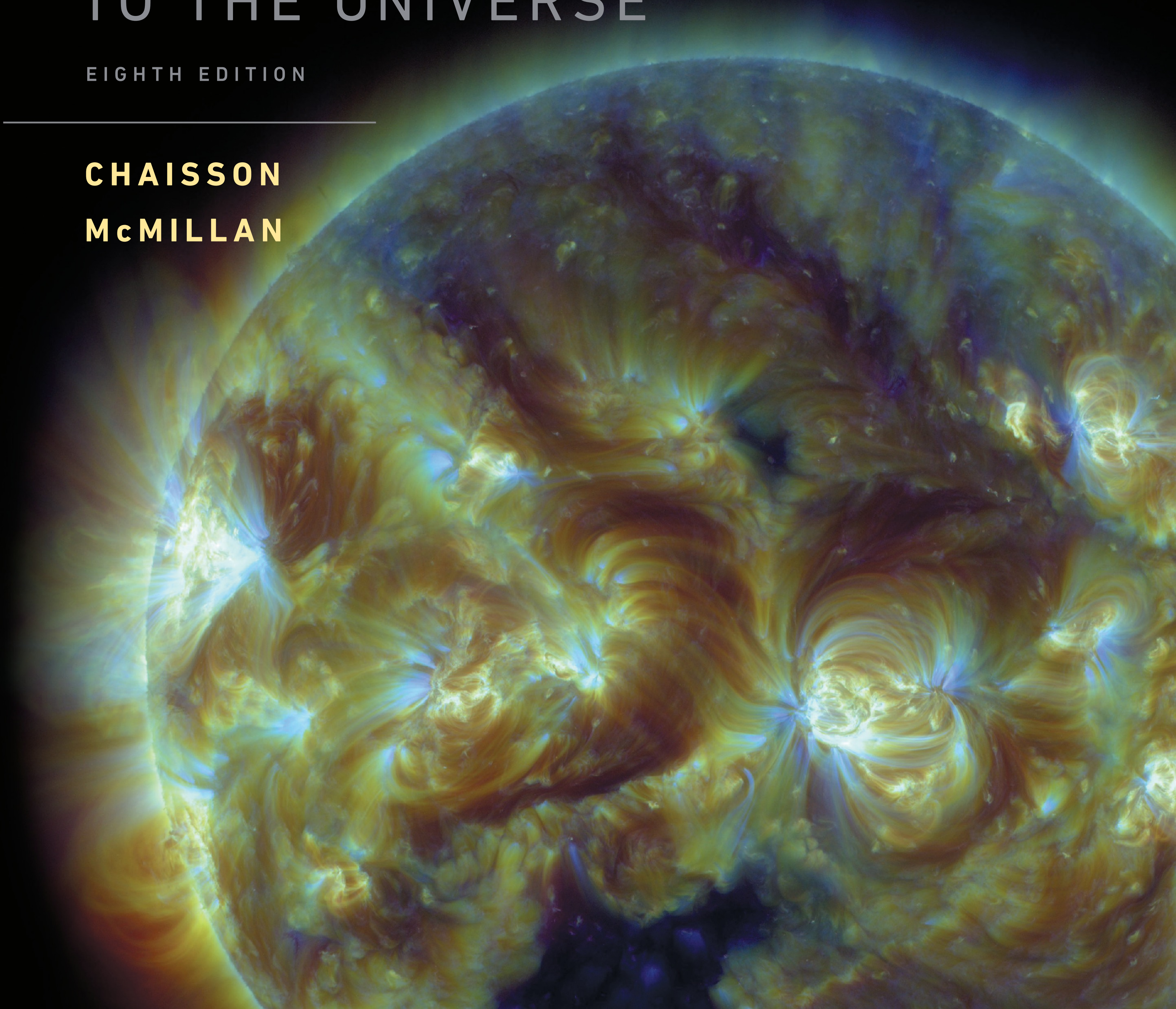
Astronomy

A BEGINNER'S GUIDE TO THE UNIVERSE

EIGHTH EDITION

CHAISSON
McMILLAN



EIGHTH EDITION

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A Beginner's Guide to the Universe

