to form distinct, separate images of objects lying close together in the field of view. The finer the resolution, the better we can distinguish the objects and the more detail we can see. In astronomy, where we are always concerned with angular measurement, "close together" means "separated by a small angle on the sky," so angular resolution is the factor that determines our ability to see fine structure (see *More Precisely 0-1* for more detail on angular measure). Astronomers typically need to resolve objects only a few arc seconds (″) across. Figure 3.12 illustrates the result of increasing resolving power with views of the Andromeda galaxy at several different resolutions.

One important factor limiting a telescope's resolution is *diffraction,* the tendency of light—and all waves, for that matter—to "bend" around corners. ∞ *(Sec. 2.2)* Diffraction introduces a certain fuzziness, or loss of resolution, into the system. The degree of fuzziness—the minimum angular separation that can be distinguished—determines the angular resolution of the telescope.

As discussed in *More Precisely 3-1,* the amount of diffraction is directly proportional to the wavelength of the radiation and inversely proportional to the diameter of the telescope mirror. For light of any given wavelength, large telescopes produce less diffraction than small ones. The resolution given by the formula in *More Precisely 3-1* is known as the **diffraction-limited resolution** of the telescope. Thus, a 5-m telescope observing in blue light has a diffraction-limited resolution of about 0.02″. A 1-m telescope would have a diffraction limit of 0.1″ at the same wavelength, and so on. For comparison, the angular resolution of the human eye in the middle of the visual range is about 0.5′.



▶ **FIGURE 3.12 Resolution** Detail becomes clearer in the Andromeda galaxy as the angular resolution is improved some 600 times, from (a) 10′, to (b) 1′, (c) 5″, and (d) 1″. (*Adapted from AURA*)

3.1 MORE PRECISELY

Diffraction and Telescope Resolution

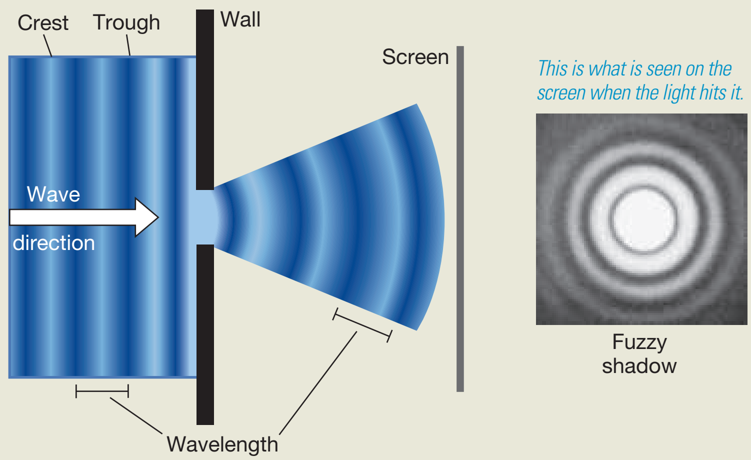
The resolution of a telescope is ultimately controlled by *diffraction*, the process where light spreads out as it passes a corner or through an opening. ∞ *(Sec. 2.2)* Because of diffraction, it is impossible to focus a parallel beam of light to a sharp point, even with a perfectly constructed mirror. As illustrated in the accompanying figure, a wave passing through a gap is diffracted, creating a "fuzzy" shadow on the screen at right. Light and dark gradations represent crests and troughs of the wave, which define the wavelength (see Figure 2.3). In the absence of any diffraction, the shadow would be perfectly sharp—but that never happens in reality.

The amount of diffraction—that is, the amount of "fuzziness" introduced into an instrument—depends both on the *wavelength* of the radiation and the *size* of the opening (in our case, the *diameter* of the primary mirror). For a circular mirror and otherwise perfect optics, the angular resolution of a telescope (in convenient units) is

$$\text{angular resolution (arc seconds)} = 0.25\,\frac{\text{wavelength } (\mu\text{m})}{\text{mirror diameter (m)}},$$

where 1 μm (micrometer) $= 10^{-6}$ m $=$ 1000 nm. (Recall that the symbol μ is the Greek letter mu.)

Thus, the best possible angular resolution that can be obtained using a 1-m telescope in blue light (with a wavelength of 400 nm $= 0.4\,\mu$m) is about $0.25\,(0.4/1)'' = 0.1''$. But if we were to use our 1-m telescope to make observations in the near infrared, at a wavelength of 10 μm (10,000 nm), the best resolution we could obtain would be only $0.25\,(10/1)'' = 2.5''$. Observations in the infrared or radio range are often limited by the effects of diffraction. A 1-m radio telescope operating at a wavelength of 1 cm would have an angular resolution of just under 1°.



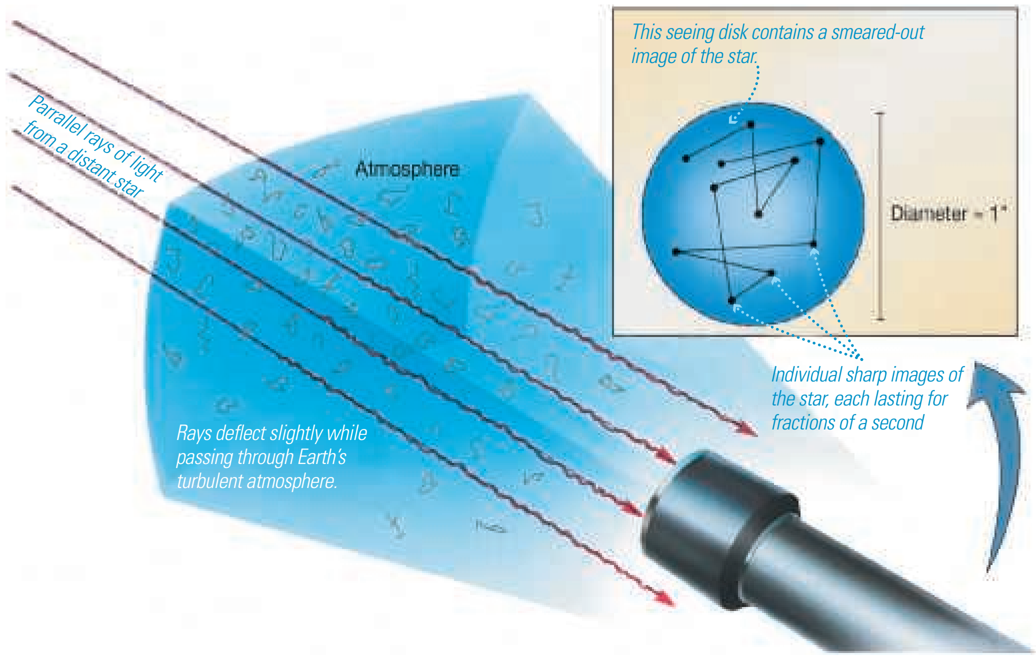
3.3 High-Resolution Astronomy

Even large telescopes have limitations. For example, according to the discussion in the preceding section, the 10-m Keck telescope should have an angular resolution of around 0.01″ in blue light. In practice, however, without the technological advances discussed in this section, it could not do better than about 1″. In fact, apart from instruments using special techniques developed to examine some particularly bright stars, *no* ground-based optical telescope built before 1990 can resolve astronomical objects to much better than 1″. The reason is *turbulence* in Earth's atmosphere—small-scale eddies of swirling air all along the line of sight, which blur the image of a star even before the light reaches our instruments.

Atmospheric Blurring

As we observe a star, atmospheric turbulence produces continuous small changes in the optical properties of the air between the star and our telescope (or eye). The light from the star is refracted slightly, again and again, and the stellar image dances around on the detector (or retina). This is the cause of the well-known twinkling of stars. The same basic process makes objects appear to shimmer when viewed across a hot roadway on a summer day because turbulent hot air just above the road surface constantly deflects and distorts the light rays reaching us.

On a typical night at a good observing site, the maximum deflection produced by the atmosphere is around 1″. Consider taking a photograph of a



◀ **FIGURE 3.13 Atmospheric Turbulence** Light rays from a distant star strike a telescope detector at slightly different locations because of turbulence in Earth's atmosphere. Over time, the light covers a roughly circular region on the detector, and even the point-like image of a star is recorded as a small disk, called the seeing disk.

star under such conditions. After a few minutes' exposure time (long enough for the intervening atmosphere to have undergone many small, random changes), the dancing sharp image of the star has been smeared out over a roughly circular region 1″ or so in diameter (Figure 3.13). Astronomers use the term **seeing** to describe the effects of atmospheric turbulence. The circle over which a star's light is spread is called the **seeing disk.** In this jargon, "good seeing" means that the air is relatively stable and the seeing disk is small—as little as a few tenths of an arc second across in some exceptional cases.

To achieve the best possible seeing, telescopes are sited on mountaintops (to get above as much of the atmosphere as possible) in locations where the atmosphere is known to be fairly stable and relatively free of dust, moisture, and light pollution from cities. In the continental United States, these sites tend to be in the desert Southwest. The U.S. National Observatory for optical astronomy in the Northern Hemisphere is located high on Kitt Peak near Tucson, Arizona. The site was chosen because of its many dry, clear nights, and typical seeing of around 1″. Even better conditions are found on Mauna Kea in Hawaii (Figure 3.10) and in the Andes Mountains of Chile (Figure 3.11), which is why so many large telescopes have recently been constructed at those two exceptionally clear sites.

A telescope placed above the atmosphere, in Earth orbit, can achieve resolution close to the diffraction limit, subject only to the engineering restrictions of building and placing large structures in space. The *Hubble Space Telescope* (*Discovery 3-1*) has a 2.4-m mirror and a diffraction limit of 0.05″ (in blue light).

CONCEPT CHECK

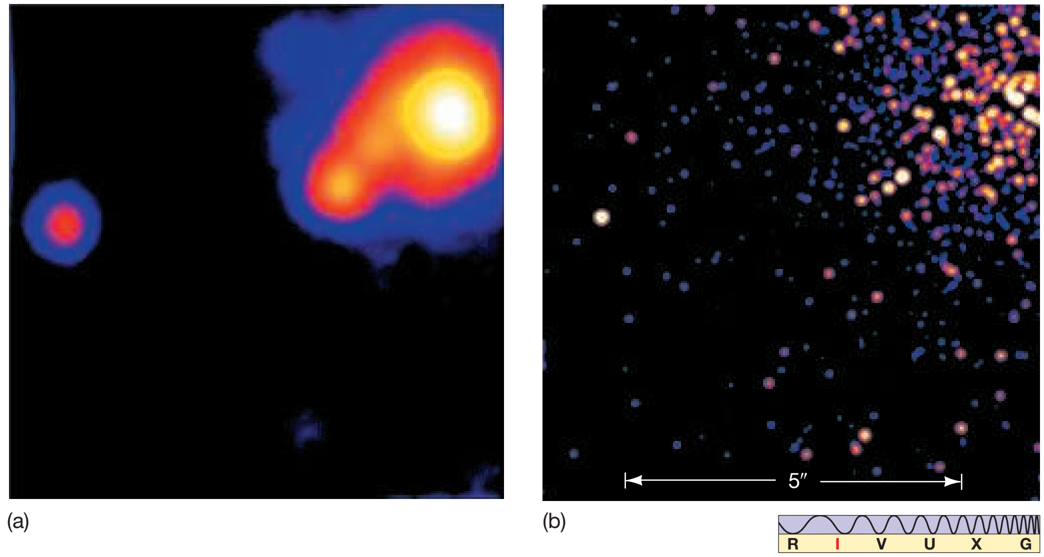
Give two reasons why astronomers need to build very large telescopes.

New Telescope Design

In addition to using high-quality optics and selecting the best observing sites, astronomers have developed other techniques to produce the sharpest possible images. By analyzing the image *while the light is still being collected,* it is possible to adjust the telescope from moment to moment to reduce the effects of mirror distortion, temperature changes, and bad seeing. By these means, an increasing number of large telescopes, including Keck and the VLT, can now achieve resolutions close to their theoretical diffraction limits.

MA ANIMATION/VIDEO Adaptive Optics

The collection of techniques aimed at controlling environmental and mechanical fluctuations in the properties of the telescope itself is known as



▸ **FIGURE 3.14 Active Optics** Infrared images of part of the star cluster R136 (see also Figure 3.8) contrast the resolution obtained (a) without and (b) with an active-optics system. *(ESO)*

active optics. Active optics systems often include improved dome design to control airflow, precise control of the mirror temperature, and the use of actuators (pistons) behind the mirror to maintain its precise shape at all times (Figure 3.14a). Figure 3.14 (b) illustrates dramatically how active optics can improve image resolution.

An even more ambitious approach is known as **adaptive optics.** This technique deforms the shape of a mirror's surface under computer control while the image is being exposed in order to undo the effects of atmospheric turbulence. In the system shown in Figure 3.15 (a), lasers probe the atmosphere above the telescope, returning information about the air's swirling motion to a computer that modifies the mirror thousands of times per second to compensate for poor seeing. Other adaptive optics systems monitor standard stars in the field of view, constantly adjusting the mirror's shape to preserve those stars' appearance. Figure 3.15 (b) presents an example of the improvement in image quality that can be obtained by these means.

Many of the world's largest telescopes now incorporate sophisticated adaptive optics systems, and resolutions as fine as a few hundredths of an arc second have been reported for observations in the near-infrared, significantly better than the resolution of the much smaller *HST* at the same wavelengths. Adaptive optics systems are giving astronomers the best of both worlds, achieving with large ground-based optical telescopes the kind of resolution once attainable only from space.

CONCEPT CHECK

Why is Earth's atmosphere a problem for optical astronomers? What can they do about it?

3.4 Radio Astronomy

In addition to the visible radiation that penetrates Earth's atmosphere on a clear day, radio radiation also reaches the ground, and astronomers have built many ground-based **radio telescopes** capable of detecting cosmic radio waves. ∞ *(Sec. 2.3)* These devices have all been constructed since the 1950s—radio astronomy is a much younger field than optical astronomy.

Essentials of Radio Telescopes

Figure 3.16 shows the world's largest steerable radio telescope, the large 105-m-diameter (340-foot-diameter) telescope located at the National Radio Astronomy Observatory in West Virginia. Conceptually, the operation of a radio telescope is the same as a prime-focus optical reflector (Figure 3.5a). It

(a)
(b)

◂ **FIGURE 3.15 Adaptive Optics** (a) In this test at the Lick Observatory's 3-m Shane telescope in California, a laser is used to create an "artificial star" to improve guiding. The laser beam probes the atmosphere above the telescope, allowing tiny computer-controlled changes to be made to the shape of the mirror surface thousands of times each second. (b) Clarity of view is very important in astronomy. The uncorrected, visible-light image (left) of the star cluster NGC 6934 is resolved to a little less than 1". With adaptive optics applied (right), the resolution in the infrared is improved to nearly 10 times better, and more stars are seen more clearly. *(L. Hatch/Lick Observatory; NOAO)*

has a large, horseshoe-shaped mount supporting a huge, curved metal dish that serves as the collecting area. The dish captures cosmic radio waves and reflects them to the focus, where a receiver detects the signals and channels them to a computer.

Radio telescopes are built large in part because cosmic radio sources are extremely faint. Many sources simply don't emit many radio photons (see for example Figure 2.11), the photons don't carry much energy, and the sources themselves are often very distant. *(Sec. 2.6)* In fact, the total amount of radio energy received by Earth's entire surface is less than a trillionth of a watt. Compare this with the roughly 10 *million* watts our planet's surface receives in the form of infrared and visible light from any of the bright stars visible in the night sky. In order to capture enough radio energy to allow detailed measurements to be made, a large collecting area is essential.

Because of diffraction, the angular resolution of radio telescopes is generally quite poor compared with that of their optical counterparts. Typical wavelengths of radio waves are about a million times longer than those of visible light, and

▲ **FIGURE 3.16 Radio Telescope** (a) The world's largest fully steerable radio telescope, the 105-m-diameter device at the National Radio Astronomy Observatory in Green Bank, West Virginia, is 150 m tall—taller than the Statue of Liberty and nearly as tall as the Washington Monument. (b) A schematic diagram shows the path taken by an incoming beam of radio radiation (colored blue). *(NRAO)*

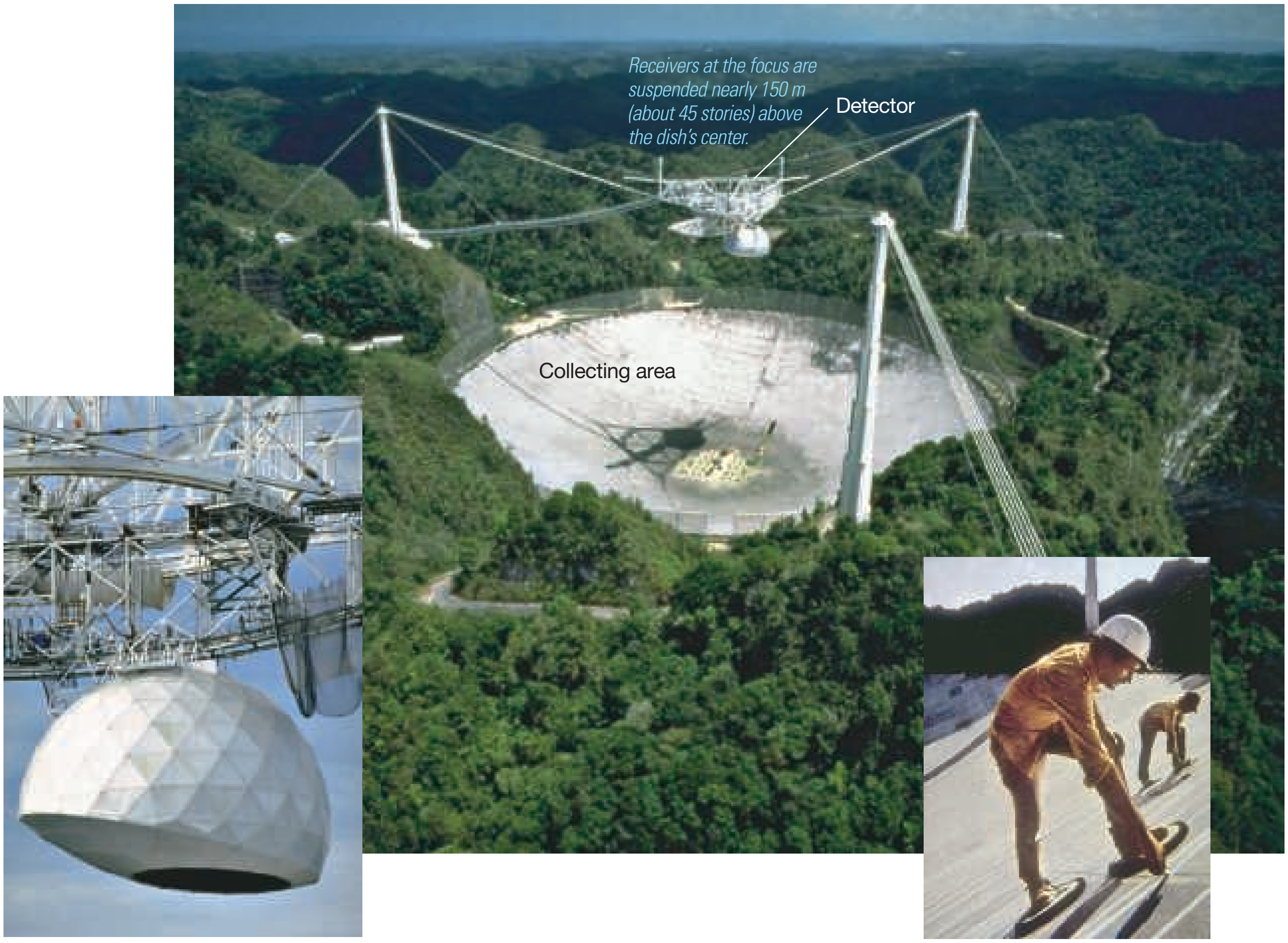
even the enormous sizes of radio dishes only partly offset this effect. The 105-m telescope shown in Figure 3.16 can achieve resolution of about 1′ at a wavelength of 3 cm, although the instrument was designed to be most sensitive to wavelengths around 1 cm, where the resolution is approximately 20′. The best angular resolution obtainable with a single radio telescope is about 10″ (for the largest instruments operating at millimeter wavelengths), about 100 times coarser than the capabilities of the best optical mirrors.

Figure 3.17 shows the world's largest radio telescope, built in 1963 in Arecibo, Puerto Rico. Approximately 300 m in diameter, the telescope's reflecting surface lies in a natural depression in a hillside and spans nearly 20 acres. The receiver is strung among several limestone hills. Its enormous collecting area makes this telescope the most sensitive on Earth. The huge but fixed dish creates one distinct disadvantage, however. The Arecibo telescope cannot be pointed to follow cosmic objects across the sky. Its observations are limited to those objects that happen to pass within about 20° of overhead as Earth rotates.

The Value of Radio Astronomy

Despite the inherent disadvantage of relatively poor angular resolution, radio astronomy enjoys some advantages too. Unlike visible light, radio waves are not deflected or scattered by Earth's atmosphere, and the Sun itself is a relatively weak source of radio energy. As a result, radio observations can cover almost the entire sky, 24 hours a day. Only within a few degrees of the Sun does solar radiation swamp radio observations of more distant objects. In addition, radio observations can often be made through cloudy skies, and radio telescopes can detect the longest-wavelength radio waves even during rain or snowstorms.

However, perhaps the greatest value of radio astronomy—and all invisible astronomies—is that it opens up a whole new window on the universe. There are



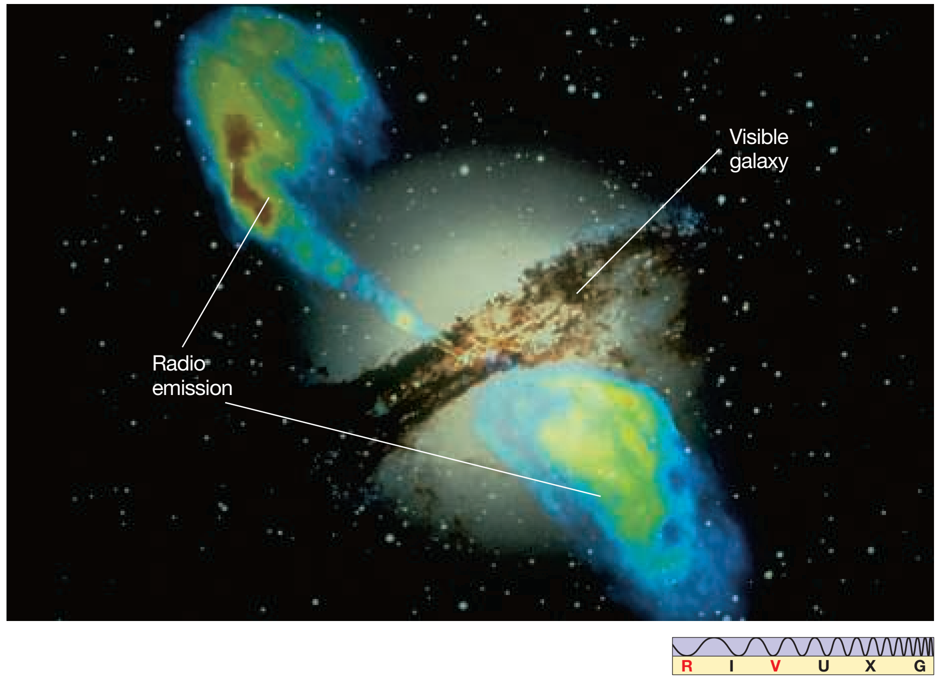
▲ **FIGURE 3.17 Arecibo Observatory** The 300-m-diameter dish at the National Astronomy and Ionospheric Center near Arecibo, Puerto Rico. The two insets show close-ups of the receivers hanging high above the dish (left) and technicians adjusting the dish surface to make it smoother (right). *(D. Parker/T. Acevedo/NAIC; Cornell University)*

two main reasons for this. First, just as objects that are bright in the visible part of the spectrum (the Sun, for example) are not necessarily strong radio emitters, many of the strongest radio sources in the universe emit little or no visible light. Second, visible light may be strongly absorbed by interstellar dust along the line of sight to a source. Radio waves, on the other hand, are generally unaffected by intervening matter. Many parts of the universe cannot be seen at all by optical means but are easily detectable at radio wavelengths. Radio observations therefore allow us to see whole new classes of objects that would otherwise be completely unknown.

Figure 3.18 shows a visible-light photograph of a distant galaxy called Centaurus A. Superimposed on the optical image is a radio map of the same region. The radio image is represented in **false color,** a technique commonly used for displaying images taken in nonvisible light. The colors do not represent the actual wavelength of the radiation emitted, but instead some other property of the source, in this case intensity, descending from red to yellow, green, and blue. Notice just how different the galaxy looks at radio and optical wavelengths. The visible galaxy emits little or no radio energy, while the large blobs (called *radio lobes,* and thought to have been ejected from the center of the galaxy by explosive events long ago) are completely invisible. Centaurus A is an example of a *radio galaxy* (to be studied in more detail in Chapter 15). It actually emits far more energy in the form of radio waves than it does as visible light, but without radio astronomy we would be entirely ignorant of this fact, and of the galaxy's violent past.

CONCEPT CHECK

Cosmic radio waves are very weak, and the resolution of radio telescopes is often poor, so what can astronomers hope to learn from radio astronomy?



▶ **FIGURE 3.18 Radio Galaxy** This is a composite image of the Centaurus galaxy, showing its optical view at center and its radio emission in lobes well beyond (here shown in false color, with red indicating greatest radio intensity, blue the least). *(J. Burns)*

(a)

(b)

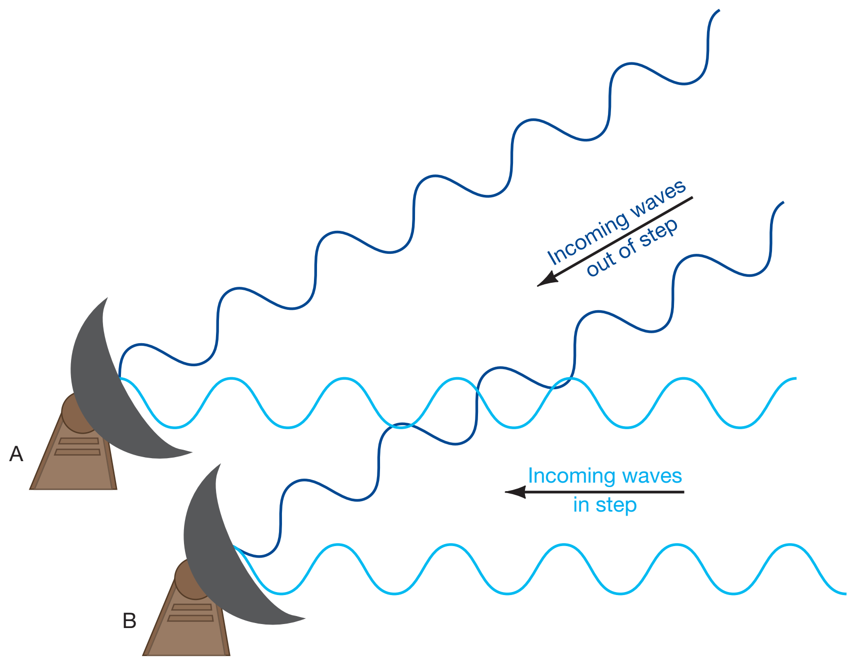
◀ **FIGURE 3.19 VLA interferometer** (a) This large interferometer, called the Very Large Array, or VLA for short, is located on the plain of San Augustin in New Mexico. It comprises 27 dishes spread along a Y-shaped pattern about 30 km across. (b) The dishes are mounted on railroad tracks so that they can be repositioned easily. (Another powerful interferometer is shown in the Chapter Opener photo on page 70.) (*NRAO*)

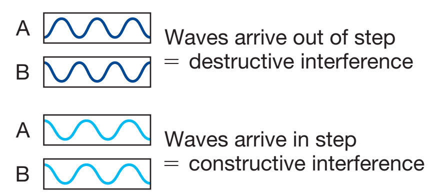
Interferometry

Radio astronomers can sometimes improve angular resolution by using a technique known as **interferometry,** making it possible to produce radio images of much higher angular resolution than can be achieved with even the best optical telescopes, on Earth or in space. In interferometry, two or more radio telescopes are used in tandem to observe the same object at the same wavelength and at the same time. The combined instruments together make up an **interferometer** (Figure 3.19). By means of electronic cables or radio links, the signals received by each antenna in the array making up the interferometer are sent to a central computer that combines and stores the data as the antennas track their target.

Interferometry works by analyzing how the signals *interfere* with each other when added together. ∞ *(Sec. 2.2)* Consider an incoming wave striking two detectors (Figure 3.20). Because the detectors lie at different distances from the source, the signals they record will, in general, be out of step with one another and, when combined, will interfere destructively, partly canceling each other out. Notice that the amount of interference depends on the *direction* in which the wave is traveling relative to the line joining the detectors. As Earth rotates and the antennae track their target, careful computer analysis of the combined signal results in a detailed image of the distant object.

Figure 3.21 shows the most powerful interferometer yet constructed. The Atacama Large Millimeter Array (ALMA) is the largest astronomical instrument

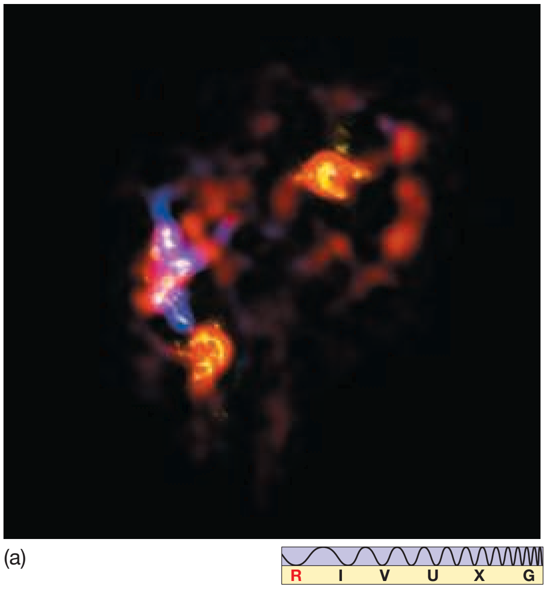


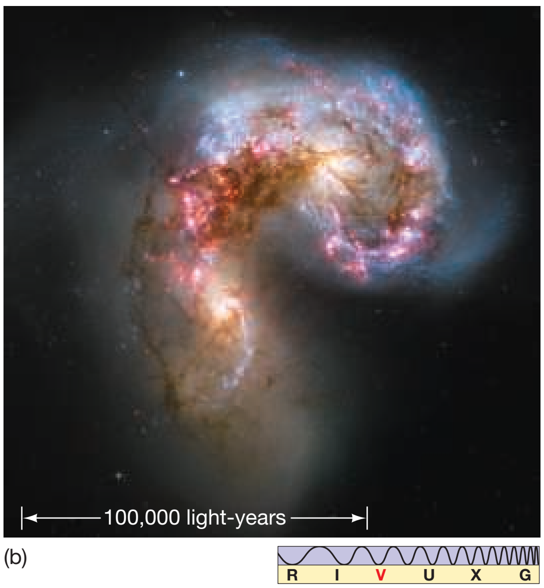


◀ **FIGURE 3.20 Interferometry** Two telescopes, A and B, record different signals from the same incoming wave because of the time it takes the radiation to traverse the distance between them. When the signals are combined, the amount of interference depends on the wave's direction of motion, providing a means of measuring the position of the source in the sky. Here, the dark blue waves come from a source high in the sky and are out of phase, thus causing destructive interference. But when the same source has moved because of Earth's rotation (light-blue waves), the interference can be constructive.

on Earth, sited at an altitude of about 5000 m in the Atacama Desert in northern Chile. Completed in 2014, the system's 66 antennas, most of them 12 m in diameter, operate at millimeter wavelengths, between 0.3 and 10 mm. ALMA is expected to be a telescopic workhorse for the next generation of astronomers, opening a whole new window on the universe and capturing never-before-seen details about the stars, galaxies, and planetary systems beyond our own solar system.

◀ **FIGURE 3.21 The ALMA Array.** Built by an international consortium of astronomers and engineers from the United States, Canada, Europe, East Asia, and Chile, and completed in 2014, the ALMA interferometer scans the universe at millimeter wavelengths from one of the remotest and driest places on our planet, without clouds, radio interference, or light pollution. This single most powerful telescope ever built is designed to probe one of astronomy's last observational frontiers. The inset shows the instrument's control room, where one of the fastest supercomputers on the planet is used to analyze the incoming data and reconstruct images of the field of view. *(ESO/NAOJ/NRAO; STScI)*





◀ **FIGURE 3.22 Radio—Optical Comparison** (a) This ALMA image of the colliding Antennae galaxies was made using just 12 of the system's antennae operating close together and has an angular resolution of a few arc seconds. The full ALMA system is capable of resolution some 10 times higher than shown here. (b) A visible-light photograph of that same galaxy, made with the HST and displayed on the same scale as (a). *(ESO NAOJ/ NRAO; STScI)*

As far as resolving power is concerned, the effective diameter of an interferometer is the distance between its outermost dishes. In other words, two small dishes can act as opposite ends of an imaginary but huge single radio telescope, dramatically improving the angular resolution. Large interferometers made up of many dishes, like the Very Large Array (VLA) shown in Figure 3.19, can attain radio resolution of a few arc seconds, comparable to that of many ground-based optical instruments (without adaptive optics). ALMA's best resolution is about 0.1″, similar to that of *HST* or VLT. Figure 3.22 compares an ALMA radio map of a nearby galaxy with a photograph of that same galaxy made using a large optical telescope. (The radio image in Figure 3.18 was also obtained by interferometric means.) The larger the distance (or *baseline*) separating the telescopes, the better the resolution attainable. Very-long-baseline interferometry (VLBI), using instruments separated by thousands of kilometers, can achieve resolution in the milliarcsecond (0.001″) range.

Although the technique was originally developed by radio astronomers, interferometry is no longer restricted to the long-wavelength domain. Radio interferometry became feasible when electronic equipment and computers achieved speeds great enough to combine and analyze radio signals from separate radio detectors without loss of data. As the technology has improved, it has become possible to apply the same methods to higher-frequency radiation. Even before ALMA, millimeter-wavelength interferometry had already become an established and important observational technique. Both the Keck and VLT telescopes are now used for both infrared and optical interferometric work.

3.5 Space-Based Astronomy

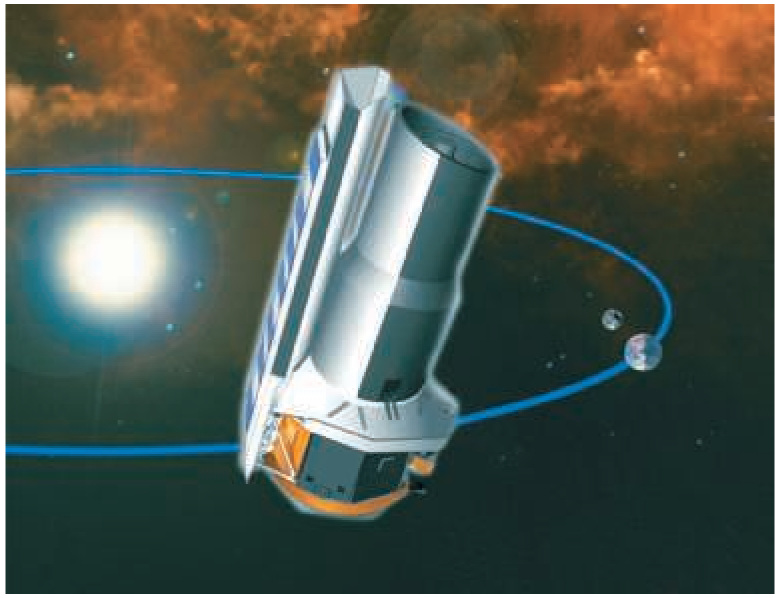
As we saw in Chapter 2, Earth's atmosphere is opaque to electromagnetic radiation outside of the radio, infrared, and optical windows. ∞ *(Sec. 2.3)* Most other wavelengths can only be studied from space. The rise of these "other astronomies" has therefore been closely tied to the development of the space program.

Infrared and Ultraviolet Astronomy

Infrared studies are a very important component of modern observational astronomy. Much of the gas between the stars has a temperature between a few tens and a few hundreds of kelvins, and Wien's law tells us that the infrared domain is the natural portion of the electromagnetic spectrum in which to study this material. ∞ *(Sec. 2.4)* Generally, **infrared telescopes** resemble optical telescopes, but the infrared detectors are sensitive to longer-wavelength radiation. Although most infrared radiation is absorbed by the atmosphere (primarily by water vapor), there are a few windows in the high-frequency part of the infrared spectrum where the opacity is low enough to permit ground-based observations. ∞ *(Fig. 2.9)* As we have seen, some of the most useful infrared observing is done from the ground using large telescopes equipped with adaptive optics systems.

For most infrared observations, astronomers must place their instruments above most or all of Earth's atmosphere. Improvements in balloon-, aircraft-,

(a)


(b)

◀ **FIGURE 3.23 Infrared Telescopes** (a) A gondola containing a 1-m infrared telescope is readied for its balloon-borne ascent to an altitude of about 30 km, where it will capture infrared radiation that cannot penetrate Earth's atmosphere. (b) This artist's conception shows the *Spitzer Space Telescope* orbiting in an Earth-trailing orbit around the Sun while surveying the infrared sky at wavelengths ranging from 3 to 200 μm. Note the large baffle at left protecting the telescope from the Sun's heat. *(SAO; JPL)*

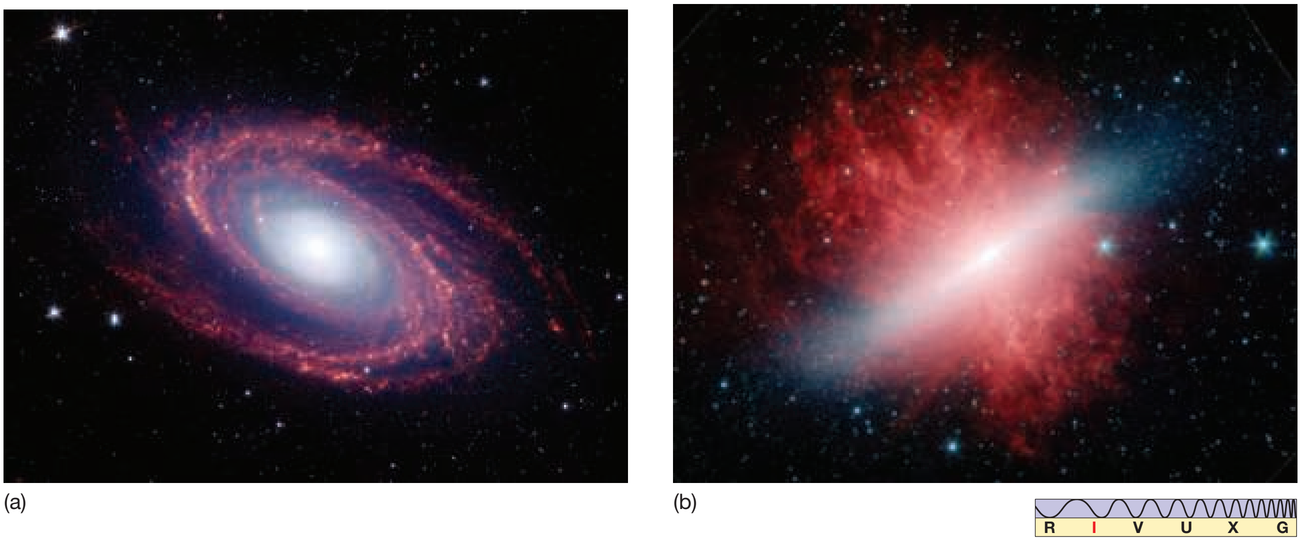
rocket-, and satellite-based telescope technologies have made infrared research a powerful tool for studying the universe (Figure 3.23). As might be expected, the infrared telescopes that can be carried above the atmosphere are considerably smaller than the massive instruments found in ground-based observatories. Nevertheless, their infrared view penetrates the clouds of dust and gas surrounding many cosmic objects, allowing astronomers to study regions of space that are completely obscured at visible wavelengths and revolutionizing our understanding of the universe. Figure 3.24 shows some terrestrial and astronomical examples of advantages gained by viewing the infrared part of the spectrum.

In 2003, NASA launched the 0.85-m *Spitzer Space Telescope (SST,* shown in Figure 3.23b), named in honor of Lyman Spitzer, Jr., a renowned astrophysicist and the first person to propose (in 1946) that a large telescope be located in space. The facility's detectors are designed to operate at wavelengths between 3.6 and 160 μm. Unlike previous space-based observatories, *SST* does not orbit Earth, but instead follows our planet in its orbit around the Sun, trailing millions of kilometers behind to minimize Earth's heating effect on its detectors. The spacecraft is currently drifting away from Earth at the rate of 0.1 AU per year. The detectors were cooled to near absolute zero in order to observe infrared signals from space without interference from the telescope's own heat. Figure 3.25 shows some examples of the spectacular imagery obtained from NASA's latest eye on the universe; many more of its images are seen throughout this book.

▶ **FIGURE 3.24 Infrared Images** (a) An optical photograph taken near San Jose, California, and (b) an infrared photo of the same area taken at the same time. Infrared radiation can penetrate smog much better than short-wavelength visible light. The same advantage pertains to astronomical observations (c). An optical view of an especially dusty part of the central region of the Orion Nebula is more clearly revealed (d) in this infrared image showing a cluster of stars behind the obscuring dust. *(Lick Observatory; NASA)*

Unfortunately, the liquid helium keeping *SST*'s detectors cool could not be confined indefinitely, and it slowly leaked away into space. In early 2009, *Spitzer* entered a new "warm" phase of operation as its temperature increased to roughly 30K—still very cool by Earth standards, but warm enough for the telescope's own thermal emission to overwhelm the long-wavelength detectors on board. (Recall how Wien's law tells us that the thermal emission of a 30-K object peaks at a wavelength of roughly 100 μm.) ∞ ***(Sec. 2.4)*** However, the craft's shorter-wavelength detectors (at around 3.6 and 4.5 μm) are still operational and will continue to be an important astronomical resource until the telescope drifts out of range of Earth controllers.

To the short-wavelength, higher-energy side of the visible spectrum lies the ultraviolet domain. This region of the spectrum, extending in wavelength from 400 nm (blue light) down to a few nanometers (the soft, or low-energy, end of the X-ray region), has only recently begun to be explored. Because Earth's atmosphere is partially opaque to radiation below 400 nm and is totally opaque to radiation below about 300 nm, astronomers cannot conduct any useful ultraviolet observations from the ground, not even from the highest mountaintop. Rockets, balloons, or satellites are therefore essential to any **ultraviolet telescope**—a device designed to capture and analyze this high-frequency radiation.

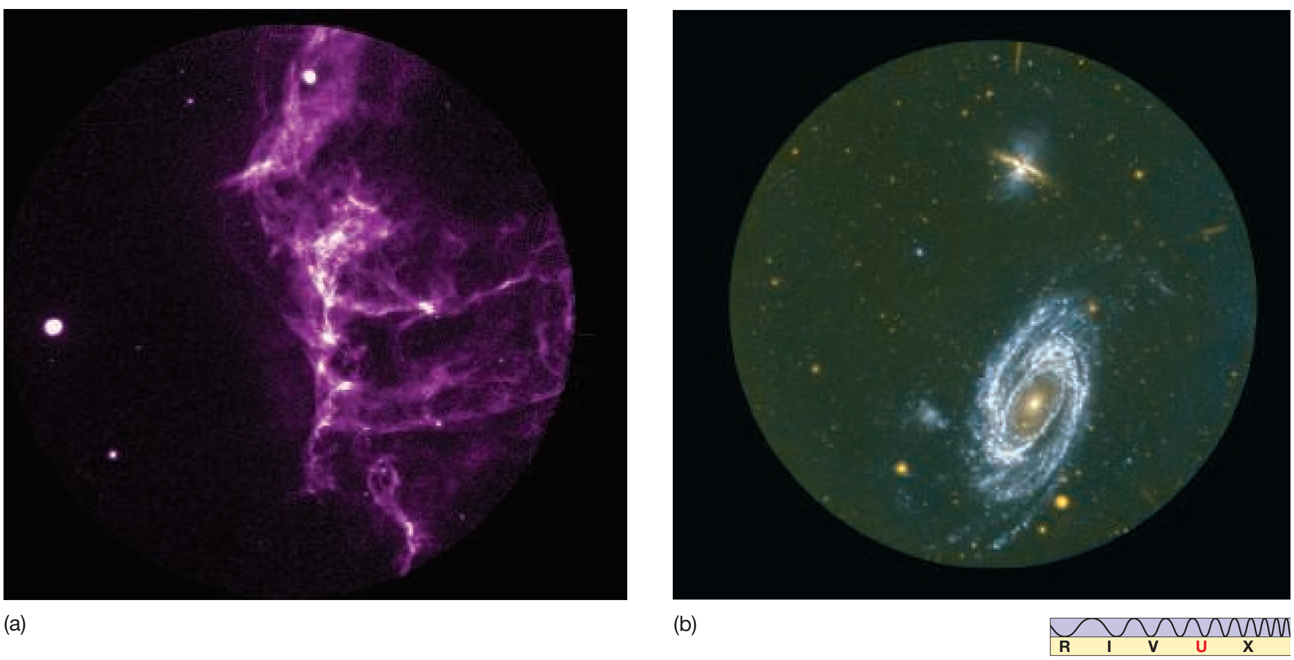


▲ **FIGURE 3.25 Spitzer Images** Images from the *Spitzer Space Telescope* show its superb capabilities. (a) The magnificent spiral galaxy M81 is about 12 million light-years away. (b) Its companion, M82, is not so serene, rather resembling a smoking hot cigar. *(JPL)*

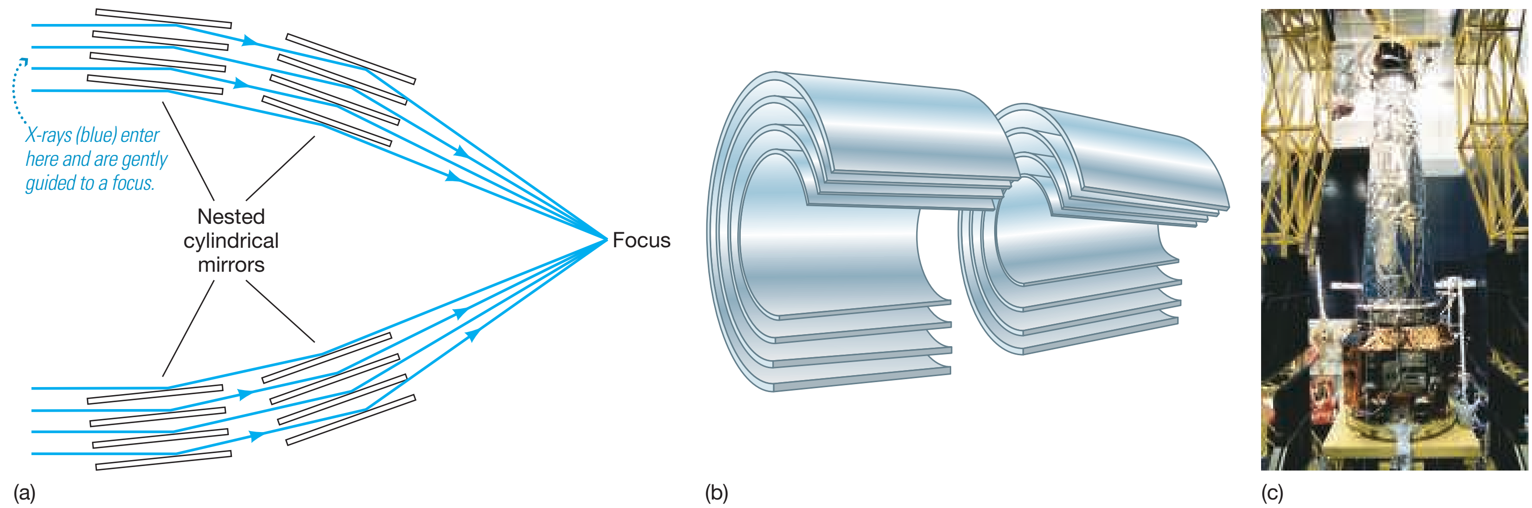
Figure 3.26 (a) shows an image of a supernova remnant—the remains of a violent stellar explosion that occurred some 12,000 years ago (see Chapter 12)—obtained by the *Extreme Ultraviolet Explorer (EUVE)* satellite, launched in 1992. Since its launch, *EUVE* has mapped out our local cosmic neighborhood as it presents itself in the far ultraviolet and has radically changed astronomers' conception of interstellar space in the vicinity of the Sun. The *Hubble Space Telescope,* best known as an optical telescope, is also a superb ultraviolet instrument, as is the *Galaxy Evolution Explorer (GALEX)* satellite, launched in 2003, one of whose images is seen in Figure 3.26 (b).

PROCESS OF SCIENCE CHECK

Describe some of the kinds of observations that astronomers make across the entire electromagnetic spectrum. Why are such observations necessary?



▲ **FIGURE 3.26 Ultraviolet Images** (a) A camera on board the *Extreme Ultraviolet Explorer* satellite captured this image of the Cygnus Loop supernova remnant, the result of a massive star having exploded. The glowing field of debris lies some 1500 light-years from Earth. Based on the velocity of the outflowing debris, astronomers estimate that the explosion occurred about 12,000 years ago. (b) This false-color image of the galaxies M81 and M82 (the same ones as in Figure 3.25), made here by the *Galaxy Evolution Explorer* satellite, reveals stars forming in the blue arms well away from the galaxy's center. *(NASA/GALEX)*



▲ **FIGURE 3.27 X-Ray Telescope** (a) The arrangement of nested mirrors in an X-ray telescope allows the rays to be reflected at grazing angles and focused to form an image. (b) A cutaway 3D rendition of the mirrors, showing their shape more clearly. (c) The *Chandra* X-ray telescope, shown here during the final stages of its construction, has an effective angular resolution of 1″, allowing it to produce images of quality comparable to those of optical photographs. *(NASA)*

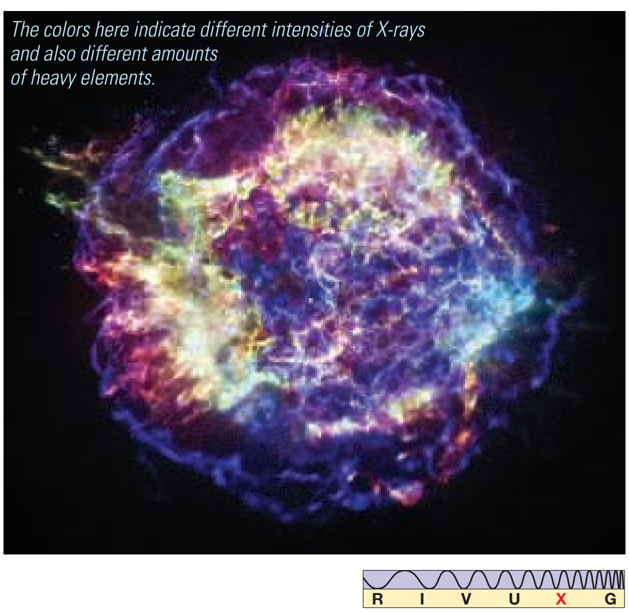
High-Energy Astronomy

ANIMATION/VIDEO MA
Chandra Light and Data Paths

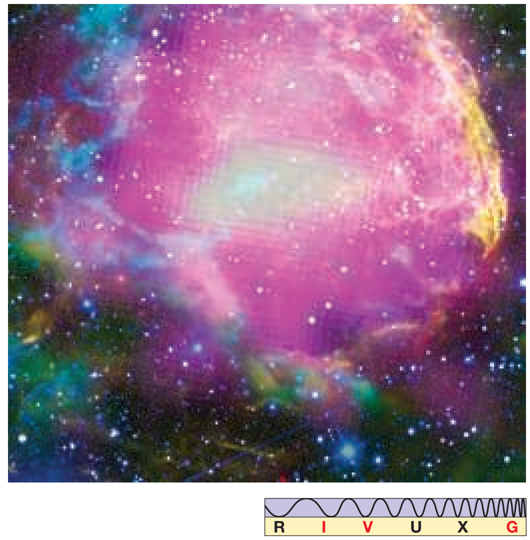
High-energy astronomy studies the universe as it presents itself to us in X-rays and gamma rays—the types of radiation whose photons have the highest frequencies and, hence, the greatest energies. How do we detect radiation of such short wavelengths? First, it must be captured high above Earth's atmosphere because none of it reaches the ground. Second, its detection requires the use of equipment basically different from that used to capture the relatively low-energy radiation discussed up to this point.

The difference in the design of **high-energy telescopes** comes about because X-rays and gamma rays cannot be reflected easily by any kind of surface. Rather, these rays tend to either pass straight through or else be absorbed by any material they strike. When X-rays barely graze a surface, however, they can be reflected from it in a way that yields an image, although the mirror design is fairly complex (Figure 3.27). High-quality data from imaging X-ray telescopes have driven major advances in our understanding of high-energy phenomena throughout the universe.

In 1999, NASA launched the *Chandra X-Ray Observatory* (named in honor of the Indian astrophysicist Subramanyan Chandrasekhar and shown in Figure 3.27c). With greater sensitivity, a wider field of view, and better resolution than any previous X-ray telescope, *Chandra* is providing high-energy astronomers with new levels of observational detail. Figure 3.28 shows the first image returned by *Chandra*—a supernova remnant known as Cas A, all that now remains of a star in the constellation Cassiopeia that was observed to explode about 320 years ago. The false-color image shows 50 million-kelvin gas in the wisps of ejected stellar material; the bright white point at the very center of the debris may be a black hole.



◄ **FIGURE 3.28 X-Ray Image** A false-color *Chandra* X-ray image of the supernova remnant Cassiopeia A, a debris field of scattered, hot gases that were once part of a massive star. Roughly 10,000 light-years from Earth and barely visible in the optical part of the spectrum, Cas A is awash in brilliantly glowing X-rays spread across some 10 light-years. *(CXC/SAO)*



▶ **FIGURE 3.29 Gamma-Ray Image** A false-color gamma-ray image from the *Fermi* telescope, showing the remains of a violent event (a supernova) in a region named IC443. The gamma rays are shown mainly in magenta and are superimposed on infrared (blue/green) and optical (yellow) images of the region. *(NASA)*

The European *X-Ray Multi-Mirror* satellite (now known as *XMM-Newton*) was launched in 1999. *XMM-Newton* is more sensitive than *Chandra* (that is, it can detect fainter X-ray sources), but it has significantly poorer angular resolution (5′, compared with 0.5″ for *Chandra*), making the two missions complementary to one another.

Gamma-ray astronomy is the youngest entrant into the observational arena. For gamma rays, no method of producing a true image (in the sense of Section 3.1) has yet been devised—present-day gamma-ray telescopes simply point in a specified direction and count photons received. As a result, only fairly coarse (1° resolution) observations can be made. Nevertheless, even at this resolution, there is much to be learned. Cosmic gamma rays were originally detected in the 1960s by the U.S. *Vela* series of satellites, whose primary mission was to monitor illegal nuclear detonations on Earth. Since then, several X-ray telescopes have also been equipped with gamma-ray detectors.