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PEARSON

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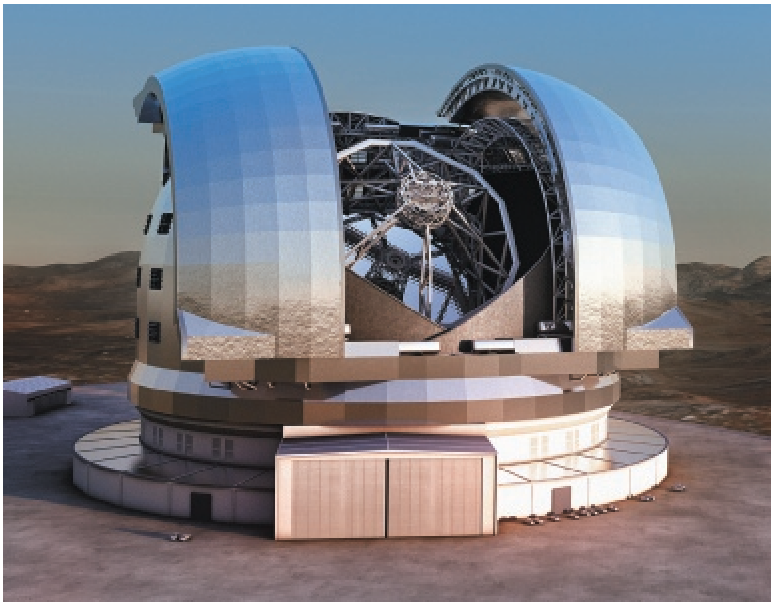
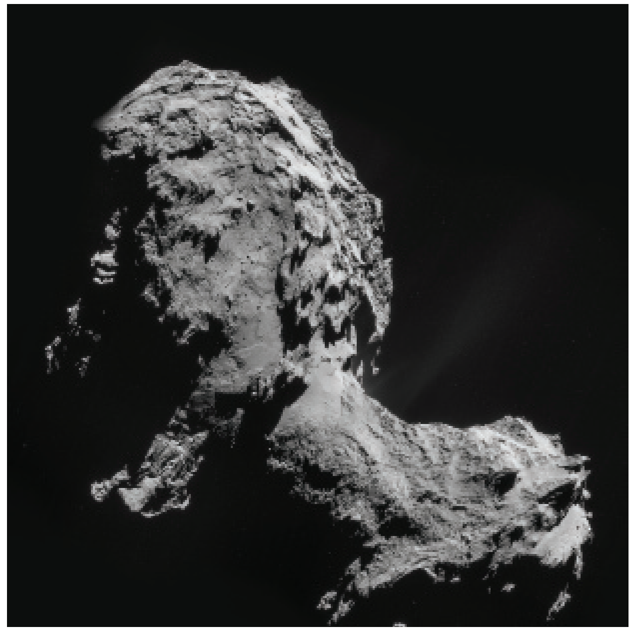
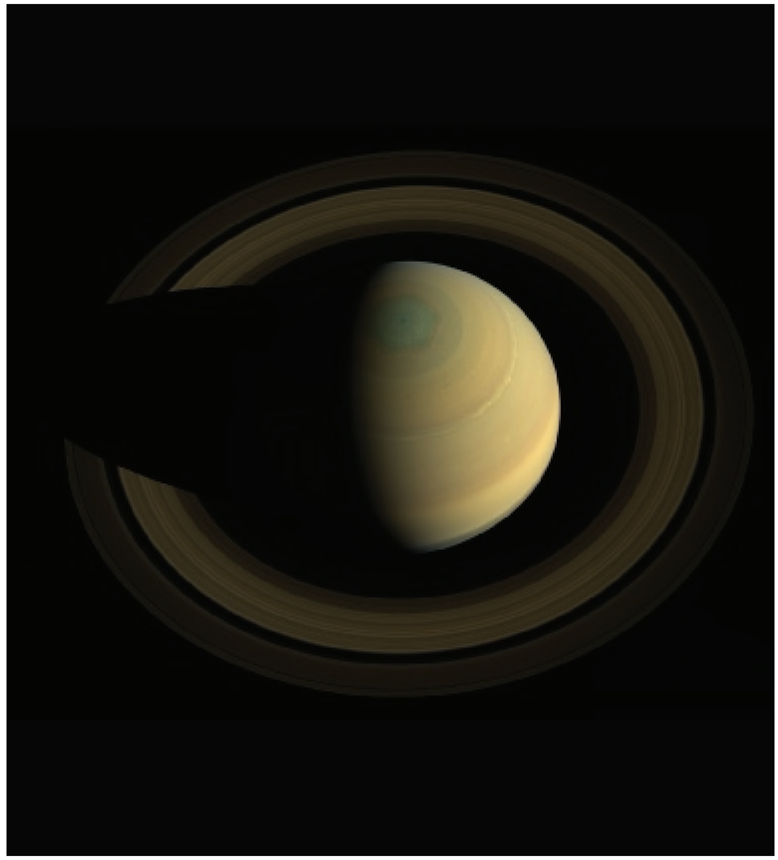