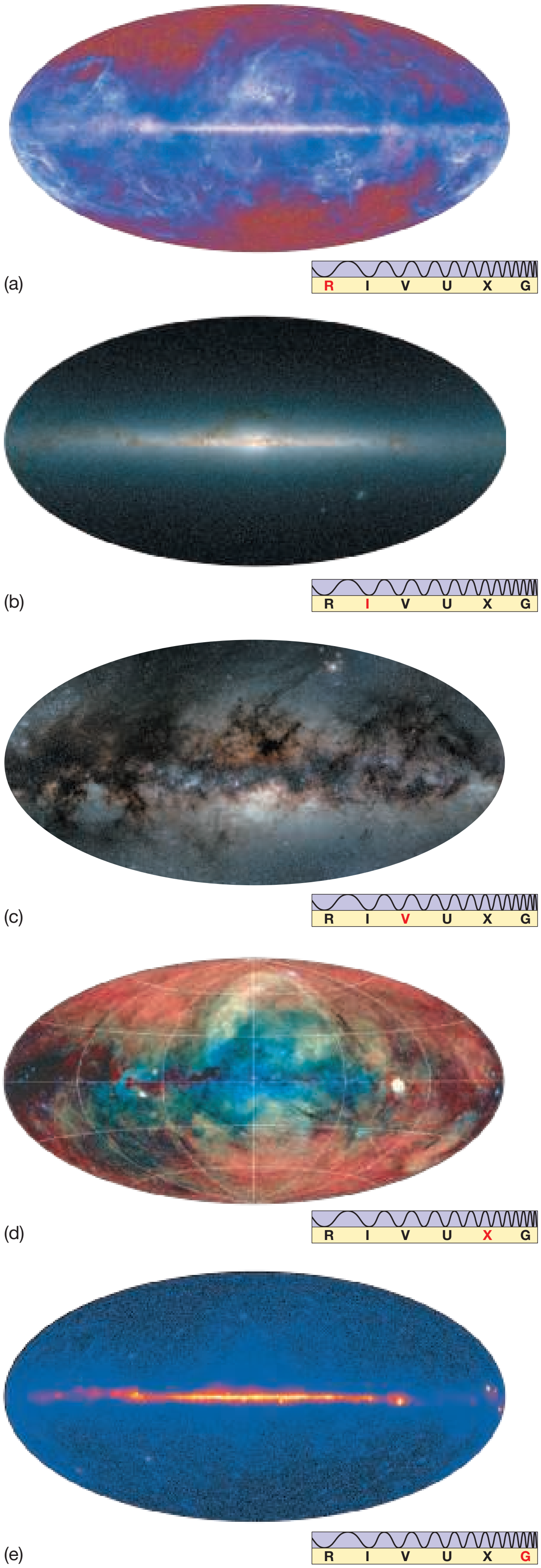
Gamma-ray astronomy traces the most violent events in the universe, on scales ranging from stars to galaxies. NASA's *Compton Gamma-Ray Observatory (CGRO),* placed in orbit in 1991, scanned the sky and studied individual objects in much greater detail than ever before. The *CGRO* mission ended in 2000 following a failure of one of the spacecraft's three gyroscopes. In 2008, NASA launched the *Fermi Gamma-Ray Space Telescope*. With greater sensitivity to a broader range of gamma-ray energies than *CGRO, Fermi's* capabilities have greatly expanded astronomers' view of the high-energy universe. Figure 3.29

CONCEPT CHECK

List two scientific benefits of placing telescopes in space. What might be some drawbacks?

TABLE 3.1 Astronomy at Many Wavelengths

Radiation	General Considerations	Common Applications (Chapter Reference)
Radio	Can penetrate dusty regions of interstellar space. Earth's atmosphere largely transparent to radio wavelengths. Can be observed day or night. High resolution at long wavelengths requires very large telescopes.	Radar studies of planets (1, 6) Planetary magnetic fields (7) Interstellar gas clouds (11) Center of Milky Way Galaxy (14) Galactic structure (14, 15) Active galaxies (15) Cosmic background radiation (17)
Infrared	Can penetrate dusty regions of interstellar space. Earth's atmosphere only partially transparent to infrared radiation, so some observations must be made from space.	Star formation (11) Cool stars (11, 12) Center of Milky Way Galaxy (14) Active galaxies (15) Large-scale structure of the universe (16, 17)
Visible	Earth's atmosphere transparent to visible light.	Planets (6, 7) Stars and stellar evolution (9, 10, 12) Galactic structure (14, 15) Large-scale structure of the universe (16, 17)
Ultraviolet	Earth's atmosphere opaque to UV radiation, so observations must be made from space.	Interstellar medium (11) Hot stars (12)
X-ray	Earth's atmosphere opaque to X-rays, so observations must be made from space. Special mirror configurations needed to form images.	Stellar atmospheres (9) Neutron stars and black holes (13) Active galactic nuclei (15) Hot gas in galaxy clusters (16)
Gamma ray	Earth's atmosphere opaque to gamma rays, so observations must be made from space. Cannot form images.	Neutron stars (13) Active galactic nuclei (15)



◀ **FIGURE 3.30 Multiple Wavelengths** The Milky Way Galaxy as it appears at (a) radio, (b) infrared, (c) visible, (d) X-ray, and (e) gamma-ray wavelengths. Each frame is a panoramic view covering the entire sky, with the center of our Galaxy at the center of each map. *ESA; UMass/Caltech; A. Mellinger; MPI; NASA*

shows a Fermi image of the aftermath of a vast stellar explosion, the kind of violent event that emits much of its energy in the form of gamma rays. An all-sky image from *Fermi* appears in Figure 3.30 (e).

Full-Spectrum Coverage

Table 3.1 lists the basic regions of the electromagnetic spectrum and describes objects typically studied in each frequency range. Bear in mind that the list is far from exhaustive and that many astronomical objects are now routinely observed at many different electromagnetic wavelengths. As we proceed through the text, we will discuss more fully the wealth of information that high-precision astronomical instruments can provide us.

As an illustration of the sort of comparison that full-spectrum coverage allows, Figure 3.30 shows a series of images of the Milky Way Galaxy. They were made by several instruments, at wavelengths ranging from radio to gamma ray, over a period of about 5 years. By comparing the features visible in each, we immediately see how multiwavelength observations can complement each other, greatly extending our perception of the universe around us.

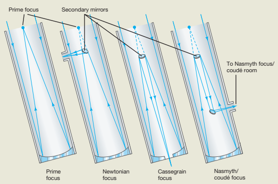
THE BIG QUESTION

Astronomy is a data-driven science. The most stunning discoveries are often made as new telescopes come online; some instruments are bigger, others operate in orbit, and almost all are better than anything available previously. The biggest advances have been made by instruments built to sense new domains of the electromagnetic spectrum. Today, astronomers are opening new, nonelectromagnetic windows, in the form of neutrinos (Chapter 9) and gravitational radiation (Chapter 13). What will we learn from them, and are there other, as yet unknown, channels still awaiting discovery?

CHAPTER REVIEW

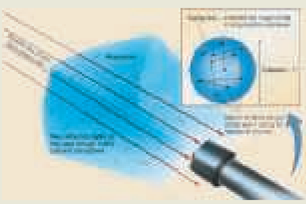
SUMMARY

LO1 A **telescope** (p. 72) is a device designed to collect as much light as possible from some distant source and deliver it to a detector for detailed study. Astronomers prefer **reflecting telescopes** (p. 72) because large mirrors are lighter and much easier to construct than large lenses, and they also suffer from fewer optical defects. Instruments may be placed inside the telescope at the **prime focus** (p. 72), or a secondary mirror may be used to reflect the light to an external detector. Most modern telescopes use **charge-coupled devices** (p. 78) to collect and store data in digital form for later analysis.

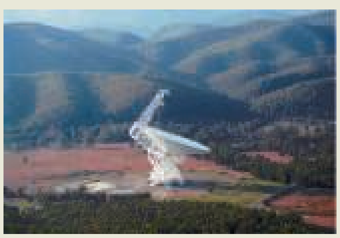


LO2 The light-gathering power of a telescope depends on its **collecting area** (p. 79), which is proportional to the square of the mirror diameter. To study the faintest sources of radiation, astronomers must use large telescopes. Large telescopes also suffer least from the effects of diffraction and, hence, can achieve better **angular resolution** (p. 81) once the blurring effects of Earth's atmosphere are overcome. The amount of diffraction is proportional to the wavelength of the radiation under study and inversely proportional to the size of the mirror.

LO3 The resolution of most ground-based optical telescopes is limited by **seeing** (p. 83)—the blurring effect of Earth's turbulent atmosphere, which smears the point-like images of a star into a **seeing disk** (p. 83) a few arc seconds in diameter. Astronomers can improve a telescope's resolution by using **active optics** (p. 84), in which a telescope's environment and focus are carefully monitored and controlled, and **adaptive optics** (p. 84), in which the blurring effects of atmospheric turbulence are corrected for in real time.

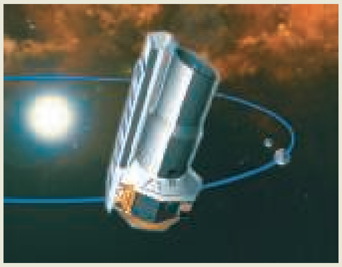


LO4 **Radio telescopes** (p. 84) are conceptually similar in construction to optical reflecting telescopes, although they are generally much larger than optical instruments, in part because so little radio energy reaches Earth from space. Their main disadvantage is that diffraction of long-wavelength radio waves limits their resolution. Their principal advantage is that they allow astronomers to explore a new part of the electromagnetic spectrum and of the universe—many astronomical radio emitters are completely undetectable in visible light. In addition, radio observations are largely unaffected by Earth's atmosphere, weather, and the location of the Sun.

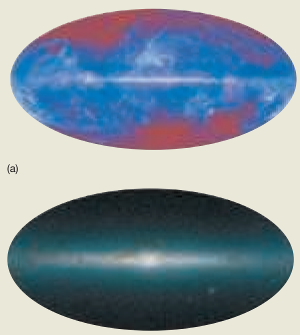


LO5 To increase the effective area of a telescope, and, hence, improve its resolution, several instruments may be combined into an **interferometer** (p. 88), in which the interference pattern of radiation received by two or more detectors is used to reconstruct a high-precision map of the source. Using **interferometry** (p. 88), radio telescopes can produce images much sharper than those from the best optical equipment.

LO6 **Infrared** (p. 90) and **ultraviolet telescopes** (p. 92) are similar in basic design to optical systems. **High-energy telescopes** (p. 94) study the X-ray and gamma-ray regions of the electromagnetic spectrum. X-ray telescopes can form images of their field of view, although the mirror design is more complex than for lower-energy instruments. Gamma-ray telescopes simply point in a certain direction and count photons received. Infrared studies in some parts of the infrared range can be carried out using large ground-based systems. However, because of atmospheric opacity, most infrared, and all ultraviolet, X-ray, and gamma-ray observations must be made from space.



LO7 Different physical processes can produce very different kinds of electromagnetic radiation, and the image of a given object in long-wavelength, low-energy radio waves may bear little resemblance to its appearance in high-energy X-rays or gamma rays. Observations at wavelengths spanning the electromagnetic spectrum are essential to a complete understanding of astronomical events.


(a)
(b)

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

REVIEW AND DISCUSSION

1. **LO1** List three advantages of reflecting telescopes over refracting telescopes.
2. **LO2** What are the largest optical telescopes in use today? Why do astronomers want their telescopes to be as large as possible?
3. How does Earth's atmosphere affect what is seen through an optical telescope?
4. What advantages does the *Hubble Space Telescope* have over ground-based telescopes? List some disadvantages.
5. What are the advantages of a CCD over a photograph?
6. **LO3** Is the resolution of a 2-m telescope on Earth's surface limited more by atmospheric turbulence or by the effects of diffraction?
7. Why do radio telescopes have to be very large?
8. **LO4** Which astronomical objects are best studied with radio techniques?
9. **LO5** What is interferometry, and what problem in radio astronomy does it address?
10. Compare the highest resolution attainable with optical telescopes to the highest resolution attainable with radio telescopes (including interferometers).
11. What special conditions are required to conduct observations in the infrared?
12. In what ways do the mirrors in X-ray telescopes differ from those found in optical instruments?
13. **LO6** Why was *Fermi* placed in space, rather than on the ground?
14. **LO7 POS** What are the main advantages of studying objects at many different wavelengths of radiation?
15. **POS** Our eyes can see light with an angular resolution of about 1′—equivalent to about a third of a millimeter at arm's length. Suppose our eyes detected only infrared radiation, with 1° angular resolution. Would we be able to make our way around on Earth's surface? To read? To sculpt? To create technology?

CONCEPTUAL SELF-TEST: TRUE OR FALSE/MULTIPLE CHOICE

1. The main advantage to using the *HST* is the increased amount of "nighttime" viewing it affords. (T/F)
2. The term "seeing" is used to describe how faint an object can be detected by a telescope. (T/F)
3. One of the primary advantages of CCDs over photographic plates is the former's high efficiency in detecting light. (T/F)
4. Radio telescopes are large in part to improve their angular resolution, which is poor because of the long wavelengths at which they are used to observe the skies. (T/F)
5. Infrared astronomy can only be done from space. (T/F)
6. Gamma-ray telescopes employ the same basic design that optical instruments use. (T/F)
7. Because gamma rays have very short wavelengths, gamma-ray telescopes can achieve extremely high angular resolution. (T/F)
8. The main reason that most professional research telescopes are reflectors is that (a) mirrors produce sharper images than lenses do; (b)their images are inverted; (c)they do not suffer from the effects of seeing; (d)large mirrors are easier to build than large lenses.
9. If telescope mirrors could be made in odd sizes, the one with the *most* light-gathering power would be a triangle with 1-m sides; a square with 1-m sides; a circle 1 m in diameter; a rectangle with two 1-m sides and two 2-m sides.
10. The primary reason professional observatories are built on the highest mountaintops is to (a) get away from city lights; (b) be above the rain clouds; (c) reduce atmospheric blurring; (d) improve chromatic aberration.
11. When multiple radio telescopes are used for interferometry, resolving power is most improved by increasing (a) the distance between telescopes; (b) the number of telescopes in a given area; (c) the diameter of each telescope; (d) the electrical power supplied to each telescope.
12. The *Spitzer Space Telescope* is stationed far from Earth because (a) this increases the telescope's field of view; (b) the telescope is sensitive to electromagnetic interference from terrestrial radio stations; (c) doing so avoids the obscuring effects of Earth's atmosphere; (d) Earth is a heat source and the telescope must be kept very cool.
13. The best way to study young stars hidden behind interstellar dust clouds would be to use (a) X-rays; (b) infrared light; (c) ultraviolet light; (d) blue light.
14. **VIS** The image shown in Figure 3.12 (Resolution) is sharpest when the ratio of wavelength to telescope size is (a) large; (b) small; (c) close to 1; (d) none of these.
15. **VIS** Table 3.1 (Astronomy at Many Wavelengths) suggests that the best frequency range in which to study the hot (million-kelvin) gas found among the galaxies in the Virgo cluster would be (a) at radio frequencies; (b) in the infrared; (c) in X-rays; (d) in gamma rays.

PROBLEMS

The number of squares preceding each problem indicates its approximate level of difficulty.

1. ■ A certain telescope has a 10′ × 10′ field of view that is recorded using a CCD chip having 2048 × 2048 pixels. What angle on the sky corresponds to 1 pixel? What would be the diameter of a typical seeing disk (1″ radius), in pixels?
2. ■ The *SST*'s planned operating temperature is 5.5 K. At what wavelength (in micrometers, μm) does the telescope's own blackbody emission peak? How does this wavelength compare with the wavelength range in which the telescope is designed to operate? (**∞ *More Precisely 2-2***)
3. ■ A 2-m telescope can collect a given amount of light in 1 hour. Under the same observing conditions, how much time would be required for a 6-m telescope to perform the same task? A 12-m telescope?
4. ■ A space-based telescope can achieve a diffraction-limited angular resolution of 0.05″ for red light (wavelength 700 nm). What would the resolution of the instrument be (a) in the infrared, at wavelength 3.5 μm, and (b) in the ultraviolet, at wavelength 140 nm?
5. ■■ Two identical stars are moving in a circular orbit around one another with an orbital separation of 2 AU. The system lies 200 light-years from Earth. If we happen to view the orbit head-on, how large a telescope would we need to resolve the stars, assuming diffraction-limited optics at a wavelength of 2 μm?
6. ■■ What is the greatest distance at which *HST*, operating in blue light (400 nm), could resolve the stars in the previous question?
7. ■ The photographic equipment on a telescope is replaced by a CCD. If the photographic plate records 5 percent of the light reaching it, but the CCD records 90 percent, how much time will the new system take to collect as much information as the old detector recorded in a 1-hour exposure?
8. ■ The Andromeda galaxy lies about 2.5 million light-years away. To what distances do the angular resolutions of *SST* (3″), *HST* (0.05″), and a radio interferometer (0.001″) correspond at that distance?
9. ■ What would be the equivalent single-mirror diameter of a telescope constructed from two separate 10-m mirrors? Four separate 8-m mirrors?
10. ■ Estimate the angular resolutions of (a) a radio interferometer with a 5000-km baseline, operating at a frequency of 5 GHz, and (b) an infrared interferometer with a baseline of 50 m, operating at a wavelength of 1 μm.

ACTIVITIES

Collaborative

1. Determine the maximum size interferometer your group could build if you placed 2-m radio telescopes at each of your homes. What would be its resolution at a wavelength of 1 cm?
2. Your group has been assigned to observe the region of the sky around Orion to look for hot, bright young stars hidden in molecular clouds. Explain which of the telescopes described in the text would be your best choice, and estimate the level of detail you might expect to see.

Individual

1. Take some photographs of the night sky. You will need a location with a clear, dark sky, a good digital camera that lets you control the exposure time, a tripod and cable release, and a watch with a seconds display visible in the dark. Set your camera to the "manual" setting for the exposure and attach the cable release so you can control it. Set the focus on infinity. Point the camera at the desired constellation, seen through the viewfinder, and take a 20- to 30-second exposure. Don't touch any part of the camera or hold on to the cable release during the exposure to minimize all vibration. Keep a log of your shots.
2. For some variation, vary your exposure times, take hours-long exposures for star trails, use different lenses such as wide-angle or telephoto, or place the camera piggyback on a telescope tracking an object in the sky so you can take exposures that are a few minutes long. Experiment and have fun!
3. Which image of the Milky Way Galaxy in Figure 3.30 (Multiple Wavelengths) provides the most interesting information? Explain your reasoning.

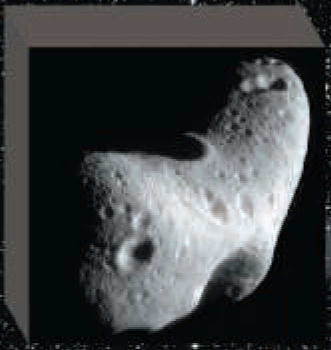
PART 2

Our Planetary System

As our study of astronomy expands, we embark on the next in a series of increasingly larger steps that will ultimately take us to the limits of the observable universe. This journey begins with Earth, progresses to the study of other planets, and continues on to the magnificent Sun. The dimension of our planetary family is so large that more than a million Earths could be stacked side by side across the whole solar system.

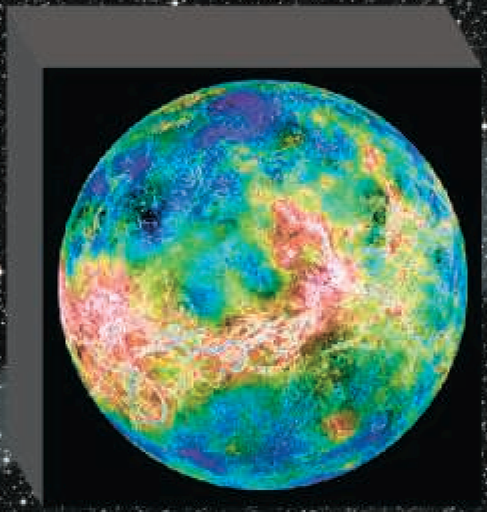
Part 2 relates our present understanding of our extended, complex home in space. That understanding is still a work in progress, but the results thus far have revolutionized our knowledge both of our present cosmic neighborhood and of Earth's rich natural history.

The images here illustrate the range of sizes encountered in Part 2, from the scattered debris of asteroids and comets to the central Sun.

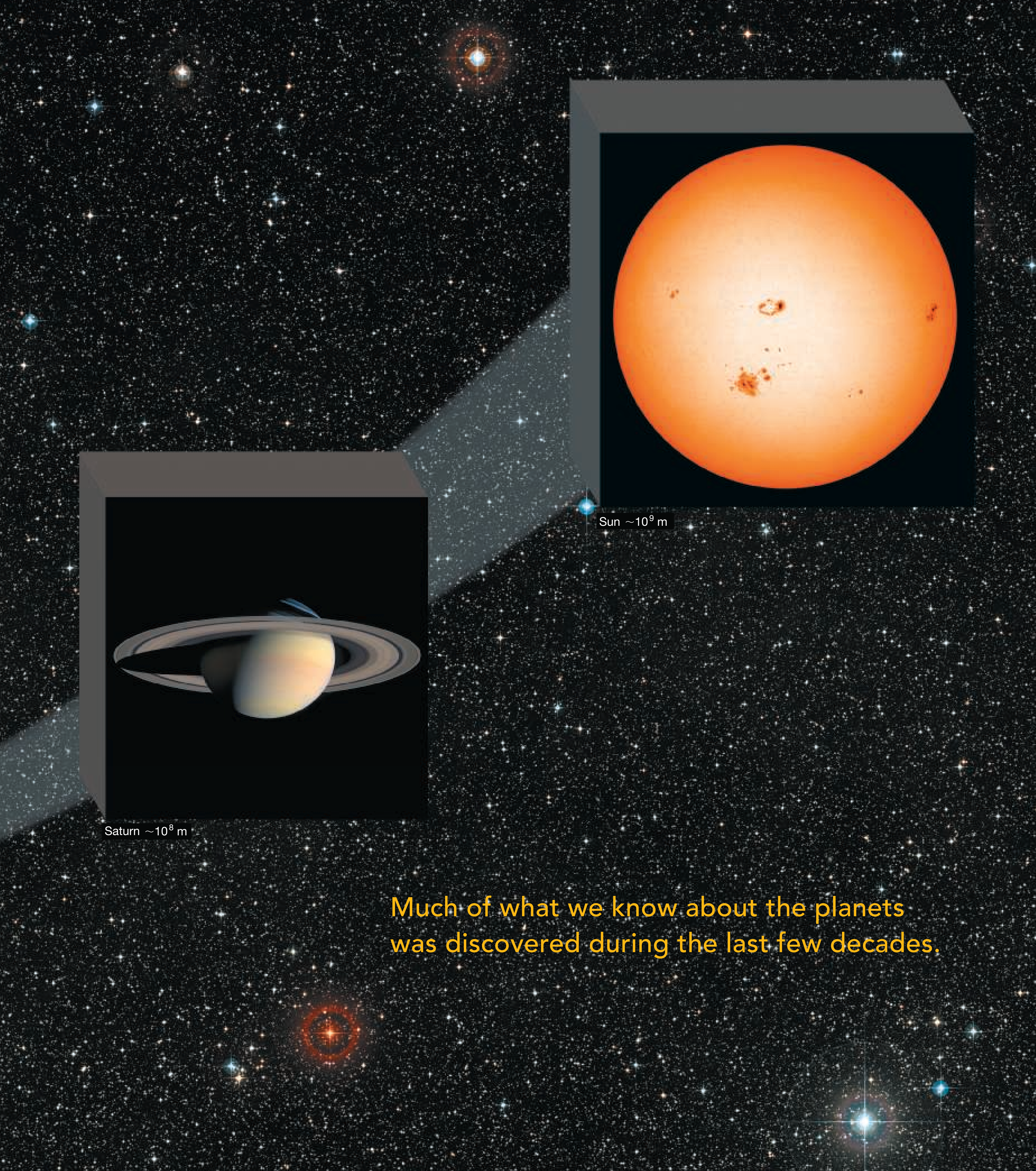


Asteroid $\sim 10^4$ m

Moon $\sim 10^6$ m



Venus $\sim 10^7$ m



Much of what we know about the planets
was discovered during the last few decades.

4

The Solar System

Interplanetary Matter and the Birth of the Planets

In less than a generation, we have learned more about our solar system—the Sun and everything that orbits it—than in all previous centuries. By studying the planets, their moons, and the countless fragments of material that orbit in interplanetary space, astronomers have gained a richer outlook on our own home in space. The discoveries of the past few decades have revolutionized our understanding not only of the present state of our cosmic neighborhood, but also of its history, for our solar system is filled with clues to its own origin and evolution. Paradoxically, the richest sources of information about the earliest days of the solar system are not the large bodies orbiting the Sun, but rather the asteroids, comets, and meteoroids that pepper interplanetary space. Far more than the planets themselves, these fragments hold a record of the formative stages of our planetary system and have much to teach us about the origin of our world.

THE BIG PICTURE

Our own solar system formed some 4.5 billion years ago, a time so ancient that it is virtually impossible to reconstruct the details of that singular event. Ironically, studies of other planetary systems far beyond our own are now helping us decipher, like Rosetta stones, our own origins. Just as comparative planetology of our own eight planets guides our understanding of Earth's formation and history, extrasolar planets have much to teach us about how planetary systems form and evolve.

◄ Comets are small but vital components of our planetary system, dating back to the earliest times and in many cases containing pristine material largely unchanged since the solar system formed. They are one of the few direct links we have with the processes that formed the Sun and the planets. This image shows comet 67 P/Churyumov–Gerasimenko, a 4-km-wide chunk of ice that orbits between Earth and Jupiter. It was taken by the European *Rosetta* spacecraft, which went into orbit around the comet in 2014 and remained with it during its closest approach to the Sun in 2015. *Rosetta* carried out detailed measurements of the comet's interior and environment, and soft-landed a small probe on the surface, providing by far the best view of a comet ever obtained. (*ESA/Rosetta/MPS*)

LEARNING OUTCOMES

Studying this chapter will enable you to:

- **LO1** Describe the scale and structure of the solar system, and list the basic differences between terrestrial and jovian planets.
- **LO2** Summarize the orbital and physical properties of asteroids.
- **LO3** Describe the composition and structure of a typical comet, and explain what a comet's orbit tells us about its probable origin.
- **LO4** Summarize the orbital and physical properties of meteoroids, and explain how these bodies are related to asteroids and comets.
- **LO5** List the major facts and exceptions that any theory of solar system formation must explain.
- **LO6** Outline the condensation theory of planetary formation, and indicate how it accounts for the major features of the solar system.
- **LO7** Explain how the condensation theory accounts for the terrestrial and jovian planets, as well as the smaller bodies scattered throughout the solar system.
- **LO8** Describe the main methods by which astronomers have detected planets beyond the solar system.
- **LO9** Outline the properties of the known extrasolar planets and relate to current theories of solar system formation.

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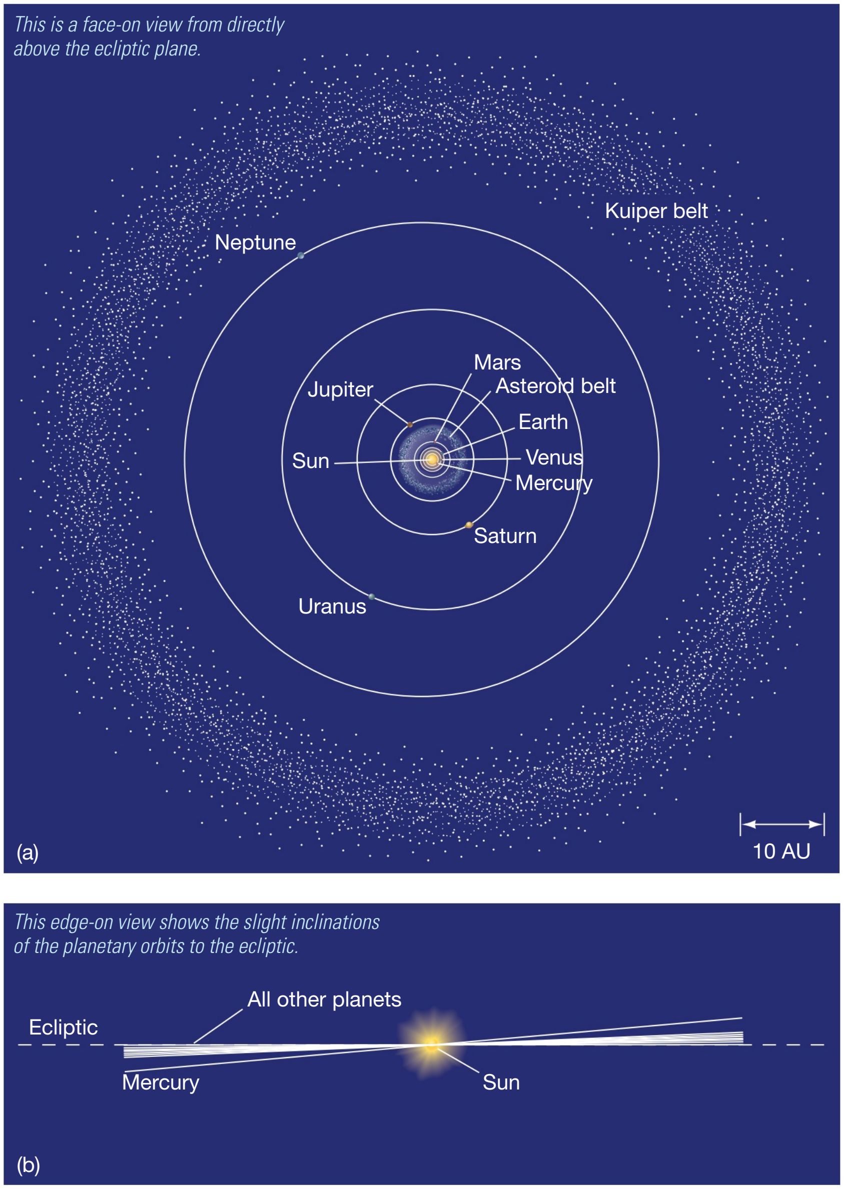
4.1 An Inventory of the Solar System

Our **solar system** contains one star (the Sun), eight planets orbiting that star, 173 moons (at last count) orbiting those planets, five *dwarf planets*, seven *asteroids* and more than 100 *Kuiper belt objects* larger than 300 km (200 miles) in diameter, tens of thousands of smaller (but well-studied) asteroids and Kuiper belt objects, myriad *comets* a few kilometers in diameter, and countless *meteoroids* less than 100 m across. This list will undoubtedly grow as we continue to explore our cosmic neighborhood.

ANIMATION/VIDEO
An Astronomical Ruler



▲ **FIGURE 4.1 Solar System** Major bodies of the solar system include the Sun, planets, and asteroids. Except for Mercury, the orbits of the planets are almost circular (a) and lie nearly in the same plane (b). The entire solar system, including the Kuiper belt, spans nearly 100 AU.

Planetary Properties

The overall arrangement of the solar system is shown in Figure 4.1. Mercury is the planet closest to the Sun, followed by Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. The asteroids lie mainly in a broad belt between the orbits of Mars and Jupiter, the Kuiper belt beyond Neptune.

The planets' distances from the Sun are known from their periods and Kepler's laws once the scale of the solar system is set by radar ranging on Venus. *(Sec. 1.3)* The distance from the Sun to Neptune is about 30 AU, some 700,000 times Earth's radius and roughly 12,000 times the distance from Earth to the Moon. Yet despite this vast extent, the planets all lie very close to the Sun, astronomically speaking. The diameter of Neptune's orbit is less than 1/3000 of a light-year, while the next nearest star to the Sun is several light-years distant. Note that the planetary orbits are not evenly spaced. Roughly speaking, the spacing between adjacent orbits doubles as we move outward from the Sun.

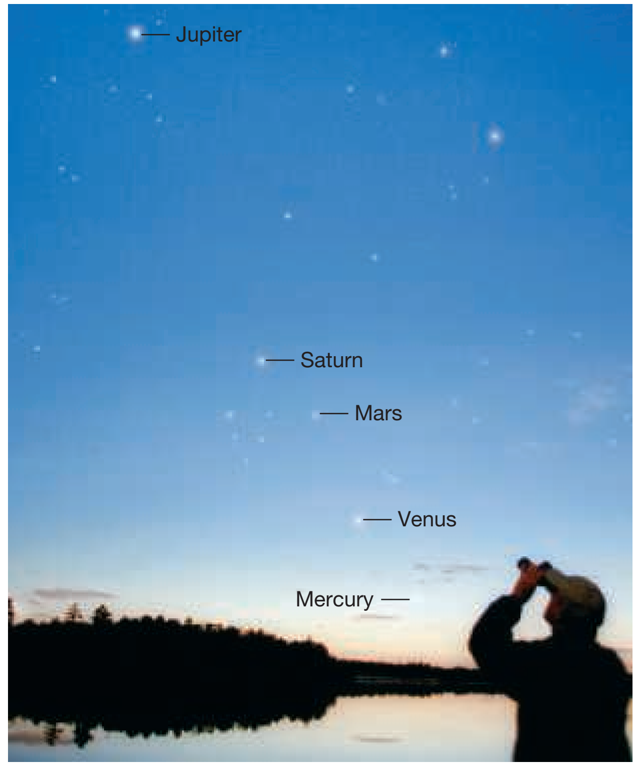
All the planets orbit the Sun counterclockwise as seen from above Earth's North Pole and in nearly the same plane as Earth (the ecliptic plane). *(Sec. 1.1)* Mercury deviates slightly from this rule—its orbital plane lies at 7° to the ecliptic. Still, as illustrated in Figure 4.1(b), we can think of the solar system as being remarkably flat. Figure 4.2 is a photograph of the planets Mercury, Venus, Mars, Jupiter, and Saturn, taken during an April 2002 planetary alignment. These five planets can (occasionally) be found in the same region of the sky in large part because their orbits lie nearly in the same plane in space.

Table 4.1 lists some basic orbital and physical properties of the eight planets, with a few other solar system objects included for comparison.

Earth's radius has long been known through conventional surveying techniques and, more recently, by satellite measurements. *(Discovery 0-1)* Other planetary radii are found by measuring the planets' angular sizes and then employing elementary geometry, as discussed in *More Precisely 4-1*. Figure 4.3 illustrates the sizes of the planets relative to the Sun.

A planet's mass is determined by observing its gravitational influence on some nearby object and applying Newton's laws of motion and gravity. ∞ *(More Precisely 1-1)* Before the Space Age, astronomers calculated planetary masses either by tracking the orbits of the planets' moons (if any) or by measuring the small but detectable distortions the planets produce in each other's orbits. Today astronomers can accurately determine the masses of most of the objects listed in Table 4.1 through their gravitational effects on artificial satellites and space probes launched from Earth. With nearly 99.9 percent of the total mass, the Sun is clearly the "senior partner" in the solar system. Its gravity dominates the motion of everything else.

The final column in Table 4.1 lists a quantity called **density,** a measure of the "compactness" of an object, computed by dividing the object's mass (in kilograms) by its volume (in cubic meters). Earth's average density is 5500 kg/m^3. For comparison, the density of water is 1000 kg/m^3, rocks on Earth's surface have densities in the range 2000–3000 kg/m^3, and iron has a density of about 8000 kg/m^3. Earth's atmosphere at sea level has a density of about 1 kg/m^3.

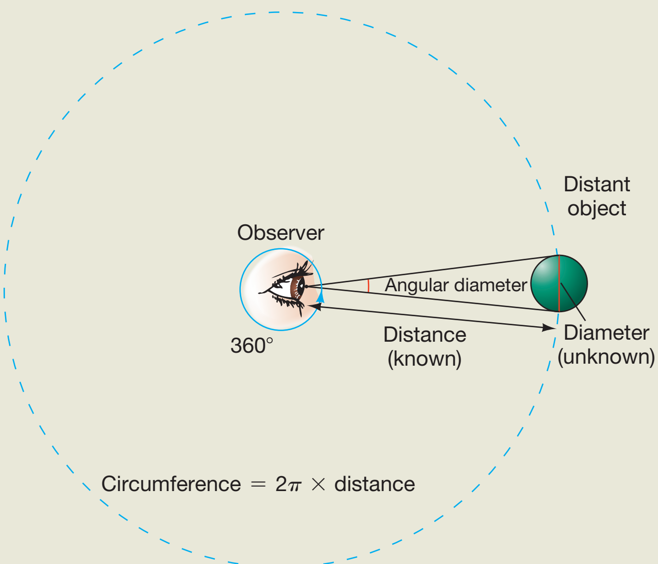


▶ **FIGURE 4.2 Planetary Alignment** Six planets—Mercury, Venus, Mars, Jupiter, Saturn, and Earth—are shown during a planetary alignment in April 2002. The Sun and Moon are just below the horizon. *(J. Lodriguss)*

4.1 MORE PRECISELY

Measuring Sizes with Geometry

We saw in Chapter 1 how astronomers use parallax, radar ranging, and Kepler's laws to determine the distances to objects in the solar system. ∞ *(Sec. 1.3)* Knowing the distance, we can convert a body's angular size into its physical size using a simple argument first made by the Greek geometer Euclid.



The accompanying figure shows an observer measuring the angular diameter of an object of known distance; we have added a large circle centered on the observer and passing through the object. To compute the object's size, we note that the ratio of its actual diameter to the circumference of the circle (2π times the distance to the object) must be equal to the ratio of the observed angular diameter to one full revolution, 360°:

$$\frac{\text{diameter}}{2\pi \times \text{distance}} = \frac{\text{angular diameter}}{360^\circ}.$$

Note the basic similarity of this reasoning to that presented in Chapter 0. ∞ *(Discovery 0-1)* From the above equation we find

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

For example, radar ranging on the Moon tells us that its distance is 384,000 km. The Moon's angular diameter is measured to be about 31 arc minutes—a little over half a degree. It therefore follows that the Moon's actual diameter is 384,000 km × (31/60)° 57.3° = 3460 km. A more precise measurement gives 3476 km.

Although the observations are straightforward and the geometrical reasoning elementary, simple measurements such as these form the basis for almost every statement made in this book about size and scale in the universe.

TABLE 4.1 Properties of Some Solar System Objects

Object	Orbital Semimajor Axis (AU)	Orbital Period (Earth Years)	Mass (Earth Masses)	Radius (Earth Radii)	Number of Known Moons	Average Density (kg/m^3)	Average Density (Earth = 1)
Mercury	0.39	0.24	0.055	0.38	0	5400	0.98
Venus	0.72	0.62	0.82	0.95	0	5200	0.95
Earth	1.0	1.0	1.0	1.0	1	5500	1.00
Moon	—	—	0.012	0.27	—	3300	0.60
Mars	1.5	1.9	0.11	0.53	2	3900	0.71
Ceres (asteroid)	2.8	4.7	0.00015	0.073	0	2700	0.49
Jupiter	5.2	11.9	318	11.2	67	1300	0.24
Saturn	9.5	29.4	95	9.5	62	700	0.13
Uranus	19.2	84	15	4.0	27	1300	0.24
Neptune	30.1	164	17	3.9	14	1600	0.29
Pluto (Kuiper-belt object)	39.5	249	0.002	0.2	5	2100	0.38
Comet Hale-Bopp	180	2400	1.0×10^{-9}	0.004	—	100	0.02
Sun	—	—	332,000	109	—	1400	0.25

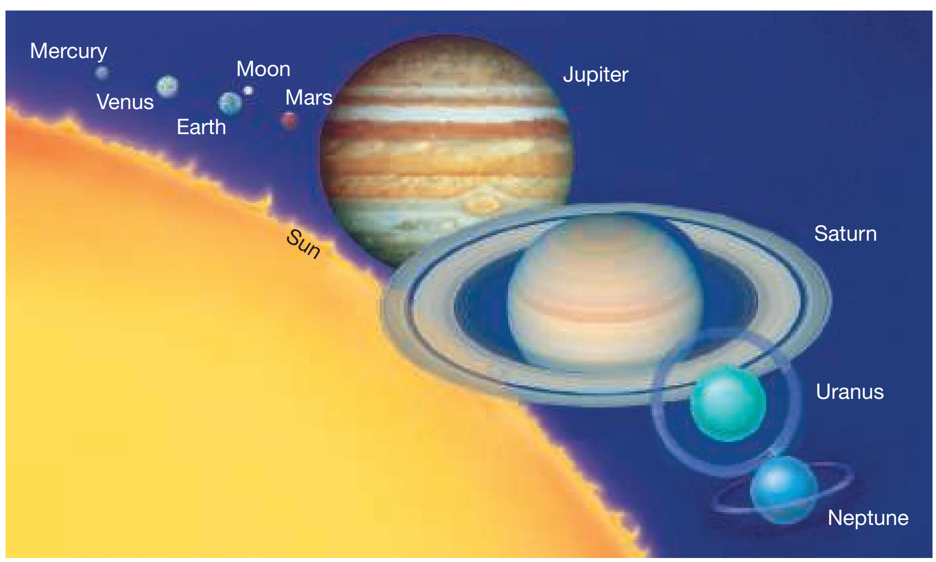
Terrestrial and Jovian Planets

ANIMATION/VIDEO MA
Size and Scale of the Terrestrial Planets I

ANIMATION/VIDEO MA
The Gas Giants

Astronomers can infer a planet's bulk composition from a combination of spacecraft data and theoretical calculations (see Chapters 5–8). Based on these, we can draw a clear distinction between the inner and outer members of our planetary system. Simply put, the inner planets—Mercury, Venus, Earth, and Mars—are small, dense, and *rocky* in composition. The outer worlds—Jupiter, Saturn, Uranus, and Neptune—are large, of low density, and *gaseous*.

Because the physical and chemical properties of Mercury, Venus, and Mars are somewhat similar to Earth's, the four innermost planets are called the **terrestrial planets.** (The word *terrestrial* derives from the Latin word *terra*, meaning "land" or "earth.") The larger outer planets—Jupiter, Saturn, Uranus, and Neptune—are all similar to one another chemically and physically (and very different from the terrestrial worlds). They are labeled the **jovian planets,** after Jupiter, the largest member of the group. The Roman god Jupiter was also known as Jove. The jovian worlds are all much larger than the terrestrials and quite



▶ **FIGURE 4.3 Sun and Planets** Relative sizes of the planets and our Sun. Notice that Jupiter, Saturn, Uranus, and Neptune are much larger than Earth and the other inner planets. However, even these large planets are dwarfed by the still larger Sun.

different from them in both composition and structure. Table 4.2 compares and contrasts some key properties of these two distinct planetary classes.

There are important variations within each category. For example, when we correct for how gravity compresses their interiors, we find that the *uncompressed densities* of the terrestrial planets decrease steadily with increasing distance from the Sun, so these planets' compositions depend on their location in the solar system. Similarly, all four jovian worlds have large, dense "terrestrial" cores of up to 20 times the mass of Earth, but these cores account for an increasing fraction of the jovian planets' total mass as we move outward.

TABLE 4.2 Comparison Between the Terrestrial and Jovian Planets

Terrestrial	Jovian
close to the Sun	far from the Sun
closely spaced orbits	widely spaced orbits
small masses	large masses
small radii	large radii
predominantly rocky	predominantly gaseous
solid surface	no solid surface
high density	low density
slower rotation	faster rotation
weak magnetic fields	strong magnetic fields
no rings	many rings
few moons	many moons

Solar System Debris

One of the principal goals of planetary science is to understand how the solar system formed and to explain the physical conditions now found on Earth and elsewhere in our planetary system. Ironically, studies of the most accessible planet—Earth itself—do not help us much in our quest because information about our planet's early stages was obliterated long ago by atmospheric erosion and geological activity, such as earthquakes and volcanoes. Similar statements hold for the other planets. The problem is that the large bodies of the solar system have all *evolved* significantly since they formed, making it difficult to decipher the circumstances of their births.

A much better place to look for hints of conditions in the early solar system is on its *small* bodies—the planetary moons and the asteroids, meteoroids, Kuiper belt objects, and comets that make up interplanetary debris—for nearly all such fragments contain traces of solid and gaseous matter from the earliest times. They represent truly ancient material—many have scarcely changed since they formed along the rest of the solar system billions of years ago.

4.2 Interplanetary Matter

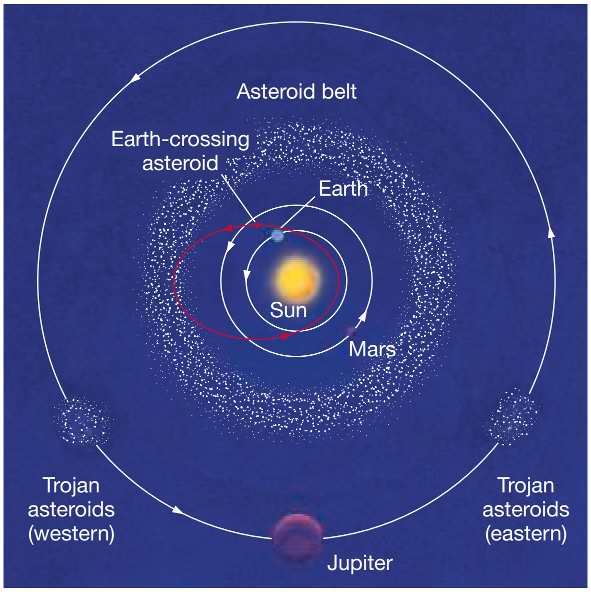
In the vast space among the eight known planets move countless small chunks of matter, ranging in size from a few hundred kilometers in diameter down to tiny grains of dust. The major constituents of this cosmic debris are asteroids, comets, Kuiper belt objects, and meteoroids. **Asteroids** and **meteoroids** are fragments of rocky material, somewhat similar in composition to the outer layers of the terrestrial planets. The distinction between the two is simply their size—anything larger than 100 m in diameter (corresponding to a mass exceeding 10,000 tons) is conventionally called an asteroid; anything smaller is a meteoroid. **Comets** are predominantly icy rather than rocky in composition (although they do contain some rocky material) and have typical diameters in the 1- to 10-km range. The **Kuiper belt** is an "outer asteroid belt" of sorts, also consisting of icy bodies, including the former planet Pluto. Comets and Kuiper belt objects are quite similar in chemical makeup to some of the icy moons of the outer planets—and may very well be the progenitors of those small bodies.

In 2006, the International Astronomical Union, the organization that oversees the rules for astronomical terminology, introduced a new category of solar system object: A **dwarf planet** is a body that orbits the Sun and is massive enough for its gravity to have pulled it into a spherical shape, but not so massive that it has cleared the region around its orbit of smaller bodies. By this definition, the three largest "small bodies" in the solar system—the asteroid Ceres, three Kuiper belt objects, including Pluto, and the "trans-Neptunian object" Eris—are all dwarf planets.

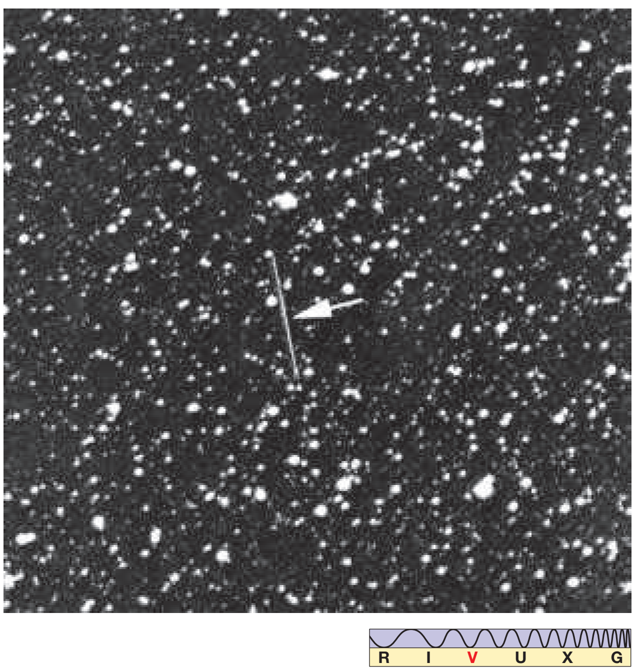
Together, these small bodies account for a negligible fraction of the total mass of the solar system—just a few millionths the mass of the Sun—and they are irrelevant to the present-day workings of the planets and their moons. Yet they are are key to answering some very fundamental questions about our planetary environment.

CONCEPT CHECK

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



▲ **FIGURE 4.4 Inner Solar System** The main asteroid belt, along with the orbits of Earth, Mars, and Jupiter. Note the Trojan asteroids clumped at two locations in Jupiter's orbit. The orbits of the main-belt asteroids generally lie within the belt region of the figure. The red ellipse shows the orbit of an Earth-crossing asteroid.



▲ **FIGURE 4.5 Asteroids, from Earth** INTERACTIVE The Earth-crossing asteroid Icarus has an orbit that passes within 0.2 AU of the Sun, well within Earth's orbit. Icarus occasionally comes close to Earth, making it one of the best-studied asteroids in the solar system. Its motion relative to the stars makes it appear as a streak (marked) in this long-exposure photograph. *(Palomar Observatory/Caltech)*

Asteroid Orbits

The name *asteroid* comes from the Greek word *asteroeides,* which means "like a star," but asteroids are definitely not stars. They are too small even to be classified as planets. Astronomers often refer to them as minor planets. Researchers have so far cataloged well over 400,000 asteroids with well-determined orbits. The total number of known asteroids (that is, including those whose orbits are not yet known with sufficient accuracy to make them "official") is now approaching 1 million. As sketched in Figure 4.4, the vast majority are found in a region of the solar system known as the **asteroid belt,** located between 2.1 and 3.3 AU from the Sun, roughly midway between the orbits of Mars (at 1.5 AU) and Jupiter (at 5.2 AU). All but one of the known asteroids revolve about the Sun in prograde orbits—in the same sense (direction) as Earth and the other planets. Again like the planets, most asteroids have orbits fairly close to the ecliptic plane (with inclinations less than 10–20°). Unlike the almost circular paths of the major planets, however, asteroid orbits are generally noticeably elliptical in shape.

In addition to the main-belt asteroids, a few hundred **Trojan asteroids** share an orbit with Jupiter, remaining a constant 60° ahead of or behind that planet as it circles the Sun. This peculiar orbital behavior is not a matter of chance—the Trojan asteroids are held in place by a stable balance between the gravitational fields of Jupiter and the Sun. Calculations first performed by the 18th-century French mathematician Joseph Louis Lagrange show that interplanetary matter that strays into one of the two regions of space now occupied by the Trojan asteroids can remain there indefinitely, perfectly synchronized with Jupiter's motion.

The orbits of most asteroids have eccentricities lying in the range 0.05–0.3, ensuring that they always remain between the orbits of Mars and Jupiter. However, some **Earth-crossing asteroids** move on orbits that intersect Earth's orbit, most likely because the gravitational field of Mars or Jupiter has deflected these small bodies into the inner solar system. Currently, some 12,000 Earth-crossing asteroids are known. Most have been discovered since the late 1990s, when systematic searches for such objects began. The mile-wide Earth-crossing asteroid Icarus is shown (as the white streak) in Figure 4.5.

Roughly 1600 Earth crossers are officially designated "potentially hazardous," meaning that they are more than about 150 m in diameter (three times the size of the impactor responsible for the Barringer crater shown in Figure 4.19) and move in orbits that could bring them within 0.05 AU (7.5 million kilometer) of our planet. All told, between 2005 and 2015, some 200 asteroids (that we know of!) passed within 0.05 AU of our planet, a couple of them coming within the orbit of the Moon. Similar numbers are expected during the next decade. None of the currently known potentially hazardous asteroids is expected to impact Earth during the next century—the closest predicted near miss will occur in April 2029, when the 350-m asteroid Apophis will pass approximately 30,000 km above our planet's surface.

Calculations indicate that most Earth-crossing asteroids *will* eventually collide with Earth and that during any given million-year period, roughly three asteroids strike our planet. Several dozen large basins and eroded craters on Earth are thought to be sites of ancient asteroid collisions. The many large impact craters on the Moon, Venus, and Mars are direct evidence of similar events on other worlds. Such an impact could be catastrophic by human standards. Even a 1-km object carries more than 100 times more energy than all the nuclear weapons currently in existence on Earth and would devastate an area hundreds of kilometers in diameter. Should a sufficiently large asteroid hit our planet, it might even cause the extinction of an entire species. Indeed, many scientists think that the extinction of the dinosaurs was the result of just such an impact. ∞ *(Discovery 4-1)*

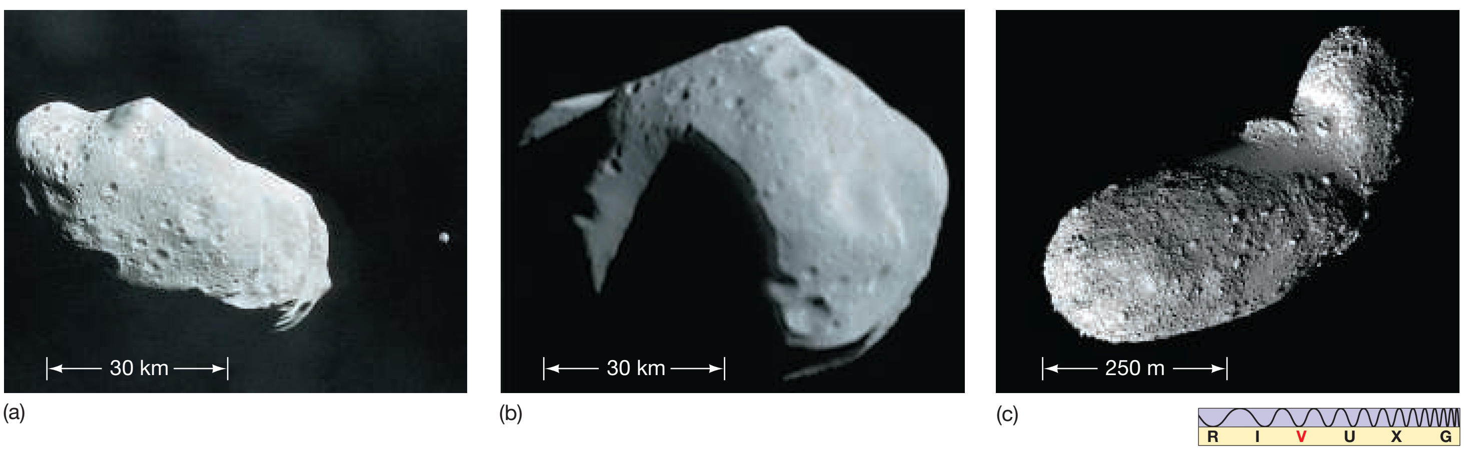
Asteroid Properties

Most asteroids are too small to resolve with even the largest Earth-based telescopes. ∞ *(Sec. 3.2)* Astronomers generally estimate asteroid sizes from the amount of sunlight they reflect and the heat they radiate. Occasionally, an asteroid passes directly in front of a star, allowing astronomers to determine its size and shape with great accuracy. The largest asteroid, the dwarf planet Ceres, has a diameter of 940 km. Only about two dozen asteroids are larger than 200 km across; most are far smaller. Large asteroids are roughly spherical because (as with planets) gravity is the dominant force determining their shape. Smaller bodies can be highly irregular in shape. The gravitational effect of an asteroid on its neighbors is very small and hard to measure accurately, so astronomers have measured the masses of only a few of them. The mass of Ceres is just 1/10,000 the mass of Earth. The total mass of all the known asteroids probably amounts to less than one-tenth the mass of the Moon.