PART 2 OUR PLANETARY SYSTEM



PART 3 THE STARS

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:

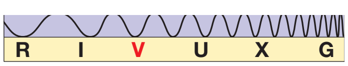
- New chapter-opening images reflecting the latest astronomical discoveries.
- Updated astronomical imagery throughout.
- Streamlined art program providing more direct and accurate representations of astronomical objects.
- Increased use of annotations to clarify figure content.
- Updates in Chapter 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

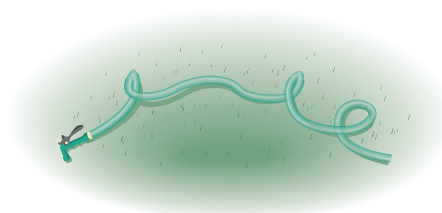
Why does a star get brighter as it runs out of fuel in its core?

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.

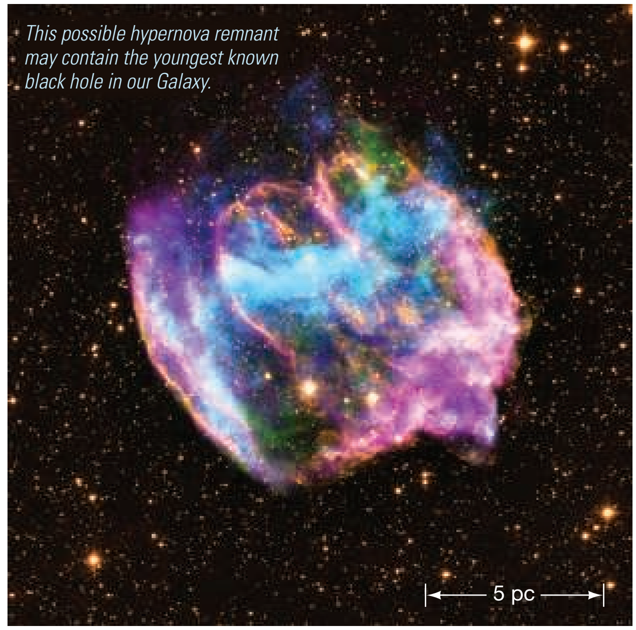


A good analogy to a tangled solar magnetic field is a garden hose with loops and kinks.