Asteroid compositions are inferred from spectroscopic and other measurements in the infrared, visible, and ultraviolet parts of the spectrum. The darkest (least reflective) carbonaceous asteroids contain significant amounts of water ice and other volatile substances and are rich in organic (carbon-based) molecules. The more reflective silicate asteroids are composed primarily of rocky material. Silicate asteroids predominate in the inner parts of the asteroid belt, but carbonaceous asteroids are more common overall, and their fraction increases as we move outward.

Several asteroids have been visited by space probes. Figure 4.6(a) shows asteroid Ida, as seen by the *Galileo* probe en route to Jupiter in 1993. Ida is an irregularly shaped, cratered body some 30 km across, covered with layers of dust of variable thickness. It is thought to be a fragment of a larger object that broke up following a violent collision hundreds of millions of years ago. It also has a small moon (named Dactyl) orbiting it. By studying Dactyl's orbit and applying Newton's laws, astronomers were able to estimate Ida's mass at about $4–5 \times 10^{16}$ kg and infer a density of 2100–3100 kg/m^3. ∞ *(Sec. 1.4)* For comparison, the density of surface rock on Earth is around 3000 kg/m^3.

In 1997 the *Near Earth Asteroid Rendezvous* (*NEAR*) spacecraft flew by the 60-km wide asteroid Mathilde (Figure 4.6b). By sensing its gravitational pull, *NEAR* measured Mathilde's mass at about 10^{17} kg, implying a density of just 1300 kg/m^3. To account for this low density, scientists speculate that the asteroid's interior must be quite porous. Indeed, many asteroids seem to be more like



▲ **FIGURE 4.6 Asteroids, Close-up** (a) Asteroid Ida photographed by the space probe *Galileo* from a distance of 3400 km. (Ida's moon, Dactyl, is visible at right.) Resolution is about 100 m. (b) Asteroid Mathilde, imaged by the *NEAR* spacecraft on its way to the asteroid Eros. The largest craters in this image are about 20 km across—much larger than those seen on Ida. The reason may be Mathilde's low density and rather soft composition. (c) A typical "rubble pile" asteroid, Itokawa, as seen by the Japanese *Hayabusa* spacecraft. It has few craters and is thought to have formed from fragments that coalesced over time. *(NASA; JAXA)*

4.1 DISCOVERY

What Killed the Dinosaurs?

The name *dinosaur* derives from the Greek words *deinos* (terrible) and *sauros* (lizard), but dinosaurs were no ordinary reptiles. In their prime, they were the rulers of Earth. Their fossilized remains have been found on every continent. They dominated Earth for well over 100 million years (for comparison, humans have been around for a little over 2 million years). Yet according to the fossil record, these creatures vanished from Earth quite suddenly about 65 million years ago. What happened to them?

Many explanations have been offered for the extinction of these creatures. Devastating plagues, magnetic field reversals, increased geological activity, severe climate change, and supernova explosions (see Chapter 12) have all been proposed. In the 1980s, it was suggested that a large extraterrestrial object—a 10- to 15-km-wide asteroid or comet—struck Earth 65 million years ago, and this is now (arguably) the leading explanation for the demise of the dinosaurs. Sketched in the first figure, the impact released millions of times more energy than the largest nuclear bombs ever constructed by humans and kicked huge quantities of dust high into the atmosphere. The dust may have shrouded our planet for years, virtually extinguishing the Sun's rays. On the darkened surface, plants could not survive. The entire food chain was disrupted, and the dinosaurs, at the top of that chain, became extinct.

(D. Hardy)

Although we have no direct astronomical evidence for or against this idea, we can estimate the chances that a large asteroid or comet will strike Earth today on the basis of the number of objects presently on Earth-crossing orbits. The second figure shows the likelihood of an impact as a function of the size of the impacting body. The horizontal scale indicates the energy released by the collision, measured in *megatons* of TNT. The megaton—4.2×10^{16} joules, the explosive yield of a large nuclear warhead—is the only common terrestrial measure of energy adequate to describe the violence of these events. ∞ ***(More Precisely 2-2)***

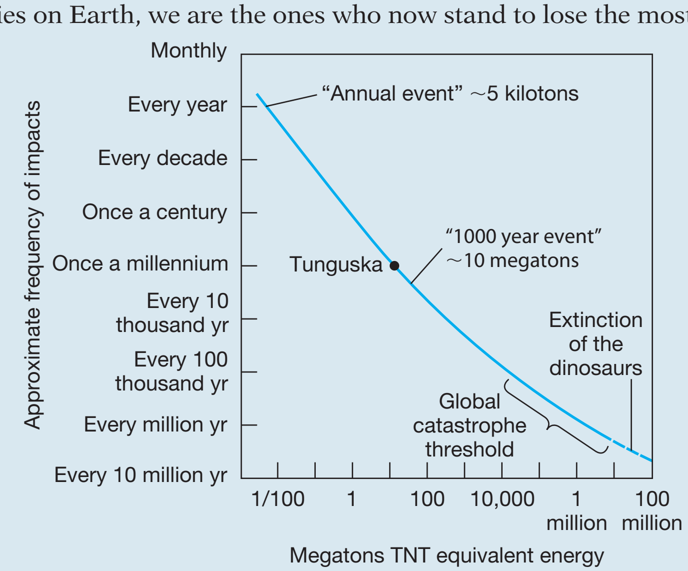
We see that 100 million-megaton impacts, like the planet-wide catastrophe thought to have wiped out the dinosaurs, are very rare, occurring only once every 10 million years or so. However, smaller impacts, equivalent to "only" a few tens of kilotons of TNT (roughly equivalent to the bomb that destroyed Hiroshima in 1945), could happen every few years. The most recent large impact was the Tunguska explosion in Siberia in 1908, which packed a roughly 1-megaton punch (see Figure 4.21).

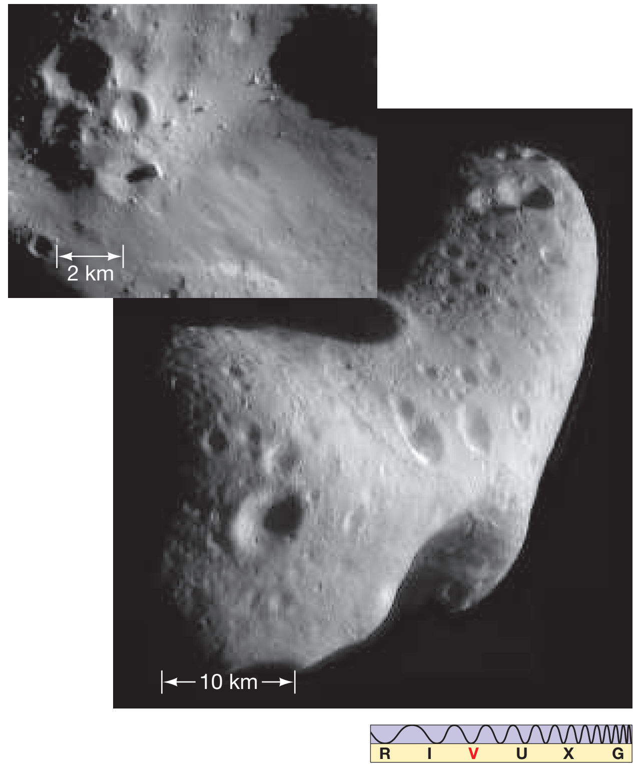
The main geological evidence supporting this theory is a layer of clay enriched with the element iridium, found in 65 million-year-old rocky sediments all around our planet. Iridium is rare on Earth's surface because most of it sank into our planet's interior long ago. The abundance of iridium in this clay layer is about 10 times greater than in other terrestrial rocks, but it matches closely the abundance of iridium found in meteorites (and, we assume, in asteroids and comets too). The site of the catastrophic impact has also been tentatively identified near Chicxulub, in the Yucatan Peninsula in Mexico, where evidence of a heavily eroded crater of just the right size and age has been found.

The idea that extraterrestrial events could cause catastrophic change on Earth was rapidly accepted by most astronomers, but it was controversial among paleontologists and geologists. Opponents argued that the amount of iridium in the clay layer varies greatly from place to place across the globe, and there is no complete explanation of why that should be so. Perhaps, they suggested, the iridium was produced by volcanoes and had nothing to do with an extraterrestrial impact at all.

Still, in the decades since the idea was first suggested, the focus of the debate seems to have shifted. As is often the case in science, the debate has evolved, sometimes erratically, as new data have been obtained, but the reality of a major impact 65 million years ago has become widely accepted. ∞ ***(Sec. 0.5)*** Much of the argument now revolves around the question of whether that event actually caused the extinction of the dinosaurs or merely accelerated a process already under way. The realization that catastrophic impacts can and do occur marked an important milestone in our understanding of planetary evolution (see also *Discovery 7-2*).

As a general rule, we can expect that global catastrophes are bad for the dominant species on a planet. As the dominant species on Earth, we are the ones who now stand to lose the most.





▶ **FIGURE 4.7 Asteroid Eros** The asteroid Eros, as seen by the *NEAR-Shoemaker* probe. Craters of all sizes, ranging from 50 m (the resolution of the image) to 5 km, pit the surface. The inset shows a close-up image of a "younger" section of the surface, where loose material from recent impacts has apparently filled in and erased all trace of older craters. *(JHU/NASA)*

loosely bound rubble piles than pieces of solid rock. Figure 4.6(c) shows another rubble pile, the tiny (0.5-km long) asteroid Itokawa, which was visited in 2005 by the Japanese spacecraft *Hayabusa*. Itokawa's average density is 1900 kg/m^3, but ground-based measurements indicate that the density of the left end is significantly greater, about 2900 kg/m^3, suggesting that the asteroid may be the result of a collision in the relatively recent past. *Hayabusa* soft-landed on Itokawa, scooped up some rocky debris, and returned it to Earth in 2010. Analysis of the debris provided strong evidence that asteroids like Itokawa are the source of most meteorites—the oldest matter in the solar system.

On February 14, 2000, the *NEAR* spacecraft (by then renamed *NEAR-Shoemaker*) went into orbit around the asteroid Eros, sending back high-resolution images and making detailed measurements of the asteroid's size, shape, gravitational and magnetic fields, composition, and structure (Figure 4.7). Eros is a heavily cratered, rocky body, with mass 7×10^{15} kg and a roughly uniform density of around 2400 kg/m^3. It is extensively fractured, apparently due to innumerable impacts in its past.

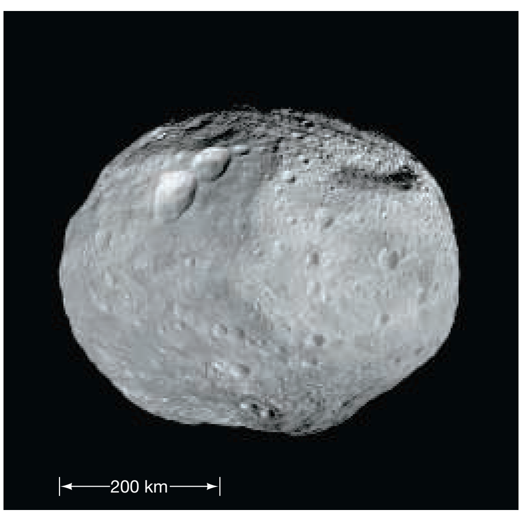
In 2011, NASA's *Dawn* probe entered orbit around Vesta, the second largest asteroid in the solar system. Vesta's most striking surface features (Figure 4.8a) are a set of deep troughs girdling the equator and one of the largest mountains in the solar system—a peak some 22 km high near the south pole. Age estimates based on the extent of cratering (see Section 5.6) indicate that Vesta's southern hemisphere is much younger than the north, suggesting that the major surface features may have been formed by an impact with another large body 1–2 billion years ago. The solar system is a violent place!

Dawn's next target was the dwarf planet Ceres, where it arrived in 2015. This small body appears to have a mainly rocky central core surrounded by an icy outer mantle and an icy/rocky surface. Figure 4.8(b) shows a portion of Ceres's southern hemisphere. The dwarf planet's heavily cratered surface actually shows fewer craters than had been expected, given its orbit in the crowded asteroid belt, perhaps indicating that past surface activity has obliterated some older features. The surface is also punctuated by a dozen or so bright white regions (one of them shown in the inset to Figure 4.8b), of unknown origin and composition.

MA ANIMATION/VIDEO
Orbiting Eros

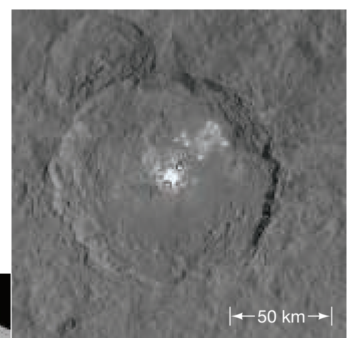
CONCEPT CHECK

Describe some basic similarities and differences between asteroids and the inner planets.



(a)

(b)



◀ **FIGURE 4.8 Vesta and Ceres** (a) Vesta, the solar system's second largest asteroid, as seen here by NASA's *Dawn* spacecraft, is 500 km across and orbits between Mars and Jupiter. Note the deep grooves at top that span much of this rocky body and the towering mountain near the bottom. (b) Part of Ceres's heavily cratered southern hemisphere, imaged by *Dawn* in 2015. The inset shows crater Occator, home to a collection of an intriguing but poorly understood complex of bright spots. *(NASA)*

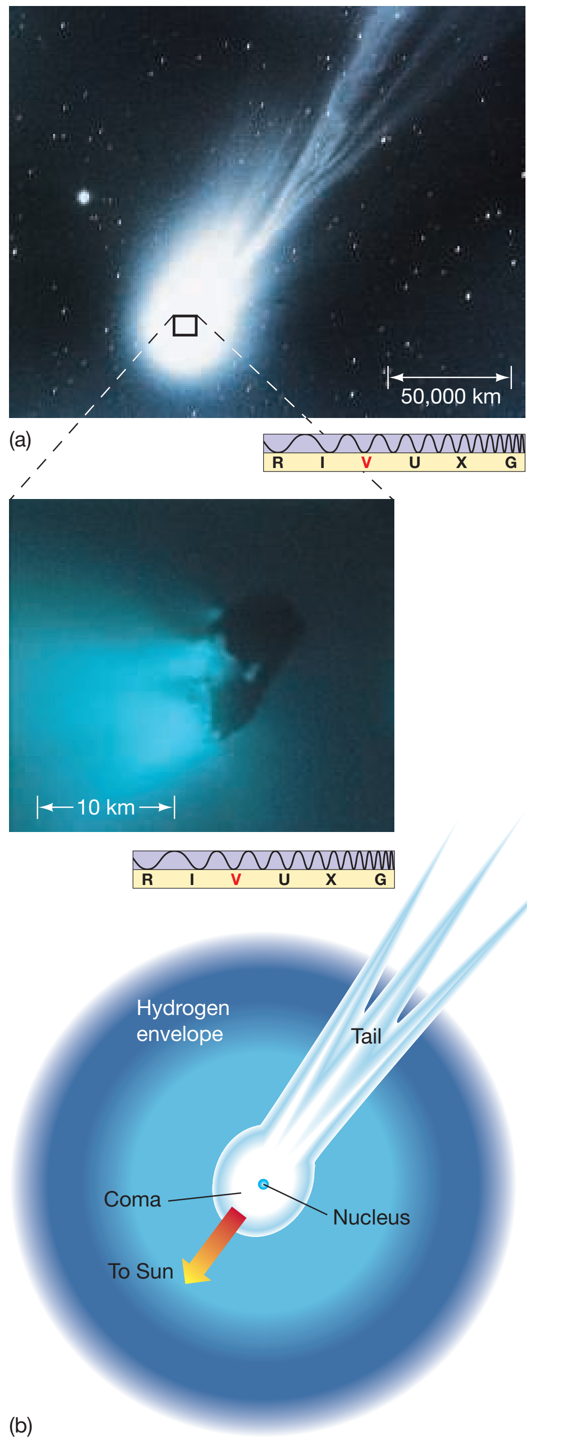
ANIMATION/VIDEO
NEAR Descent

Comets

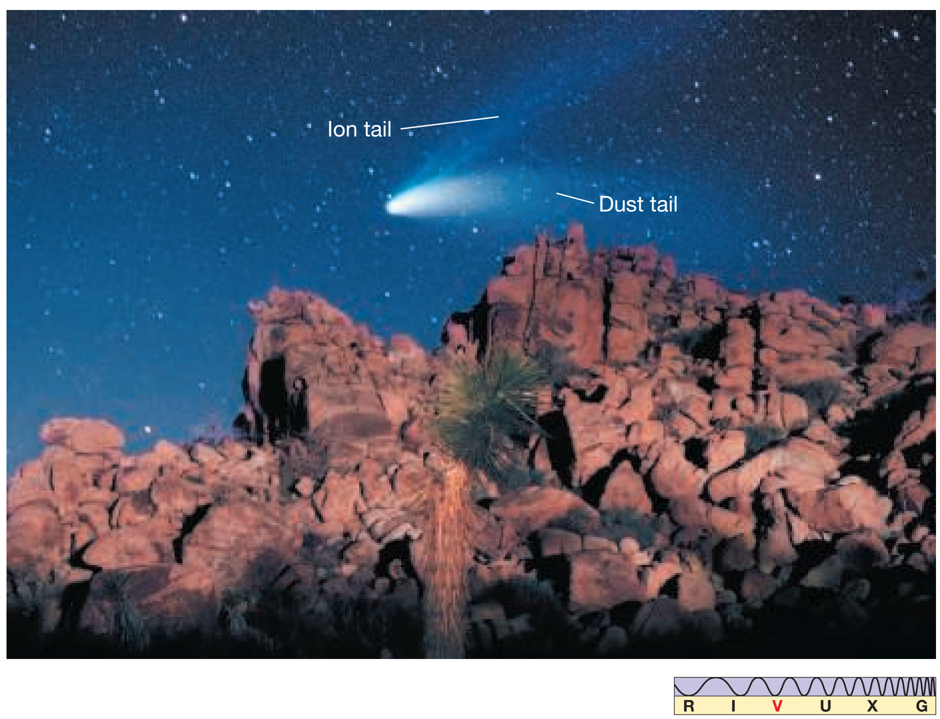
Comets are usually discovered as faint, fuzzy patches of light on the sky while still several astronomical units away from the Sun. Traveling in a highly elliptical orbit, a comet brightens and develops an extended **tail** as it nears the Sun. (The name *comet* derives from the Greek word *kome,* meaning "hair.") As the comet departs from the Sun's vicinity, its brightness and its tail diminish until it once again becomes a faint point of light receding into the distance.

Probably the most famous comet of all is Halley's Comet (Figure 4.9a), whose appearance at 76-year intervals has been documented at every passage since 240 B.C. Its most recent appearance was in 1986. A spectacular show, the tail of Halley's Comet can reach almost a full astronomical unit in length, stretching many tens of degrees across the sky. More recently, in 1997, comet Hale-Bopp, an unusually large and bright comet with a 40°-long tail, was almost certainly the most-watched comet in history (Figure 4.10).

The various parts of a typical comet are shown in Figure 4.9(b). Like the planets, comets emit no visible light of their own—they shine by reflected (or reemitted) sunlight. The **nucleus,** or main solid body, of a comet is only a few kilometers in diameter. During most of the comet's orbit, far from the Sun, only this frozen nucleus exists. But if a comet comes within a few astronomical units of the Sun, its icy surface becomes too warm to remain stable. Part of it becomes gaseous and expands into space, forming a diffuse **coma** (halo) of dust and evaporated gas around the nucleus. The inset to Figure 4.9(a) shows the nucleus of Halley's comet, as seen by the European *Giotto* spacecraft, which approached within 600 km of the nucleus in 1986. The coma gets larger and brighter as the comet nears the Sun. At maximum size, it can measure 100,000 km in diameter—as large as Jupiter or Saturn. Engulfing the coma, an invisible **hydrogen envelope** stretches across millions of kilometers of space. The comet's tail, most pronounced when the comet is closest to the Sun, is larger still, sometimes spanning as much as 1 AU. From Earth, only the coma and tail of a comet are visible to the naked eye. Most of the comet's light comes from the coma. However, most of the mass resides in the nucleus.



▲ **FIGURE 4.9 Halley's Comet** (a) Halley's Comet in 1986, about 1 month before it rounded the Sun. (b) Diagram of a typical comet, showing the nucleus, coma, hydrogen envelope, and tail, approximately to the same scale as in part (a). (c) The inset is Halley's nucleus, as seen by the European *Giotto* spacecraft, showing it to be very dark. The Sun is toward the left in this image. The brightest areas are jets of evaporated gas and dust spewing from the comet's nucleus. *(NOAO ESA/Max Planck Institute)*



▲ **FIGURE 4.10 Comet Tails** In 1997, comet Hale-Bopp displayed both an ion tail (dark blue) and a dust tail (white blue), showing the gentle curvature and inherent fuzziness of the dust. At the comet's closest approach to the Sun, its tail stretched nearly 40° across the sky. *(W. Pacholka)*

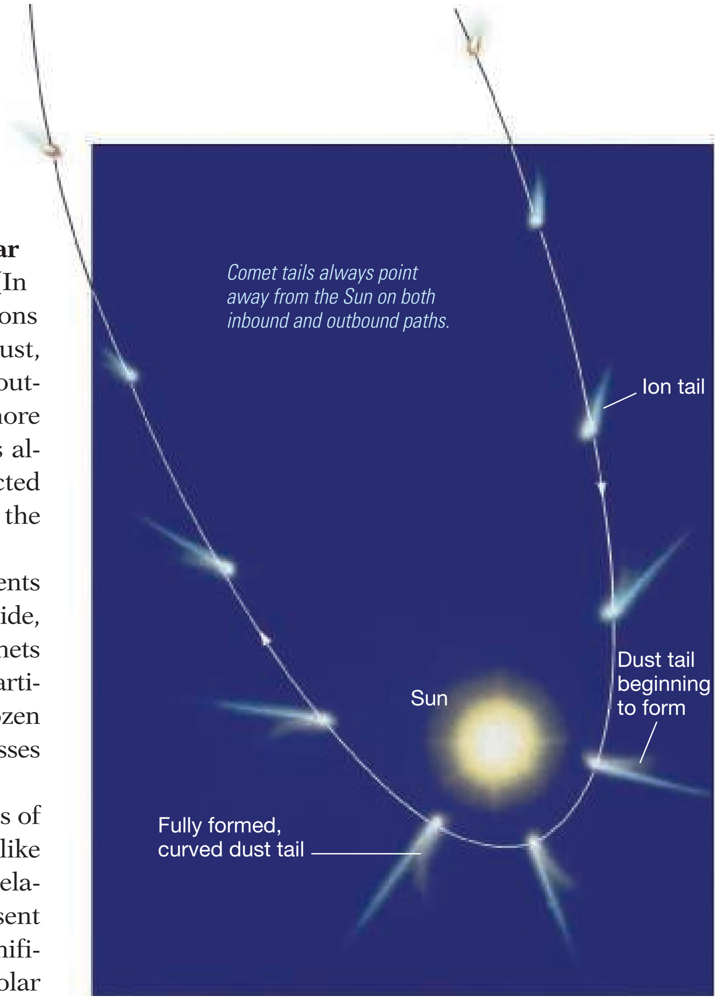
Comets can have two types of tail. An **ion tail** is approximately straight, and often made of glowing, linear streamers like those shown toward the top of Figure 4.10. Its emission spectrum indicates numerous ionized atoms and molecules that have lost some of their normal complement of electrons. ∞ *(Sec. 2.6)* A **dust tail** is usually broad, diffuse, and gently curved, as shown clearly at the center of Figure 4.10. It is rich in microscopic dust particles that reflect sunlight, making the tail visible from afar.

Both types of tails are in all cases directed away from the Sun by the **solar wind,** an invisible stream of matter and radiation escaping from the Sun. (In fact, astronomers first inferred the existence of the solar wind from observations of comet tails.) Consequently, as depicted in Figure 4.11, the tail, be it ion or dust, always lies outside a comet's orbit and actually *leads* the comet when it is outbound from the Sun. The light particles that make up the ion tails are more strongly influenced by the solar wind than by the Sun's gravity, so those tails always point directly away from the Sun. The heavier dust particles are less affected by the pressure of the solar wind and tend to follow the comet's orbit around the Sun, giving rise to the slight curvature of the dust tails.

The nucleus of a comet is composed of dust particles and small rocky fragments all trapped within a loosely packed mixture of methane, ammonia, carbon dioxide, and ordinary water ice, the density of the mixture being about 100 kg/m^3. Comets are often described as "dirty snowballs." Even as atoms, molecules, and dust particles boil off into space, creating a comet's coma and tail, the nucleus remains frozen at a temperature of only a few tens of kelvins. Estimates of typical cometary masses range from 10^{12} to 10^{16} kg, comparable to the masses of small asteroids.

In 2004, NASA's *Stardust* mission approached within 150 km of the nucleus of comet P/Wild 2, collecting cometary particles in a specially designed foam-like aerogel dust detector (see Figure 4.12). The comet was chosen because it is a relative newcomer to the inner solar system, having been deflected onto its present orbit by an encounter with Jupiter in 1974. It has therefore not undergone significant solar heating or evaporation and hasn't changed significantly since our solar system formed. On its return to Earth in 2006, *Stardust* provided researchers with the first-ever samples of cometary material. Detailed chemical analysis revealed organic material apparently formed in deep space, as well as the unexpected presence of silicate (rocky) materials that should only have formed at high temperatures, challenging astronomers' models of solar system formation.

The next year saw a much more violent encounter, when a 400-kg projectile from NASA's *Deep Impact* spacecraft crashed into comet Tempel 1 at more than 10 km/s (23,000 mph), blasting gas and debris from the comet's interior out into interplanetary space, while the spacecraft itself watched from a distance of 500 km.



▲ **FIGURE 4.11 Comet Trajectory** As it approaches the Sun, a comet develops an ion tail, which is directed away from the Sun. Closer in, the dust tail displays marked curvature and tends to lag behind the ion tail. Compare this to comet Hale-Bopp (Figure 4.10).

MA ANIMATION/VIDEO
Comet Hale-Bopp Nucleus Animation

(a) (b) (c)

▲ **FIGURE 4.12 Stardust at Wild-2** INTERACTIVE (a) The *Stardust* spacecraft captured this image (a) of comet P/Wild-2 in 2004, just before the craft passed through the comet's coma. (b) Onboard is a detector made of a foam-like jelly (called *aerogel*) that is 99.8% air, yet is strong enough to stop and store cometary dust particles as they hit the spacecraft. (c) Upon return of the craft to Earth in 2006, analysis began of the minute tracks in the aerogel, the ends of which contain captured comet dust fragments. *(NASA)*

◀ **FIGURE 4.13 Deep Impact** The 5-km-sized nucleus of Comet Tempel 1 is shown at top before impact in 2005 and at bottom shortly after collision with a small projectile launched from the *Deep Impact* robot spacecraft.*(NASA)*

Figure 4.13 shows the mothership's spectacular view of the explosion about 1 minute after impact. Spectroscopic analysis of the ejected gas has provided scientists with their clearest view yet of the internal composition of a comet, confirming the presence of water ice and many organic molecules. *(Sec. 2.8)* Observations of the crater suggest a low-density "fluffy" internal composition, consistent with the "snowball" picture of cometary structure just described.

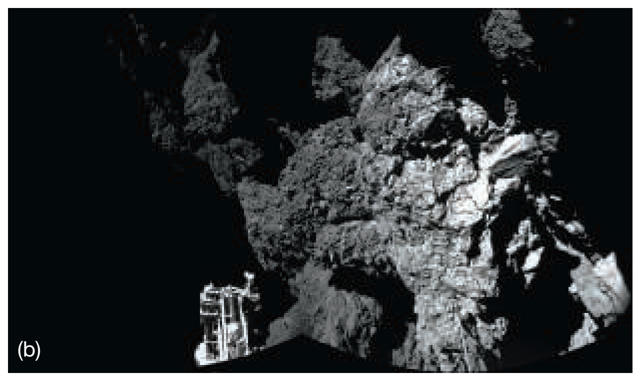
In August 2014, after a 10-year journey that took it almost as far as the orbit of Jupiter, the European *Rosetta* spacecraft rendezvoused with, and went into orbit around, a 4-km-wide comet called 67 P/Churyumov–Gerasimenko while it was still several astronomical units from the Sun. Like comet P/Wild 2, comet 67P was chosen because it is a relative newcomer to the inner solar system, having been placed on its current 3.5 AU orbit by a series of kicks from the planet Jupiter over the last 2 centuries. The chapter-opening image shows a detailed view of the comet from *Rosetta* shortly after arrival.

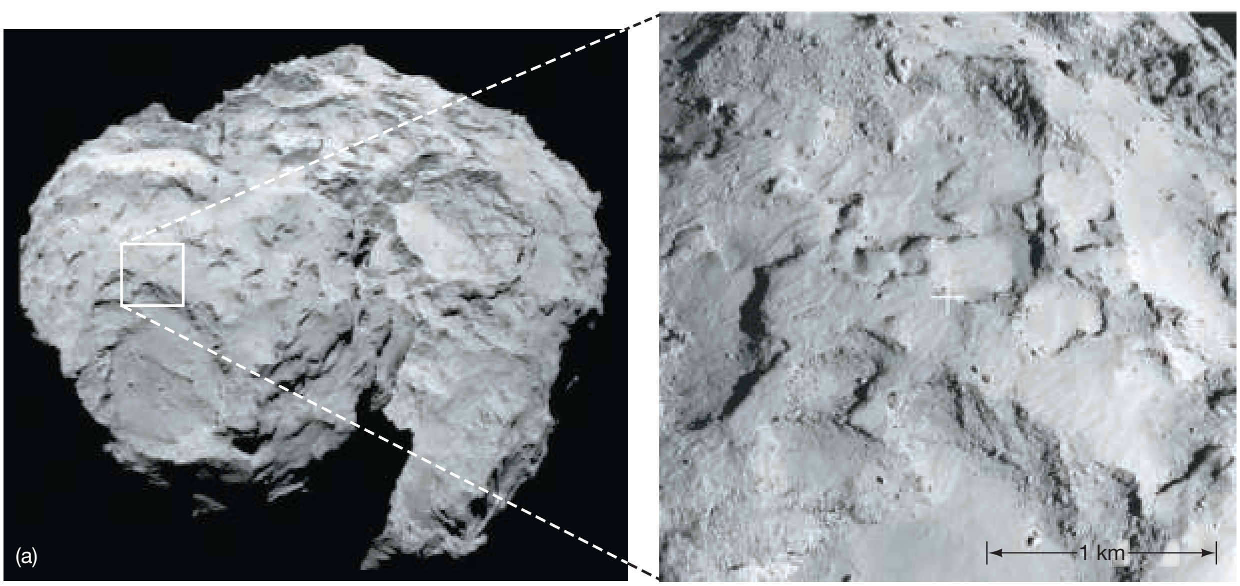
Rosetta carried an array of 12 sensors designed to study the comet's surface, interior, atmosphere, and chemical and magnetic environment. Already (see Section 4.3), some of its measurements of water on and near the comet may have upended some long-held theories of planet formation. However, the star of the show was a 100-kg lander called *Philae*, which made the first ever soft landing on a comet in November 2014 and returned data from the surface for several days before its power supply was depleted. Figure 4.14(a) shows another view of comet 67P, with

ANIMATION/VIDEO
Deep Impact Simulation MA

ANIMATION/VIDEO
Anatomy of a Comet Part I MA

▶ **FIGURE 4.14 Comet Close-Up** (a) This *Rosetta* image of comet 67 P/Churyumov–Gerasimenko shows the comet almost end-on (the view is roughly right to left along the chapter-opening image). The inset highlights the landing site of the *Philae* lander. (b) *Philae*'s view of the surface of this alien world. One of the lander's feet can be seen at the bottom of this panoramic image. *(ESA/Rosetta/MPS)*





the landing site enlarged; Figure 4.14(b) shows *Philae*'s view from the surface. Following the landing, *Rosetta* continued to orbit the comet as it rounded the Sun in August 2015, studying the evolving surface as the Sun's heat warmed and vaporized it.

Comet Orbits

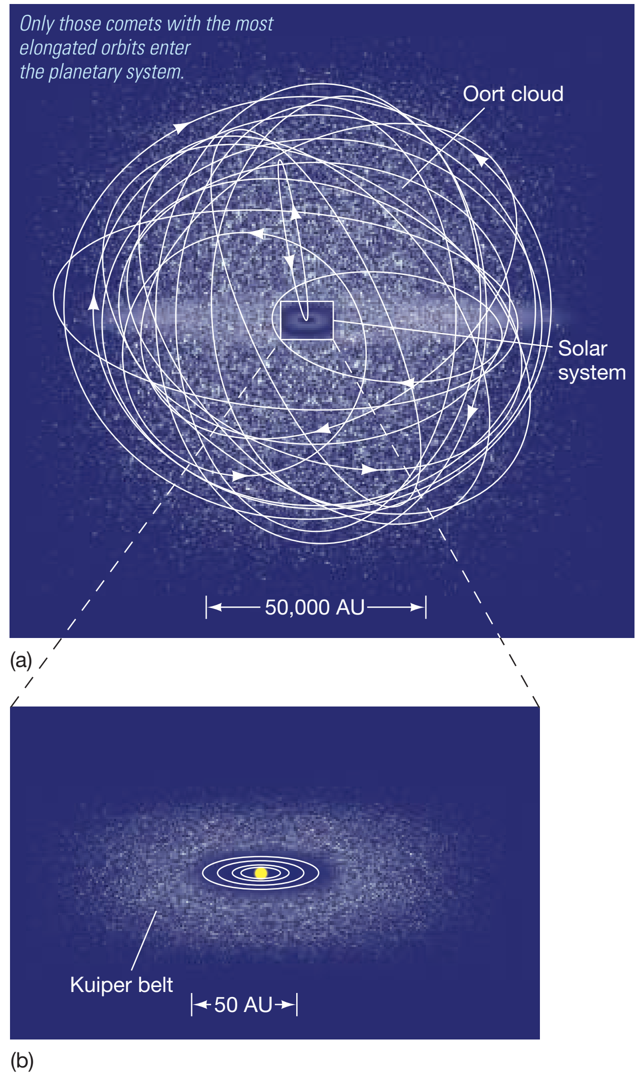
Their highly elliptical orbits take most comets far beyond Pluto, where, in accordance with Kepler's second law, they spend most of their time. ∞ *(Sec. 1.3)* The majority take hundreds of thousands, even millions, of years to complete a single orbit around the Sun. Unlike the orbits of other solar system objects, most comet orbits are not confined to within a few degrees of the ecliptic plane. Rather, they exhibit all inclinations and orientations, roughly uniformly distributed in all directions from the Sun. Only a tiny portion of a cometary orbit can lie within the inner solar system, so it follows that for every comet we see, there must be many more similar objects far from the Sun.

Thus, astronomers reason, there must be a huge cloud of comets lying far beyond the orbit of Pluto, completely surrounding the Sun in all directions (Figure 4.15a). It is named the **Oort cloud,** after the Dutch astronomer Jan Oort, who first wrote in the 1950s of the possibility of such a vast reservoir of inactive, frozen comets. Researchers think that the Oort cloud may be up to 100,000 AU (0.5 light-years) in diameter. However, most Oort cloud comets never come anywhere near the Sun. Indeed, Oort cloud comets rarely approach even the orbit of Pluto. Only when the gravity of a passing star happens to deflect a comet into an extremely eccentric orbit that passes through the inner solar system do we get to see it at all.

A few *short-period comets* (conventionally defined as those having orbital periods of less than 200 years) are exceptions to the above general statements. According to Kepler's third law, these bodies never venture far beyond the orbit of Pluto. Their orbital orientations also differ from the norm—they tend to be prograde and lie close to the ecliptic plane, like the orbits of the planets and most asteroids.

Short-period comets originate beyond the orbit of Neptune in or near a region of the outer solar system called the **Kuiper belt** (after Gerard Kuiper, a pioneer in infrared and planetary astronomy). A little like the asteroids in the inner solar system, most Kuiper belt objects move in roughly circular orbits between about 30 and 100 AU from the Sun, always remaining outside the orbits of the jovian planets (Figure 4.15b). Occasionally, either a chance encounter between two objects or (more likely) the gravitational influence of Neptune "kicks" a Kuiper belt object into an eccentric orbit that brings it into the inner solar system and into our view. The observed orbits of these comets reflect the flattened structure of the Kuiper belt.

More than 1000 Kuiper belt objects are currently known. Because they are so small and distant, only a tiny fraction of the total has so far been observed. Researchers estimate that the total mass of the Kuiper belt may exceed that of the asteroid belt by a factor of 100 or more (although it is probably still less than the mass of Earth). The best-known Kuiper belt object is the former planet Pluto, but larger bodies orbit beyond Neptune. In 2005, astronomers discovered an object (since named Eris) some 10 percent larger and 30 percent more massive than Pluto, moving on an eccentric orbit with a semimajor axis of 70 AU. The discovery of Eris was a major factor in Pluto's demotion from major planet status in 2006.



▲ **FIGURE 4.15 Comet Reservoirs** (a) Diagram of the Oort cloud, showing a few cometary orbits. The solar system is smaller than the overlaid box at the center of the figure. (b) The Kuiper belt, the source of short-period comets, whose orbits hug the ecliptic plane.

MA ANIMATION/VIDEO
Anatomy of a Comet Part II

CONCEPT CHECK

In what sense are the comets we see very unrepresentative of comets in general?

Meteoroids

On a clear night it is possible to see a few *meteors*—shooting stars—every hour. A **meteor** is a sudden streak of light in the night sky caused by friction between air molecules in Earth's atmosphere and an incoming piece of asteroid, meteoroid, or comet. This friction heats and excites the air molecules, which then emit light as they return to their ground states, producing the characteristic bright streak

(a)

(b)

▶ **FIGURE 4.16 Meteor Trails** A bright streak of light called a meteor is produced when a fragment of interplanetary debris plunges into the atmosphere, heating the air to incandescence. (a) A small meteor photographed against a backdrop of stars and the Northern Lights. (b) These meteors (one with a red smoke trail) streaked across the sky during the height of the Leonid meteor storm in November 2001. *(P. Parviainen, J. Lodriguss)*

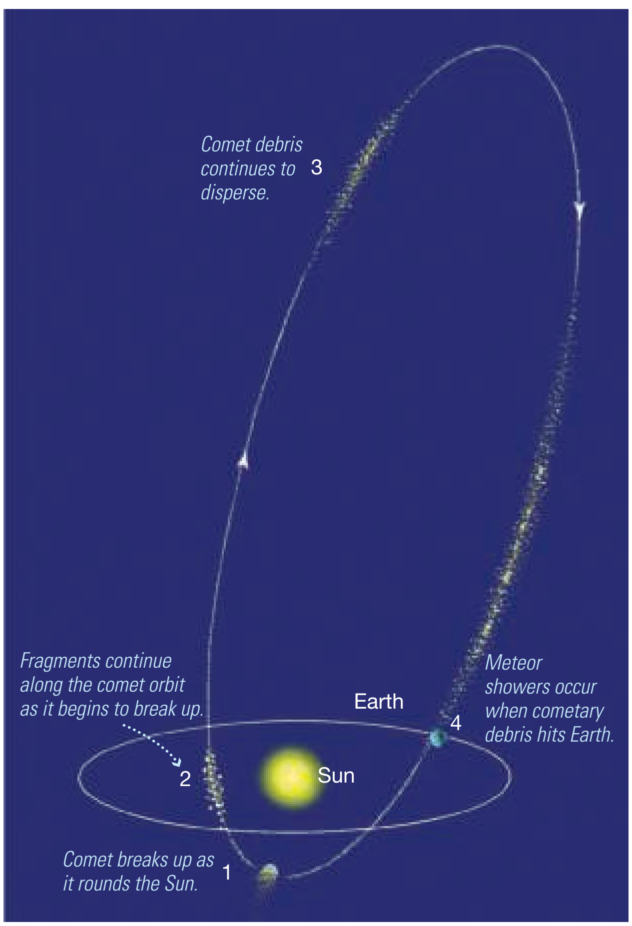
shown in Figure 4.16. Note that the brief flash that is a meteor is in no way similar to the broad, steady swath of light associated with a comet's tail. A meteor is a fleeting event in Earth's atmosphere, whereas a comet tail exists in deep space and can remain visible in the sky for weeks or even months.

Before encountering the atmosphere, the chunk of debris causing a meteor was almost certainly a meteoroid, simply because these small interplanetary fragments are far more common than either asteroids or comets. Any piece of interplanetary debris that survives its fiery passage through our atmosphere and finds its way to the ground is called a **meteorite.**

The smallest meteoroids are mainly the rocky remains of broken-up comets. Each time a comet passes near the Sun, some fragments dislodge from the main body. The fragments initially travel in a tightly knit group of dust or pebble-sized objects called a **meteoroid swarm,** moving in nearly the same orbit as the parent comet. Over the course of time, the swarm gradually disperses along the orbit, so that eventually the **micrometeoroids,** as these small meteoroids are known, become more or less smoothly spread around the parent comet's orbit. If Earth's orbit happens to intersect the orbit of such a young cluster of meteoroids, a spectacular *meteor shower* can result. Earth's motion takes it across a given comet's orbit at most twice a year (depending on the precise orbit of each body). Because the intersection occurs at the same time each year (Figure 4.17), the appearance of certain meteor showers is a regular and (fairly) predictable event (Table 4.3).

Meteor showers are named for their *radiant,* the constellation from whose direction they appear to come (Figure 4.18). For example, the Perseid shower appears to emanate from the constellation Perseus. It can last for several days but reaches its maximum every year on the morning of August 12, when upward of 50 meteors per hour can be observed. Astronomers use the speed and direction of a meteor's flight to compute its interplanetary trajectory. This is how some meteoroid swarms have come to be identified with well-known cometary orbits.

Larger meteoroids—those more than a few centimeters in diameter—are usually *not* associated with comets. They are more likely small bodies that have strayed from the asteroid belt, possibly as the result of asteroid collisions. Their

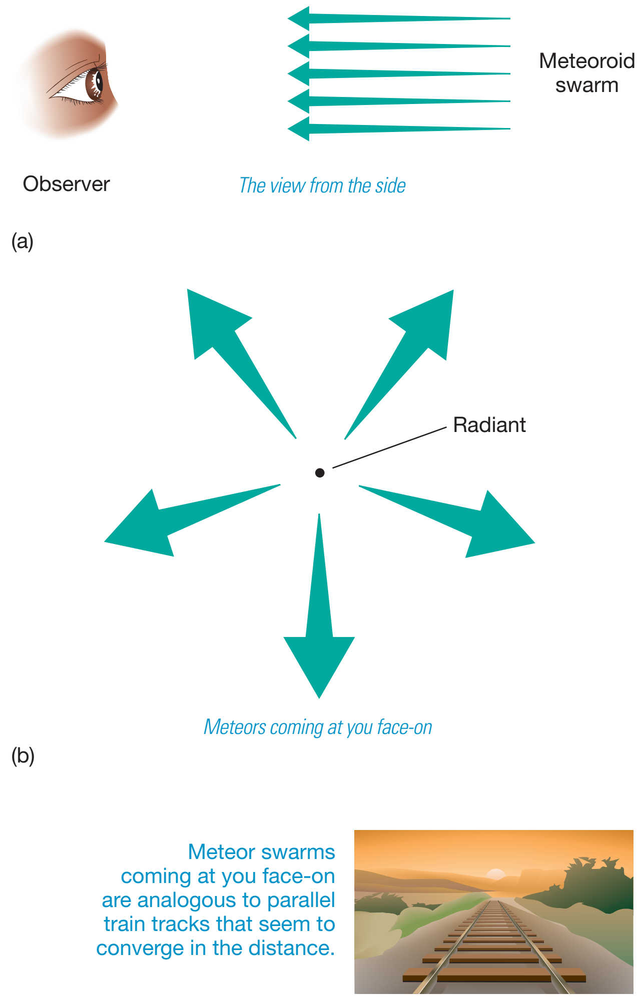


◀ **FIGURE 4.17 Meteor Showers** A meteoroid swarm associated with a given comet intersects Earth's orbit at specific locations, giving rise to meteor showers at specific times of the year. If the comet's path happens to intersect Earth's, the result is a meteor shower each time Earth passes through the intersection (point 4).

TABLE 4.3 Some Prominent Meteor Showers

Morning of Maximum Activity	Shower Name/Radiant	Rough Hourly Count	Parent Comet
Jan. 3	Quadrantid/Bootes	40	—
Apr. 21	Lyrid/Lyra	10	1861I (Thatcher)
May 4	Eta Aquarid/Aquarius	20	Halley
June 30	Beta Taurid/Taurus	25	Encke
July 30	Delta Aquarid/Aquarius/ Capricorn	20	—
Aug. 12	Perseid/Perseus	50	1862III (Swift-Tuttle)
Oct. 9	Draconid/Draco	up to 500	Giacobini-Zimmer
Oct. 20	Orionid/Orion	30	Halley
Nov. 7	Taurid/Taurus	10	Encke
Nov. 16	Leonid/Leo	12[1]	1866I (Tuttle)
Dec. 13	Geminid/Gemini	50	3200 Phaeton[2]

[1]Every 33 years (most recently in 1999 and 2000), as Earth passes through the densest region of this meteoroid swarm, we see intense showers, reaching 1000 meteors per minute for brief periods of time.
[2]Phaeton is an asteroid with no cometary activity, but its orbit matches the meteoroid paths very well.

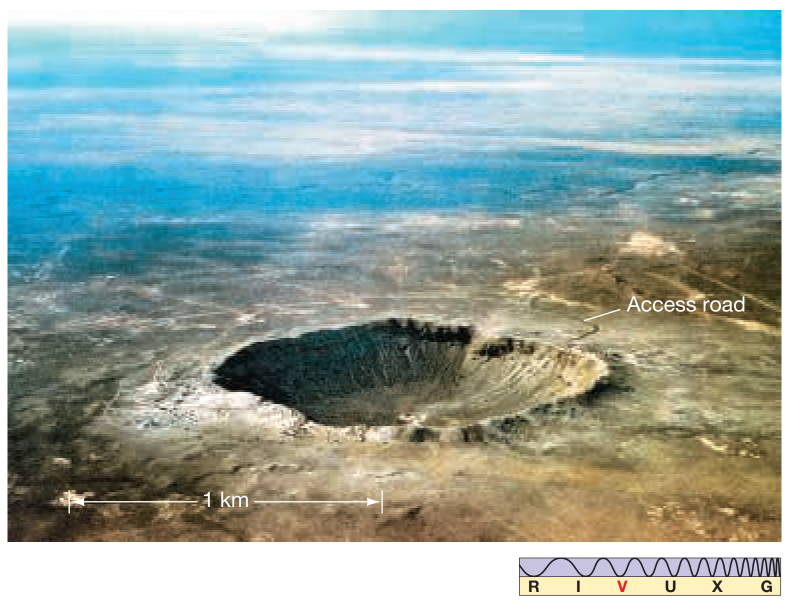


▲ **FIGURE 4.18 Radiant** (a) A group of meteoroids approaches an observer, all of them moving in the same direction at the same speed. (b) From an observer's viewpoint, the trajectories of the meteoroids (and the meteor shower they produce) appear to spread out from a central point, called the radiant.

orbits can sometimes be reconstructed in a manner similar to that used to determine the orbits of meteor showers. In most cases, their computed orbits do indeed intersect the asteroid belt, providing the strongest evidence we have that this is where they originated. These objects are responsible for most of the cratering on the surfaces of the Moon, Mercury, Venus, Mars, and some of the moons of the jovian planets. A few meteorites have been identified as originating on the Moon or Mars, blasted off the surfaces of those bodies by some impact long ago.

Meteoroids smaller than about a meter across (roughly a ton in mass) generally burn up in Earth's atmosphere. Larger bodies reach the surface, where they can cause significant damage, such as the kilometer-wide Barringer Crater shown in Figure 4.19. From the size of this crater, we can estimate that the meteoroid responsible must have had a mass of about 200,000 tons and a diameter of perhaps 50 m. Only 25 tons of iron meteorite fragments have been found at the crash site. The remaining mass must have been scattered by the explosion at impact, broken down by subsequent erosion or buried in the ground. Currently, Earth is scarred with nearly 100 craters larger than 0.1 km in diameter. Most of these are so heavily eroded by weather and geological activity that they can be identified only in satellite photography, as in Figure 4.20. Fortunately, such major collisions between Earth and large meteoroids are thought to be rare events now. On average, they occur only once every few hundred thousand years (see *Discovery 4-1*).

One of the most recent documented meteoritic events occurred in central Siberia on June 30, 1908 (Figure 4.21). The presence of only a shallow depression as well as a complete lack of fragments implies that this intruder exploded several kilometers above the ground, leaving a blasted depression at ground level but no well-formed crater. Recent calculations suggest that the object in question



▶ **FIGURE 4.19 Barringer Crater** The Barringer Meteor Crater, near Winslow, Arizona, 1.2 km in diameter and 0.2 km deep, resulted from a meteorite impact about 25,000 years ago. The meteoroid was probably about 50 m across and likely weighed around 200,000 tons. *(U.S. Geological Survey)*

▲ **FIGURE 4.20 Manicouagan Reservoir** This photograph, taken from orbit by the U.S. *Skylab* space station, shows the ancient impact basin that forms Quebec's Manicouagan Reservoir. A large meteorite landed there about 200 million years ago. *(NASA)*

◀ **FIGURE 4.21 Tunguska Debris** The Tunguska event of 1908 leveled trees over a vast area. Although the impact of the blast was tremendous and its sound audible for hundreds of kilometers, this Siberian site is so remote that little was known about the event until scientific expeditions arrived to study it many years later. *(Sovfoto/Eastfoto)*

was a rocky meteoroid about 30 m across. The explosion, estimated to have been equal in energy to a 10-megaton nuclear detonation, was heard hundreds of kilometers away and produced measurable increases in atmospheric dust levels all across the Northern Hemisphere.

Most meteorites are rocky (Figure 4.22a), although a few are composed mainly of iron and nickel (Figure 4.22b). Their composition is much like that of the rocky inner planets or the Moon, except that some of their lighter elements—such as hydrogen and oxygen—are depleted. Scientists think that the rocky meteorites are associated with the rocky, silicate asteroids and that their light elements boiled away when the bodies on which they originated were wholly or partially molten. Some meteorites do show evidence of strong heating in the past, most likely during the collisions that liberated them from their parent asteroids. Others show no evidence of past heating and may date back to the formation of the solar system. Oldest of all are the *carbonaceous* meteorites, black or dark gray in color and very likely related to the carbonaceous asteroids.

Finally, almost all meteorites are *old*. Radioactive dating shows most of them to be between 4.4 and 4.6 billion years old—roughly the age of the oldest Moon rocks brought back to Earth by *Apollo* astronauts (Chapter 5). Meteorites, along with asteroids, comets, and some lunar rocks, provide essential clues to the original state of matter in the solar neighborhood and to the birth of our planetary system.

CONCEPT CHECK

Why are astronomers so interested in interplanetary matter?

(a) (b)

▶ **FIGURE 4.22 Meteorite Samples** (a) A stony (silicate) meteorite often has a dark crust, created when its surface is melted by the tremendous heat generated during its passage through the atmosphere. The coin at the bottom is for scale. (b) Iron meteorites are much rarer than the stony variety. Most, like the one in this photo, show characteristic crystalline patterns when their surfaces are cut, polished, and etched with acid. *(Science Graphics)*

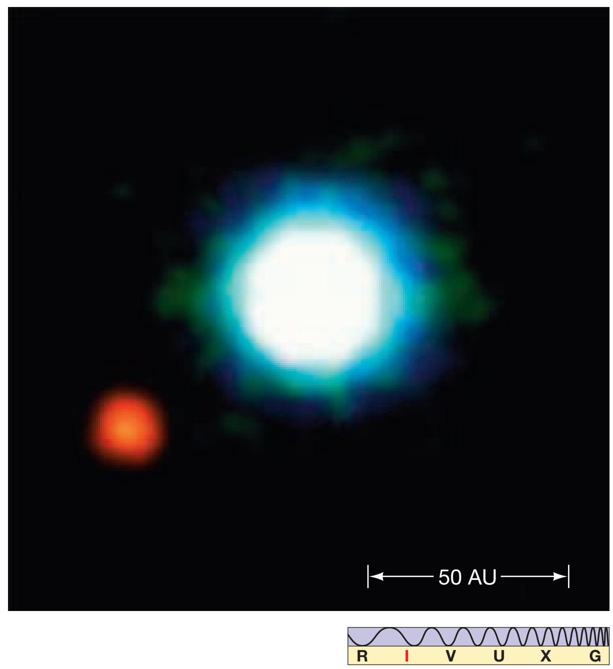
4.3 Formation of the Solar System

You might be struck by the vast range of physical and chemical properties found in the solar system. Our astronomical neighborhood may seem more like a great junkyard than a smoothly running planetary system. Is there some underlying principle that unifies the facts just outlined? Remarkably, the answer is yes. The origin of the solar system is a complex and as yet incompletely solved puzzle, but (we think!) the basic outlines are at last becoming understood.

A comprehensive theory of the formation of the solar system has been a dream of astronomers for centuries. Its development is a case study in the scientific method, on a par with the sweep of ideas presented in Chapters 1 and 2, although in this case the final form of the theory remains to be determined. ∞ *(Sec. 0.5)* As we will see, competing hypotheses have risen, fallen, and in some cases risen again in response to improved observations of our planetary environment. Nevertheless, we now seem to have a coherent picture of how our solar system formed.

Until the mid-1990s, theories of planetary system formation concentrated almost exclusively on our own solar system, for the very good reason that astronomers had no other examples of planetary systems on which to test their ideas. However, all that has now changed. We currently know of about 700 **extrasolar planets**—planets orbiting stars other than the Sun (Figure 4.23)—to challenge our theories. And challenge them they do! As we will see in Section 4.4, the new planetary systems discovered so far seem to have properties quite different from our own and may require us to rethink in some radical ways our concept of how stars and planets form.

Still, we currently have only limited information on these systems—little more than orbits and mass estimates for the largest planets. Accordingly, we begin our study by outlining the comprehensive theory that accounts, in detail, for most of the observed properties of our own planetary system: the solar system. Bear in mind, though, that no part of the scenario we describe here is in any way unique to our own system. The same basic processes should have occurred during the formative stages of many of the stars in our Galaxy. Later we will see how our theories hold up in the face of the new extrasolar data.



▲ **FIGURE 4.23 Extrasolar Planet** Most known extrasolar planets are too faint to be detectable against the glare of their parent stars. However, in this system, called 2M1207, the parent itself (centered) is very faint—a so-called *brown dwarf* (see Chapter 12)—allowing the planet (lower left) to be detected in the infrared. This planet has a mass about five times that of Jupiter and orbits 55 AU from the star, which is 230 light-years away. *(VLT/ESO)*

Model Requirements

Based on the measured ages of the oldest meteorites, as well as the ages of Earth and lunar rocks, planetary scientists think that the age of the solar system is 4.6 billion years—an enormous period of time (although still far less than the 14 billion-year age of the universe—see Chapter 17). What happened so long ago to create the planetary system we see today? And what evidence survives from those early times to constrain our theories? Any theory of the origin and architecture of our planetary system must adhere to these 10 known facts:

1. *Each planet is relatively isolated in space.* The planets orbit at progressively larger distances from the central Sun; they are not bunched together.
2. *The orbits of the planets are nearly circular.* With the exception of Mercury, which we will argue is a special case, each planetary orbit closely describes a perfect circle.
3. *The orbits of the planets all lie in nearly the same plane.* The planes swept out by the planets' orbits are accurately aligned to within a few degrees. Again, Mercury is a slight exception.
4. *The planets all orbit the Sun in the same direction (counterclockwise as viewed from above Earth's North Pole).* Virtually all the large-scale motions in the solar

system (other than cometary orbits) are in the same plane and in the same sense. The plane is that of the Sun's equator, and the sense is that of the Sun's rotation.
5. *Most planets rotate on their axis in roughly the same sense as the Sun.* Exceptions are Venus and Uranus.
6. *Most of the known moons revolve about their parent planet in the same direction as the planet rotates on its axis.* Of the large moons in the solar system, only Neptune's moon Triton is an exception.
7. *Our planetary system is highly differentiated.* The terrestrial planets are characterized by high densities, moderate atmospheres, slow rotation rates, and few or no moons. The jovian planets have low densities, thick atmospheres, rapid rotation rates, and many moons.
8. *Asteroids are very old and exhibit a range of properties not characteristic of either the terrestrial or the jovian planets or their moons.* Asteroids share, in rough terms, the bulk orbital properties of the planets. However, they appear to be made of primitive, unevolved material, and the meteorites that strike Earth are the oldest rocks known.
9. *The Kuiper belt is a collection of asteroid-sized icy bodies orbiting beyond Neptune.* Pluto is now considered such a Kuiper belt object.
10. *The Oort cloud comets are primitive, icy fragments that do not orbit in the plane of the ecliptic and reside primarily at large distances from the Sun.* While similar to the Kuiper belt in composition, the Oort cloud is a completely distinct part of the outer solar system.

These 10 facts strongly suggest a high degree of order in our solar system. The large-scale architecture is too neat, and the ages of the components too uniform, to be the result of random chaotic events. The overall organization points toward a single formation, an ancient but one-time event 4.6 billion years ago.

In the next few chapters we will see that some planetary properties (such as atmospheric composition and interior structure) have gradually *evolved* into their present states during the billions of years since the planets formed. However, *no* such evolutionary explanation exists for the items in the preceding list. For example, Newton's laws imply that the planets must move in elliptical orbits with the Sun at one focus, but they offer no explanation of why the observed orbits should be roughly circular, coplanar, and prograde. We know of no way in which the planets could have started off in random paths, then later evolved into the orbits we see today. Their basic orbital properties must have been established at the outset.

In addition to its many regularities, our solar system also has many notable *irregularities,* some of which we have already mentioned. Far from threatening our theory, however, these irregularities are important facts for us to consider in shaping our explanations. For example, any theory explaining solar system formation must not insist that *all* planets rotate in the same sense or have only prograde moons, because that is not what we observe. Instead, the theory should provide strong reasons for the observed planetary characteristics yet be flexible enough to allow for and explain the deviations, too. And, of course, the existence of the asteroids and comets that tell us so much about our past must be an integral part of the picture. That's a tall order, yet many researchers now think we are close to that level of understanding.

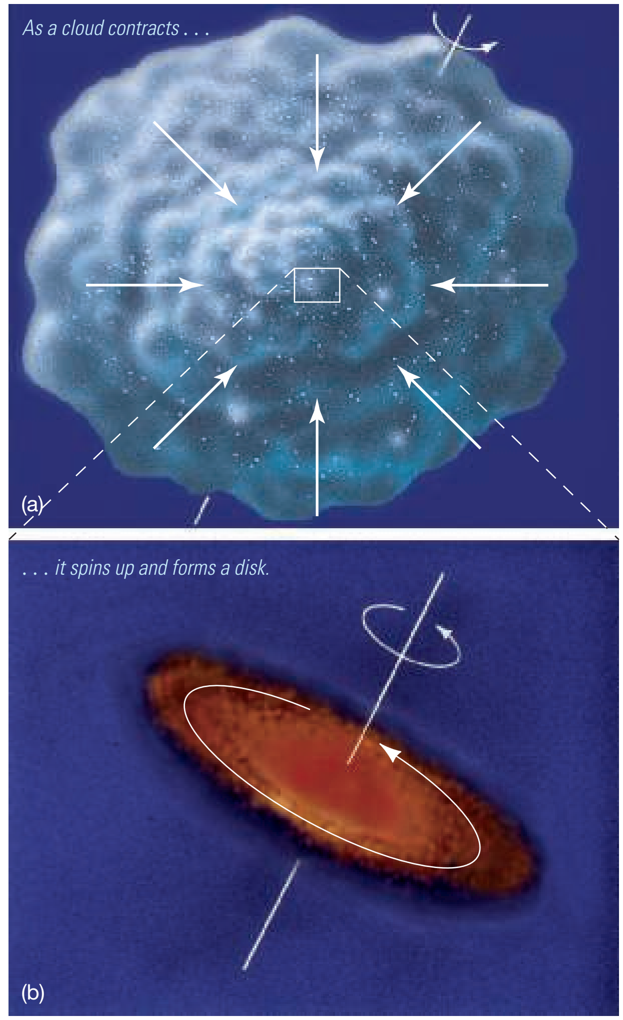
PROCESS OF SCIENCE CHECK

Why is it important that a theory of solar system formation make clear statements about how planets arose yet not be too rigid in its predictions?

Nebular Contraction

Modern theory holds that planets are by-products of the process of star formation (Chapter 11). Imagine a large cloud of interstellar dust and gas—called a **nebula**—a light-year or so across. Now suppose that due to some external influence, such as a collision with another interstellar cloud or perhaps the explosion of a nearby star, the nebula starts to contract under the influence of its own gravity. As it contracts, it becomes denser and hotter, eventually forming a star—the Sun—at its center.

ANIMATION/VIDEO
Beta Pictoris Warp



▶ **FIGURE 4.24 Angular Momentum INTERACTIVE** (a) Conservation of angular momentum demands that a contracting, rotating cloud must spin faster as its size decreases. (b) Eventually, a small part of it destined to become the solar system came to resemble a gigantic pancake. The large blob at the center ultimately became the Sun.

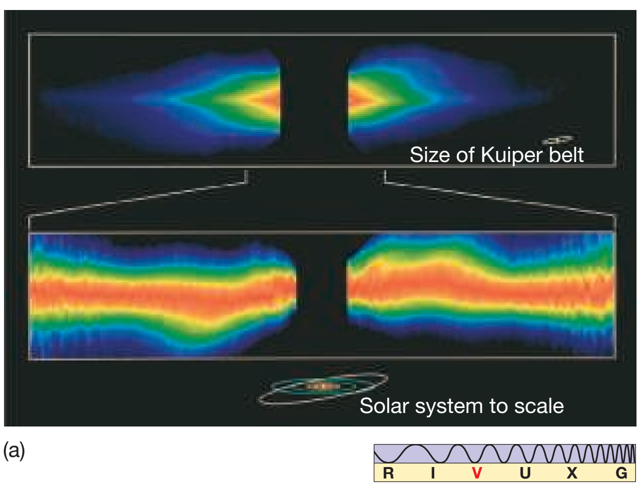
In 1796 the French mathematician-astronomer Pierre Simon de Laplace showed mathematically that conservation of angular momentum (objects spin faster as they shrink—see *More Precisely 4-2*) demands that our hypothetical nebula must spin faster as it contracts. The increase in rotation speed, in turn, causes the nebula's *shape* to change as it shrinks. Centrifugal forces (the outward "push" due to rotation) tend to oppose the contraction in directions perpendicular to the rotation axis, with the result that the nebula collapses most rapidly along the rotation axis. As shown in Figure 4.24, by the time it has shrunk to about 100 AU, the cloud has flattened into a pancake-shaped disk. This swirling mass destined to become our solar system is usually referred to as the **solar nebula.**

If we now suppose that planets form out of this spinning disk, we can begin to understand the origin of much of the architecture observed in our planetary system today, such as the near-circularity of the planets' orbits and the fact that they move in the same sense in almost the same plane. The idea that planets form from such a disk is called the **nebular theory.**

Astronomers are fairly confident that the solar nebula formed such a disk because we can see similar disks around other stars. Figure 4.25(a) shows a visible-light image of the region around the star Beta Pictoris, which lies about 50 light-years from the Sun. When the light from Beta Pictoris itself is removed and the resulting image enhanced by a computer, a faint disk of matter (viewed almost edge-on here) can be seen. This particular disk is roughly 1000 AU across—about 10 times the diameter of the Kuiper belt. Astronomers think that Beta Pictoris is a very young star, perhaps only 100 million years old, and that we are witnessing it pass through an evolutionary stage similar to that experienced by our own Sun 4.6 billion years ago. Figure 4.25(b) shows an artist's conception of the disk.

As we saw in Chapter 0, scientific theories must continually be tested and refined as new data become available. ∞ *(Sec. 1.5)* Unfortunately for the original nebular theory, while Laplace's description of the collapse and flattening of the

MA ANIMATION/VIDEO
The Formation of the Solar System



▲ **FIGURE 4.25 Beta Pictoris** (a) A computer-enhanced view of a disk of warm matter surrounding the star Beta Pictoris. False color is used here to accentuate the details. The bottom image is a close-up of the inner part of the disk, whose warp is possibly caused by the gravitational pull of unseen companions. In both images, the overwhelmingly bright central star has been covered to let us see the much fainter disk surrounding it. (b) An artist's conception of the disk of clumped matter, showing the warm disk with a young star at the center and several comet-sized or larger bodies already forming. Mottled dust is seen throughout—such protoplanetary regions are probably very "dirty." *(NASA; D. Berry)*

4.2 MORE PRECISELY

The Concept of Angular Momentum

Most celestial objects rotate. Planets, moons, stars, and galaxies all have some *angular momentum,* which we may define loosely as the tendency of a body to keep spinning or moving in a circle, or, equivalently, how much effort must be expended to stop it. Angular momentum is a fundamental property of any rotating object, as important a quantity as its mass or its energy.

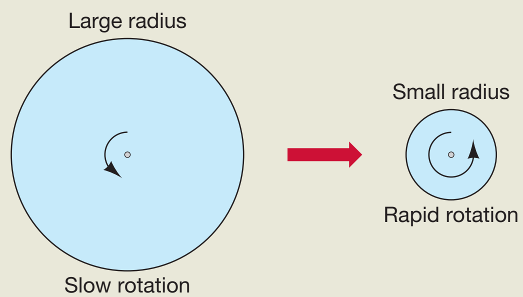
Intuitively, we know that the more massive an object, or the larger it is, or the faster it spins, the harder it is to stop. In fact, angular momentum depends on the object's *mass, rotation rate* (measured in, say, revolutions per second), and *radius,* in a very specific way:

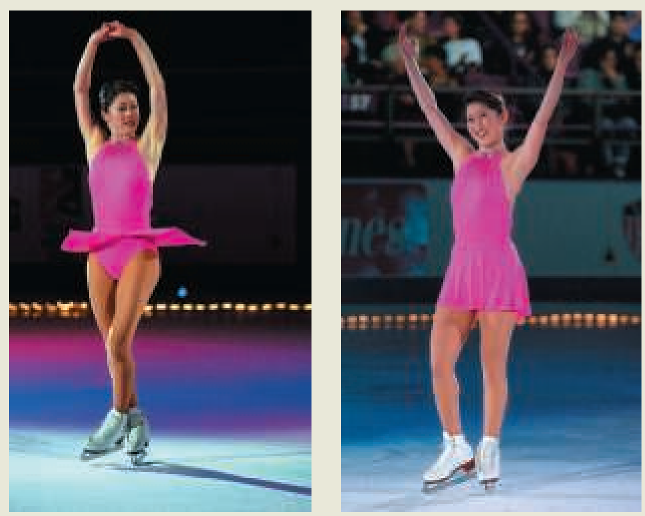
$$\text{angular momentum} \propto \text{mass} \times \text{rotation rate} \times \text{radius}^2.$$

Recall that the symbol $\propto$ means "is proportional to." The constant of proportionality depends on the details of how the object's mass is distributed.

According to Newton's laws of motion, angular momentum is *conserved* at all times—that is, it must remain constant before, during, and after a physical change in any object, so long as no external forces act. This allows us to relate changes in size to changes in rotation rate. As illustrated in the accompanying figure, if a spherical object having some spin begins to contract, the above relationship demands that it spin faster, so that the product mass $\times$ angular speed $\times$ radius^2 remains constant. The sphere's mass does not change during the contraction, but its radius clearly decreases. The rotation speed must therefore increase in order to keep the total angular momentum unchanged. Figure skaters use this principle to spin faster by drawing in their arms and slow down by extending them (as shown in the second accompanying figure). The mass of the human body remains the same, but its overall radius changes, causing the body's rotation rate to change in order to keep the angular momentum constant.

To take an example from the text, suppose that the interstellar gas cloud from which our solar system formed was initially 1 light-year across and rotating very slowly—once every 10 million years, say. The cloud's mass doesn't change (we assume) during the contraction, but its radius decreases. The rotation rate must therefore *increase* in order to keep the total angular momentum unchanged. By the time it has collapsed to a radius of 100 AU, its radius has shrunk by a factor of (1 light-year/100 AU) $\approx 9.5 \times 10^{12}$ km/$1.5 \times 10^{10} \approx 630$. Conservation of angular momentum then implies that its (average) spin rate increases by a factor of $630^2 \approx 400{,}000$, to roughly one revolution every 25 years, close to the orbital period of Saturn.

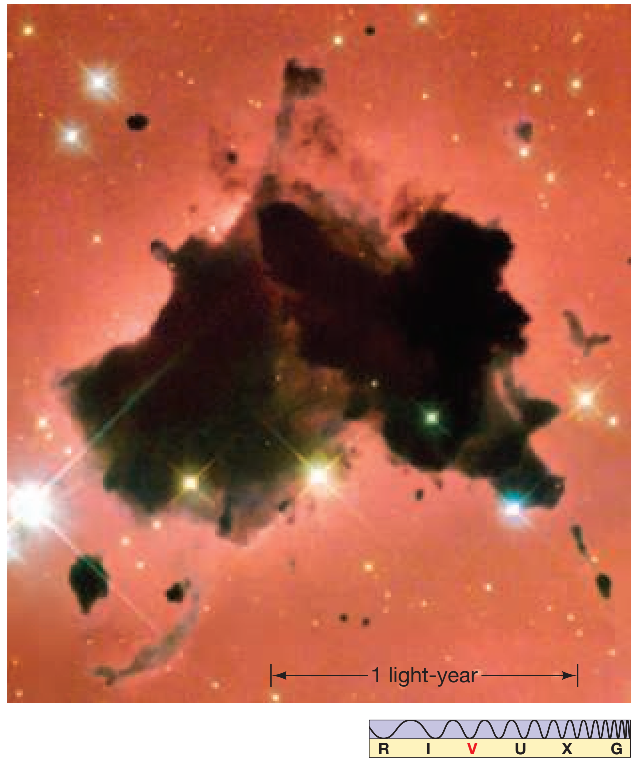




D. Lefranc/Gamma-Rapho/Getty Images

solar nebula was essentially correct, we now know that a disk of gas would *not* form clumps of matter that would subsequently evolve into planets. In fact, modern computer calculations predict just the opposite: Any clumps in the gas would tend to disperse, not contract further. However, the model currently favored by most astronomers, known as the **condensation theory,** rests squarely on the old nebular theory, combining its basic physical reasoning with new information about interstellar chemistry to avoid most of the original theory's problems.

The key new ingredient is *interstellar dust* in the solar nebula. Astronomers now recognize that the space between the stars is strewn with microscopic dust grains, an accumulation of the ejected matter of many long-dead stars. These dust particles probably formed in the cool atmospheres of old stars, then grew by accumulating more atoms and molecules from the interstellar gas. The end result is



▶ FIGURE 4.26 **Dark Clouds** Glowing interstellar gas and dark dust clouds mark this region of star formation. These opaque dense dust clouds, called globules, are silhouetted here against bright emission and newborn stars in the star-forming region IC 2944. *(NASA)*

that interstellar space is littered with tiny chunks of icy and rocky matter, having typical diameters of about 10^{-5} m. Figure 4.26 shows one of many such dusty regions in the vicinity of the Sun.

Dust grains play an important role in the evolution of any gas cloud. Dust helps to cool warm matter by efficiently radiating heat away in the form of infrared radiation. When the cloud cools, its molecules move around more slowly, reducing the internal pressure and allowing the nebula to collapse more easily. ∞ *(More Precisely 2-1)* Furthermore, the dust grains greatly speed up the process of collecting enough atoms to form a planet. They act as **condensation nuclei**—microscopic platforms to which other atoms can attach, forming larger and larger balls of matter. This is similar to the way raindrops form in Earth's atmosphere; dust and soot in the air act as condensation nuclei around which water molecules cluster.

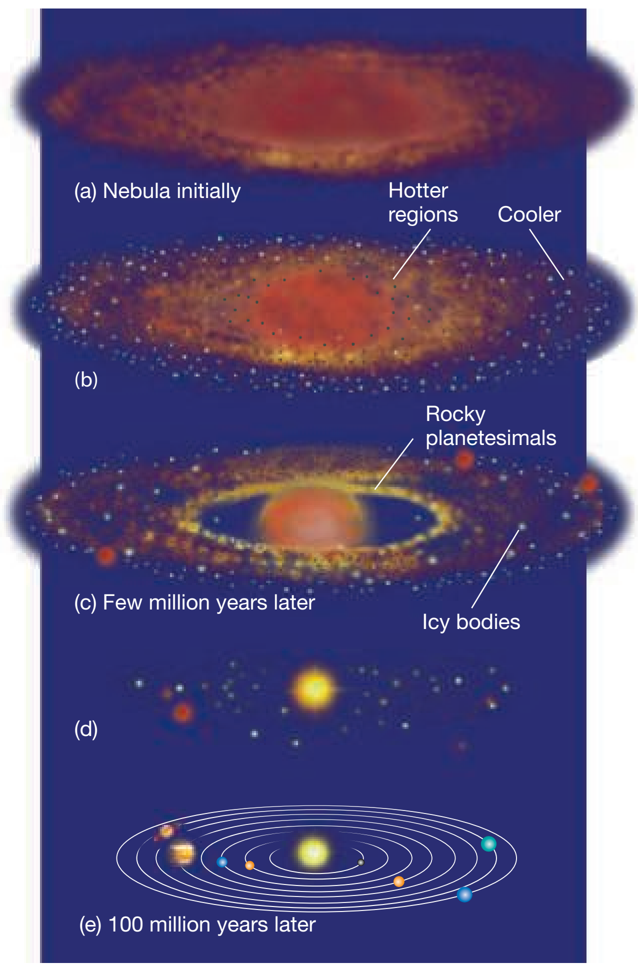
Planet Formation

According to the condensation theory, the planets formed from the solar nebula (Figure 4.27a) in three distinct stages. The first two apply to all planets, the third only to the giant jovian worlds.

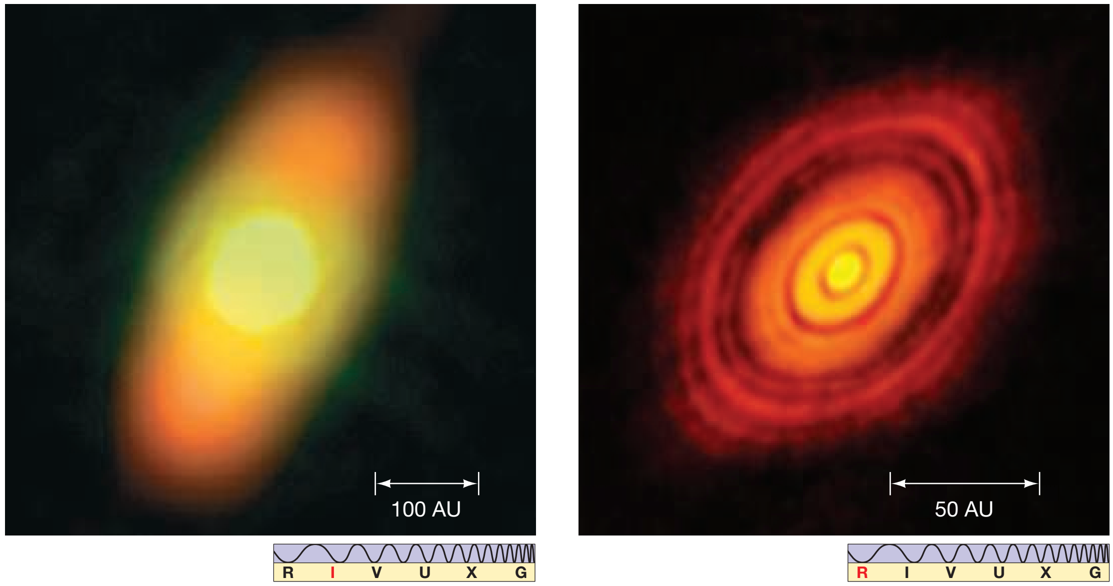
The first stage of planet formation began when dust grains in the solar nebula formed condensation nuclei around which matter began to accumulate (Figure 4.27b). This vital step greatly hastened the critical process of forming the first small clumps of matter. Once these clumps formed, they grew rapidly by sticking to other clumps. (Imagine a snowball thrown through a fierce snowstorm, growing bigger as it encounters more snowflakes.)

As the clumps grew larger, their surface areas increased, and consequently, the rate at which they swept up new material accelerated. They gradually formed larger and larger objects, the size of pebbles, baseballs, basketballs, and boulders. Figure 4.28 shows radio and infrared views of two young stars whose protostellar disks are thought to be in just this state. Eventually, this process of **accretion**—the gradual growth of small objects by collision and sticking—created objects a few hundred kilometers across.

At the end of the first stage of planet formation, the solar system was made up of hydrogen and helium gas and millions of **planetesimals**—objects the size of small moons, having gravitational fields just strong enough to affect their neighbors. By then, their gravity was strong enough to sweep up material that would otherwise not have collided with them, so their rate of growth became faster still. During this second phase of planet formation, gravitational forces between planetesimals caused them to collide and merge, forming larger and larger objects. Because larger bodies exert stronger gravitational pulls, eventually almost all the planetesimal material was swept up into a few large **protoplanets**—accumulations of matter that would eventually evolve into the planets we know today.



▶ FIGURE 4.27 **Solar System Formation** The condensation theory of planet formation. (a) The solar nebula after it has contracted and flattened to form a spinning disk (Figure 4.24b). The large red blob in the center will become the Sun. Smaller blobs in the outer regions may become jovian planets (see Figure 4.29). (b) Dust grains act as condensation nuclei, forming clumps of matter that collide, stick together, and grow into moon-sized planetesimals. (c) After a few million years, strong winds from the still-forming Sun begin expelling nebular gas, and some massive planetesimals in the outer solar system have already captured gas from the nebula. (d) With the gas ejected, planetesimals continue to collide and grow. (e) Over the course of a hundred million years or so, planetesimals are accreted or ejected, leaving a few large planets that travel in roughly circular orbits.



▶ **FIGURE 4.28 Newborn Solar Systems?** (a) This infrared image, taken by the *Spitzer Space Telescope,* of the bright star Fomalhaut, some 25 light-years from Earth, shows a circumstellar disk in which the process of accretion is underway. The star itself is well inside the yellowish blob at center. (b) This ALMA image of the disk around the star HL Tauri, 450 light-years away, shows fine structure in the gas thought to be caused by still-forming planets. The angular resolution is a remarkable 35 milliarcseconds—finer than available even using *HST*. *(NASA)*

As the protoplanets grew, a competing process became important. Their strong gravitational fields produced many high-speed collisions between planetesimals and protoplanets. These collisions led to **fragmentation** as small objects broke into still smaller chunks that were then swept up by the protoplanets. Only a relatively small number of 10- to 100-km fragments escaped capture by a planet or a moon and became the asteroids and comets.

After about 100 million years, the primitive solar system had evolved into eight protoplanets, dozens of protomoons, and a glowing **protosun** at the center. Roughly a billion more years were required to sweep the system clear of interplanetary trash. This was a period of intense meteoritic bombardment whose effects on the Moon and elsewhere are still evident today (see Chapter 5).

Making the Jovian Planets

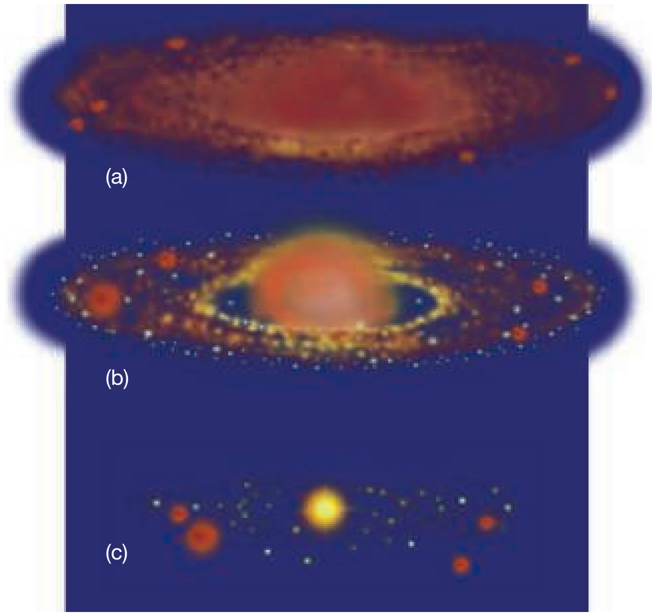
The two-stage accretion picture just described has become the accepted model for the formation of the terrestrial planets in the inner solar system. However, the origin of the giant jovian worlds is less clear. Two somewhat different views, with important consequences for our understanding of extrasolar planets, have emerged.

ANIMATION/VIDEO MA
Protoplanetary Disk Destruction

ANIMATION/VIDEO MA
Protoplanetary Disks in the Orion Nebula

In the first, more conventional scenario depicted in Figures 4.27(c and d), the four largest protoplanets in the outer solar system grew rapidly and became massive enough to enter a third phase of planetary development—their strong gravitational fields swept up large amounts of gas directly from the solar nebula. As we will see, there was a lot more raw material available for planet building in the outer solar system, so protoplanets grew much faster there. In this scenario, the cores of the jovian planets reached the point where they could capture nebular gas in less than a few million years. Compare this to the inner solar system, where the smaller, terrestrial protoplanets never reached this stage. Their growth was slow, taking 100 million years to form the planets we know today, and their masses remained relatively low.

In the second scenario, the giant planets formed through instabilities in the cool outer regions of the solar nebula—not so different from Laplace's original idea—mimicking on small scales the collapse of the initial interstellar cloud. In this view, the jovian protoplanets formed directly and very rapidly, skipping the initial accretion stage and perhaps taking less than a thousand years to acquire much of their mass. These first protoplanets had gravitational fields strong enough to scoop up gas and dust from the solar nebula, allowing them to grow into the giants we see today. Figure 4.29 illustrates this alternative formation path.



▶ **FIGURE 4.29 Jovian Condensation INTERACTIVE** As an alternative to the growth of massive protoplanetary cores followed by accretion of nebular gas, some or all of the giant planets may have formed directly by instabilities in the cool gas of the outer solar nebula. Part (a) shows the same instant as Figure 4.27(a). (b) Only a few thousand years later, four gas giants have formed (red blobs), circumventing the accretion process sketched in Figure 4.27. With the nebula gone (c), the giant planets have taken their place in the outer solar system.

Ongoing studies of planetary composition and internal structure (for example, the size of the protoplanetary core), as well as observations of extrasolar planets, may one day allow us to distinguish between these competing theories. In either case, once the jovian protoplanets reached the critical size at which they could capture nebular gas, they grew rapidly. Their growth rate increased further as their gravitational fields intensified, and they reached their present masses in just a few million years.

Many of the jovian moons probably also formed by accretion, but on a smaller scale, in the gravitational fields of their parent planets. Once nebular gas began to flow onto the large jovian protoplanets, conditions probably resembled a miniature solar nebula, with condensation and accretion continuing to occur. The large moons of the outer planets almost certainly formed in this way. Some of the smaller moons may be captured planetesimals.

What of the gas that made up most of the original cloud? Why don't we see it today throughout the planetary system? All young stars apparently experience a highly active evolutionary stage known as the *T-Tauri phase* (see Chapter 11), during which their radiation emission and stellar winds are very intense. When our Sun entered this phase, a few million years after the solar nebula formed, any gas remaining between the planets was blown away into interstellar space by the solar wind and the Sun's radiation pressure. Afterward, all that remained were protoplanets and planetesimal fragments, ready to continue their long evolution into the solar system we know today. Note that the evolution of the Sun sets the time frame for the formation of the jovian planets. The outer planets *must* have formed before the nebula dispersed.

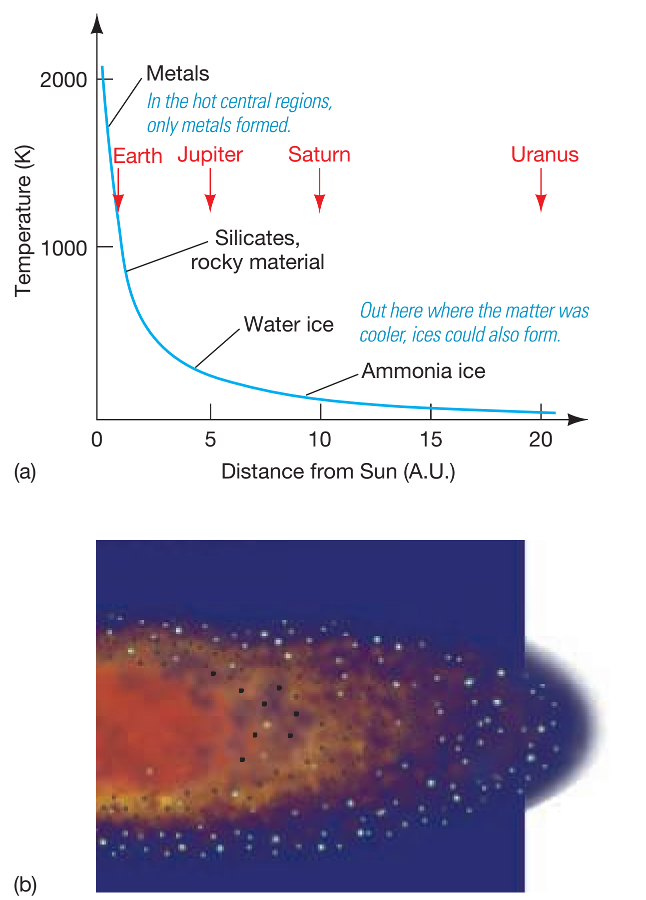
Differentiation of the Solar System

The condensation theory explains the basic composition differences among the terrestrial and jovian planets and the smaller bodies that constitute the solar system. Indeed, it is in this context that the term *condensation* derives its true meaning.

As the solar nebula contracted under the influence of gravity, it heated up as it flattened into a disk. The density and temperature were greatest near the central protosun and much lower in the outlying regions. In the hot inner regions, dust grains broke apart into molecules, which in turn split into atoms. Most of the original dust in the inner solar system disappeared at this stage, although the grains in the outermost parts probably remained largely intact.

The destruction of the dust in the inner solar nebula introduced an important new ingredient into the theoretical mix, one that we omitted from our earlier discussion. With the passage of time, the gas radiated away its heat, and the temperature decreased at all locations except in the very core, where the Sun was forming. Everywhere beyond the protosun new dust grains began to condense out, much as raindrops, snowflakes, and hailstones condense from moist, cooling air here on Earth. It may seem strange that although there was plenty of interstellar dust early on, it was mostly destroyed, only to form again later. However, a critical change had occurred. Initially, the nebular gas was uniformly peppered with dust grains. When the dust re-formed later, the distribution of grains was very different.

Figure 4.30 shows the temperature in various parts of the primitive solar system just before the onset of accretion. At any given location, the only materials to



▲ **FIGURE 4.30 Temperature in the Early Solar Nebula** (a) Theoretically computed variation of temperature across the primitive solar nebula illustrated in part (b), which shows half of the disk in Figure 4.27(b).

condense out were those able to survive the temperature there. In the innermost regions, around Mercury's present orbit, only metallic grains could form—it was simply too hot for anything else to exist. Farther out, at about 1 AU, it was possible for rocky, silicate grains to form, too. Beyond about 3 or 4 AU, water ice could exist, and so on. More and more material could condense out at greater and greater distances from the Sun. The composition of the grains at any given distance from the Sun determined the type of planetesimal—and ultimately planet—that formed there. The present-day structure of the asteroid belt, with rocky silicates more common in the inner regions and carbonaceous bodies, descendents of icier planetesimals, most prevalent at larger radii, still reflects these early conditions.

Beyond about 5 AU from the center, the temperature was low enough to allow several abundant gases—water vapor, ammonia, and methane—to condense into solid form. As we will see, these compounds are still important constituents of jovian atmospheres. Consequently, the planetesimals destined to become the cores of the jovian planets were formed under cold conditions out of low-density, icy material. Because more material could condense out of the solar nebula at these radii than in the inner regions near the protosun, accretion began sooner, with more resources to draw on. If they hadn't already formed through instabilities in the cold nebular gas, the outer planets grew rapidly to the point where they could accrete not just grains, but nebular gas also, and the eventual result was the hydrogen-rich jovian worlds we see today.

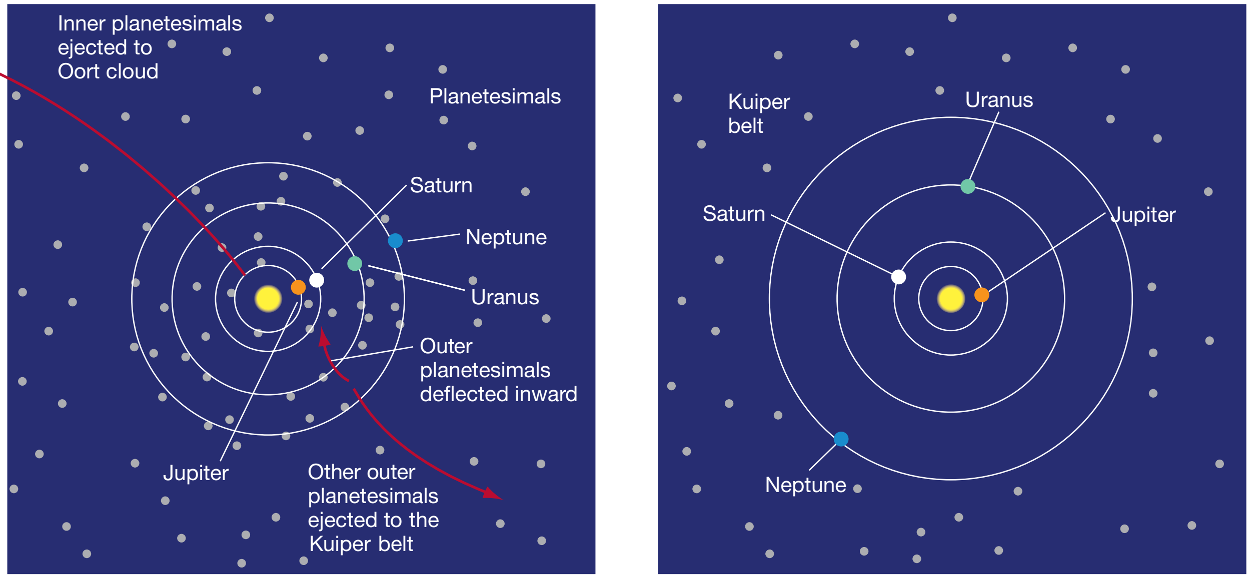
In the inner regions of the primitive solar system, the environment was too hot for ices to survive. Many of the abundant heavier elements, such as silicon, iron, magnesium, and aluminum, combined with oxygen to produce a variety of rocky materials. Planetesimals in the inner solar system were therefore rocky or metallic, as were the protoplanets and planets they ultimately formed. Here is an additional reason why the jovian planets grew so much bigger than the terrestrial worlds. The inner regions of the nebula had to wait for the temperature to drop so that a few rocky grains could appear and begin the accretion process, whereas accretion in the outer solar system began almost as soon as the solar nebula collapsed to a disk.

The heavier materials condensed into grains in the outer solar system, too, of course. However, there they would have been vastly outnumbered by the far more abundant light elements. The outer solar system is not deficient in heavy elements—rather, the inner solar system is *underrepresented in light material*.

Asteroids and Comets

In the inner solar system, most rocky planetesimals collided with or were ejected by the growing terrestrial planets. Only a few remain today as the asteroid belt. Planetesimals beyond the orbit of Mars failed to accumulate into a protoplanet because the huge gravitational field of nearby Jupiter continuously disturbed their motion, nudging and pulling at them, preventing them from aggregating into a planet. Many of the Trojan asteroids have likely been locked in their odd orbits by the combined gravitational pulls of Jupiter and the Sun since those earliest times.

Once the jovian planets formed, they exerted strong gravitational forces on the planetesimals in the outer solar system. Over a period of hundreds of millions of years, and after repeated gravitational "kicks" from the giant planets, particularly Jupiter and Saturn, most of the interplanetary fragments in the outer solar system were flung into orbits taking them far from the Sun (Figure 4.31). Those fragments now make up the Oort cloud. Interactions with Uranus and Neptune were gentler, and generally did not eject planetesimals to large distances. Rather, these encounters tended to deflect small bodies into eccentric orbits that carried them into the inner solar system, where they collided with a planet or were kicked into the Oort cloud by Jupiter or Saturn. Most of the original planetesimals formed beyond the orbit of Neptune are still there, making up the Kuiper belt.



▲ **FIGURE 4.31 Planetesimal Ejection INTERACTIVE** The ejection of icy planetesimals to form the Oort cloud and Kuiper belt. (a) Initially, once the giant planets had formed, leftover planetesimals were found throughout the solar system. Interactions with Jupiter and Saturn apparently "kicked" planetesimals out to very large radii (the Oort cloud). (b) After hundreds of millions of years and as a result of the inward and outward "traffic," the orbits of all four giant planets were significantly modified by the time the planetesimals inside Neptune's orbit had been ejected. As depicted here, Neptune was affected most and may have moved outward by as much as 10 AU.

The interactions that cleared the outer solar system of comets also caused significant changes in the orbits of the planets themselves. Computer simulations indicate that, during the ejection process, Jupiter moved slightly closer to the Sun, its orbital semimajor axis decreasing by a few tenths of an astronomical unit, while the other giant planets migrated outward—possibly by as much as 10 AU in the case of Neptune (Figure 4.31b).

The deflection of icy planetesimals into the inner solar system may have played an important role in the evolution of the terrestrial planets too. A long-standing puzzle in the condensation theory's account of the formation of the inner planets was the origin of the water and other volatile gases on Earth and elsewhere. At formation, the inner planets' surface temperatures were far too high, and their gravity too low, to capture and retain those gases. The answer may be that the comets from the outer solar system bombarded the newly born inner planets, supplying them with water *after* their formation.

This theory has been a leading, if controversial, explanation for Earth's water for some time, but recent data from *Rosetta* has cast doubt on it. *Rosetta's* sensors found that the amount of deuterium (a heavy form of hydrogen) in the ice and water vapor surrounding comet 67P is three times greater than is found in Earth's oceans, implying that comets like 67P from the outer solar system could not be responsible for our planet's water. Meteorites from the asteroid belt do match Earth's deuterium levels, however, suggesting that bombardment by asteroids, rather than comets, could have been the source of water on Earth.

CONCEPT CHECK

Would you expect to find asteroids and comets orbiting other stars?

Solar System Regularities and Irregularities

The condensation theory accounts for the 10 facts listed at the start of this section. The growth of planetesimals throughout the solar nebula, with each protoplanet ultimately sweeping up the material near it, accounts for the planets' wide spacing (point 1, although the theory does not adequately explain the regularity of the spacing). That the planets' orbits are circular (2), in the same plane (3), and in the same direction as the Sun's rotation on its axis (4) is a direct consequence of the solar nebula's shape and rotation. The rotation of the planets (5) and the orbits of the moon systems (6) are due to the tendency of smaller structures to inherit the overall sense of rotation of their parent. The heating of the nebula and the Sun's ignition resulted in the observed differentiation (7), while the debris from the accretion–fragmentation stage naturally accounts for the asteroids (8) and comets (9).

We mentioned earlier that an important aspect of any theory of solar system formation is its ability to accommodate deviations. In the condensation theory, that capacity is provided by the randomness inherent in the encounters that combined planetesimals into protoplanets. As the numbers of large bodies decreased and their masses increased, individual collisions acquired greater and greater importance. The effects of these collisions can still be seen today in many parts of the solar system.

We will discuss many solar system irregularities in the next few chapters; most can be explained as the results of random collisions. A case in point is the anomalously slow and retrograde rotation of Venus (Chapter 6), which can be explained if we assume that the last major collision in the formation history of that planet just happened to involve a near head-on encounter between two protoplanets of comparable mass. A similar encounter, this time involving Earth, may have formed our Moon (Chapter 5). Scientists usually do not like to invoke random events to explain observations. However, there seem to be many instances where pure chance has played an important role in determining the present state of the universe.

4.4 Planets Beyond the Solar System

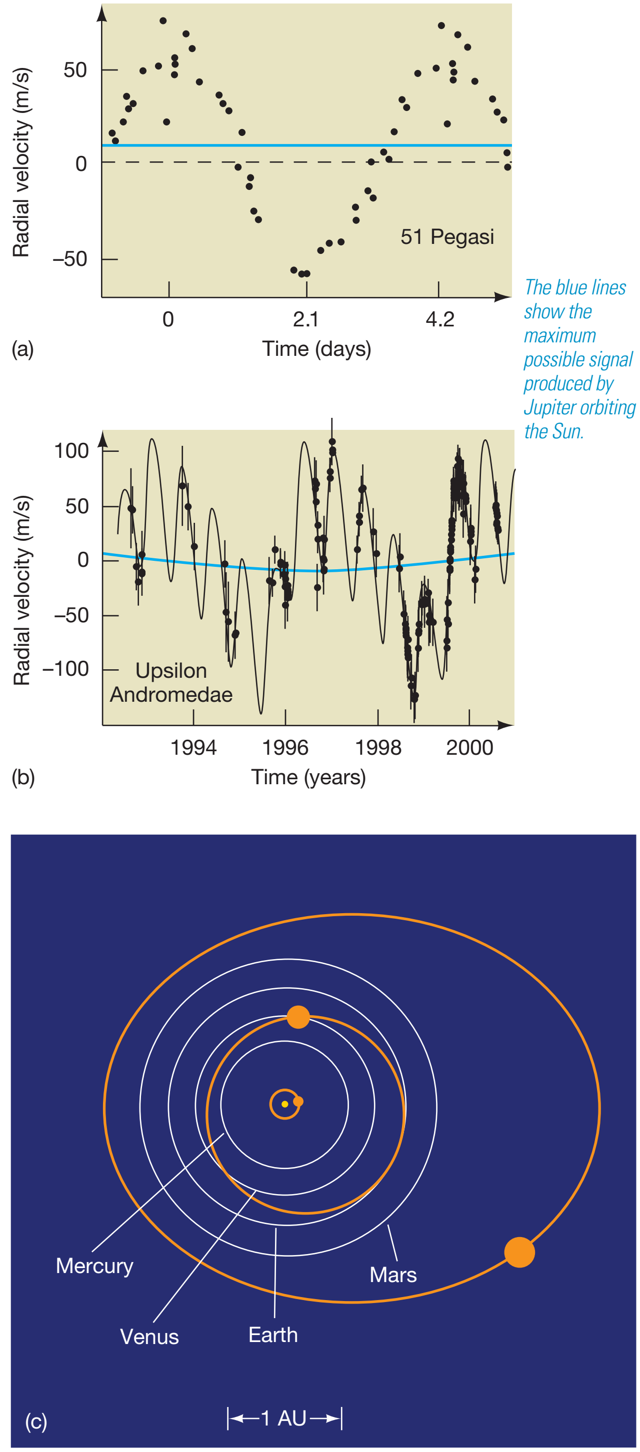
The condensation theory was developed to explain just one planetary system—our own. But a critical test of any scientific theory is its applicability and predictive power outside the context in which it was originally conceived. ∞ *(Sec. 0.5)* The discovery in recent years of numerous planets orbiting other stars presents astronomers with the opportunity—indeed, the scientific obligation—to confront their theories of solar system formation against a new body of observational data.

Detecting Extrasolar Planets

The past few years have seen enormous strides in the search for extrasolar planets. These advances have been achieved through steady improvements in both telescope and detector technology and computerized data analysis. With few exceptions it is not yet possible to obtain images of these newly discovered worlds. The techniques used to find them are generally indirect, based on analysis of light from the parent star, not from the unseen planet.

To date, some 600 planets have been discovered via their gravitational effect on their parent star. As a planet orbits a star, gravitationally pulling one way and then the other, the star "wobbles" slightly. The more massive the planet or the closer its orbit to the star, the greater its gravitational pull and hence the star's movement. If the wobble happens to occur along our line of sight to the star, then we see small fluctuations in the star's radial velocity, which astronomers can measure using the Doppler effect. ∞ *(Sec. 2.7)*

Figure 4.32 shows two sets of radial velocity data that betray the presence of planets orbiting other stars. Part (a) shows the line-of-sight velocity of the star 51 Pegasi, a near-twin to our Sun some 40 light-years away. These data were acquired in 1994 by Swiss astronomers using the 1.9-m telescope at Haute-Provence Observatory in France, and they were the first firm evidence for an extrasolar planet orbiting a Sun-like star. The regular 50 m/s fluctuations in the star's velocity have since been



▶ **FIGURE 4.32 Planets Revealed INTERACTIVE** (a) *Discovery* data of the Doppler shift of the star 51 Pegasi reveal a clear periodic signal indicating the presence of a planetary companion of mass at least half the mass of Jupiter. (b) Radial velocity data for Upsilon Andromedae are more complex, but are well fit (solid line) by a three-planet system orbiting the star. (c) A sketch of the inferred orbits of the three planets in the Upsilon Andromedae system (in orange) with the orbits of the terrestrial planets superimposed for comparison (in white).

confirmed by several groups of astronomers and imply that a planet of at least half the mass of Jupiter orbits 51 Pegasi in a circular orbit with a period of 4.2 days.

Figure 4.32(b) shows another set of Doppler data, this time revealing a much more complex planetary system—a triple-planet system orbiting another nearby Sun-like star named Upsilon Andromedae. The three planets have minimum masses of 0.7, 2.1, and 4.3 times the mass of Jupiter, and orbital semimajor axes of 0.06, 0.83, and 2.6 AU, respectively. Figure 4.32(c) sketches their orbits, with the orbits of the solar system terrestrial planets shown for scale.

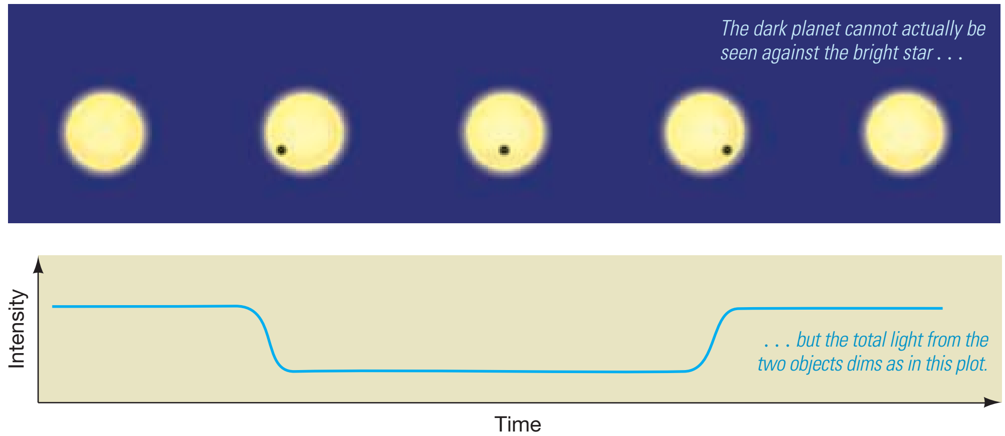
The Doppler technique suffers from the limitation that the angle between the line of sight and the planet's orbital plane cannot be determined. Simply put, we cannot distinguish between a low-speed orbit seen edge-on and a high-speed orbit seen almost face-on (so only a small component of the orbital motion contributes to the line-of-sight Doppler effect). However, in some systems this is not the case. For example, observations of the solar-type star HD 209458, lying some 150 light-years from Earth, reveal a small (1.7 percent) but clear drop in brightness each time its 0.6-Jupiter-mass companion, orbiting just 7 million km (0.05 AU) away, passes between the star and Earth (Figure 4.33). The drop in brightness occurs every 3.5 days—the orbital period inferred from radial-velocity measurements. Such **planetary transits** are relatively rare because they require us to see the orbit almost exactly edge-on, but when they do occur, taken in conjunction with radial velocity measurements, they allow an unambiguous determination of the planet's mass and radius. In this case, the resulting density of the planet is just 200 kg/m^3, consistent with a high-temperature gas giant planet orbiting very close to its parent star.

Only a small fraction of planetary systems are oriented in just the right way to show transits, so planet hunters adopt the strategy of repeatedly surveying thousands of stars in the hope of detecting a transit should one occur. Space-based telescopes are particularly well suited to this task, as they can stare continuously at a given region of the sky, making simultaneous, high-precision observations of the target stars. Orbiting instruments can measure the tiny brightness changes (less than 1 part in 10^4) needed to detect an Earth-like planet orbiting a Sun-like star. NASA's *Kepler* mission, launched in 2009, has been spectacularly successful in finding exoplanets among the hundreds of thousands of stars it has monitored. It has produced more than 4000 exoplanet candidates, of which more than 1000 have so far been confirmed, including some of the smallest (i.e., Earth-sized) exoplanets yet discovered. Suspended in 2013 following the failure of a gyroscope needed to accurately point the spacecraft, the mission was redefined in 2014 to monitor planets orbiting low-mass stars.

In total, some 1200 confirmed extrasolar planets have been detected by the transit method. Unfortunately, in most cases, radial velocity measurements are not available, so we know these planets' orbits and radii, but not their masses.

Exoplanet Properties

To date (as of mid-2015), astronomers have confirmed almost 2000 extrasolar planets orbiting more than 1000 stars. Most lie within 500 light years of the Sun, although many of the planets discovered by *Kepler* lie at much greater distances. About 10 percent of the nearby stars surveyed to date have been found to host planets. In most cases only a single planet has been detected, but roughly 500 *multiple-planet systems* are also known. Most astronomers expect both the



▶ **FIGURE 4.33 Extrasolar Transit** INTERACTIVE As an extrasolar planet passes between us and its parent star, the light from the star dims in a characteristic way. The planet orbiting a Sun-like star known as HD 209458 is 200,000 km across and transits every 3.5 days, blocking about 2 percent of the star's light each time it does so.

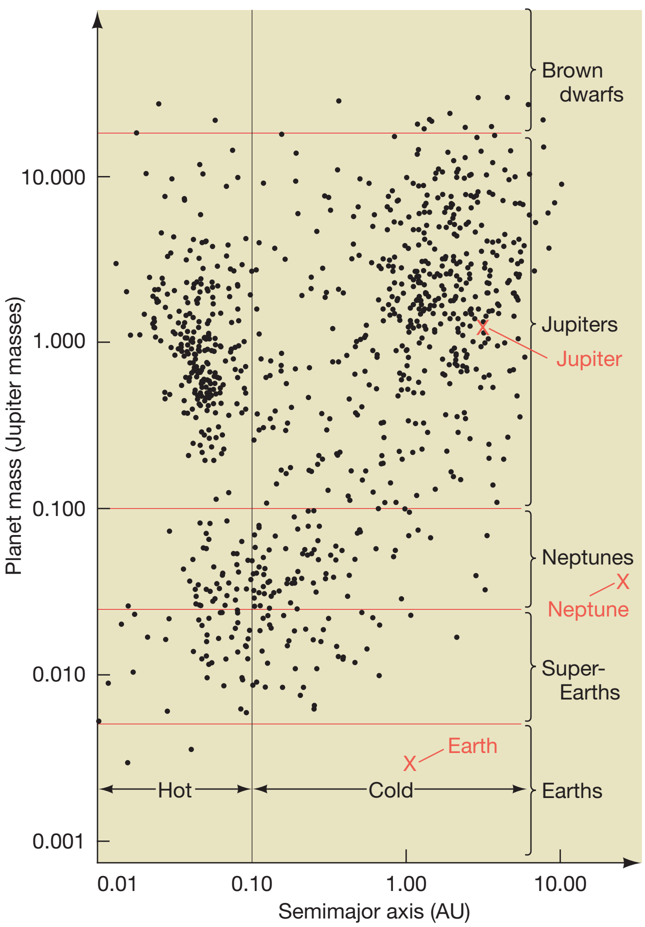
MA ANIMATION/VIDEO
Survey for Transiting Extrasolar Planets

fraction of stars with planets and the number of planets per star to increase as detection and data analysis technology continue to improve.

Figure 4.34 presents the observed masses and semimajor axes of about 1000 extrasolar planets. Each dot in the figure represents a planet, and we have added points corresponding to Earth, Neptune, and Jupiter in our own solar system. Massive exoplanets are often referred to as *Jupiters,* while less massive, but still "jovian" planets are called *Neptunes*. The dividing line between Jupiters and Neptunes is somewhat arbitrary, but is often taken at about twice the mass of Neptune, or 0.1 Jupiter masses. The terminology is intended to distinguish between planets that are mostly gas, like Jupiter, and those that have substantial rocky cores, like Neptune, but bear in mind that the division is based only on mass—we have no information on most of these planets' composition or internal structure.

Planets having masses between roughly 2 and 10 Earth masses (about half the mass of Neptune) are known as **super-Earths.** The upper limit in this case is significant, as theorists think that 10 Earth masses represents the minimum mass of a planetary core needed for it to accrete large amounts of nebular gas and begin to form a gas giant (Section 4.3). Below 2 Earth masses, exoplanets are simply called *Earths*.

As just mentioned, many transiting exoplanets have known radii but do not have measured masses. Making reasonable assumptions about planet properties, astronomers conventionally extend the above definitions as follows: Jupiters have radii greater than 5 Earth radii, Neptunes are between 2 and 5 Earth radii, super-Earths between 1.25 and 2 Earth radii, and Earths less than 1.25 Earth radii.



▲ **FIGURE 4.34 Extrasolar Planetary Parameters** Masses and orbital semimajor axes of roughly 1000 extrasolar planets. Each point represents one planetary orbit. Corresponding points for Earth, Jupiter, and Neptune in our solar system are also shown. Planets are classified by familiar solar system names, depending on mass, and as hot or cold, depending on distance from their parent star.

Exoplanets are further subdivided depending on their distances from their parent stars. Planets with orbital semimajor axes less than 0.1 AU are said to be *hot,* while those on wider orbits are called *cold.* Again, the dividing line is arbitrary—the actual temperature of a planet depends not just on its orbit, but also on the composition of the planet's atmosphere and the temperature and brightness of the central star.

Most of the planets observed so far fall into the "cold Jupiter" or "cold Neptune" categories, like the jovian planets in our own solar system, although their orbits are generally somewhat smaller than those of the jovian planets—less than a few astronomical units across—and much more eccentric. Fewer than 20 percent have eccentricities less than 0.1, whereas no jovian planet in our solar system has an eccentricity greater than 0.06. Figure 4.35 plots the actual orbits of some of these planets, with Earth's orbit superimposed for comparison. A sizable minority—about a third—of all observed exoplanets move in "hot" orbits very close to their parent stars and have surface temperatures as high as 1000–2000 K. The most massive ones were the first to be discovered, and they were quickly dubbed **hot Jupiters.** They represent a new class of planet and have no counterparts in our own solar system.

More than 300 confirmed super-Earths are currently known. They are found in both hot and cold orbits. Some, especially the lower-mass ones, might be large terrestrial planets. Others could be icy planetary cores that never managed to accrete