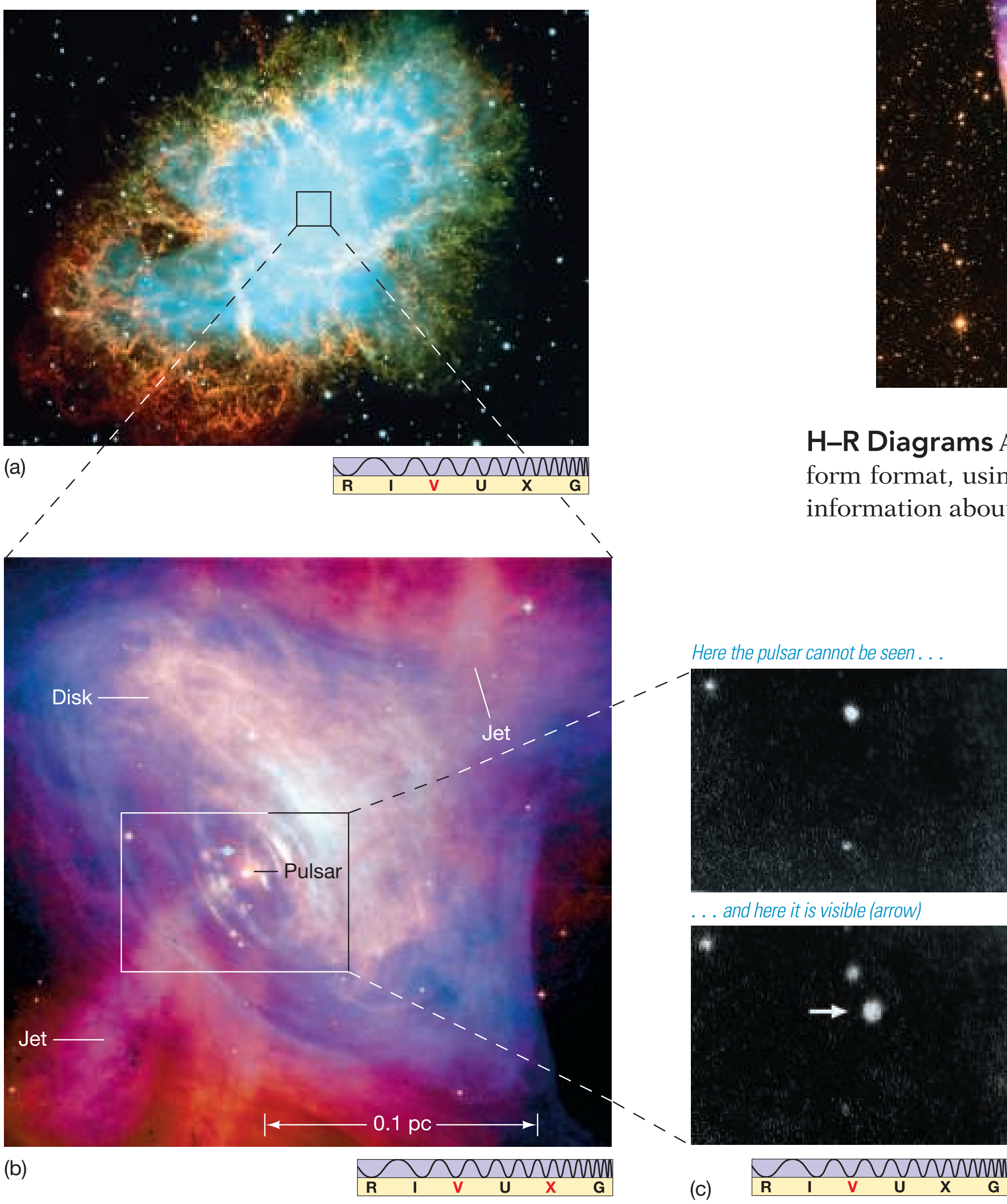
▼ **Compound Art** It is rare that a single image, be it a photograph or an artist's conception, can capture all aspects of a complex subject. Wherever possible, multiple-part figures are used in an attempt to convey the greatest amount of information in the most vivid way:

- 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 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.



◀ **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)*

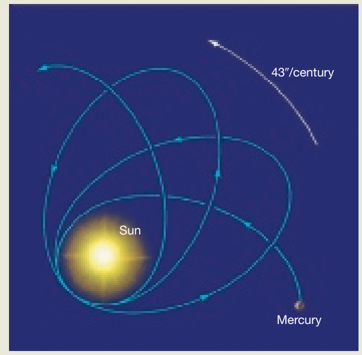
▶ **MORE PRECISELY Boxes** These boxes provide more quantitative treatments of subjects discussed qualitatively in the text. Removing these more challenging topics from the main flow of the narrative and placing them within a separate modular element of the chapter design allow instructors greater flexibility 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

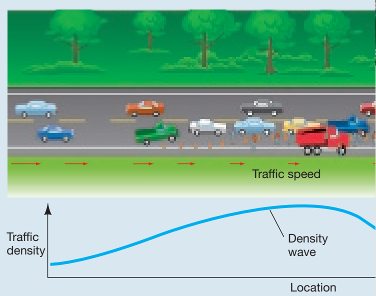
In the late 1960s, American astrophysicists C. C. Lin and Frank Shu proposed a way in which spiral arms in the Galaxy could persist for many Galactic rotations. They argued that the arms themselves contain no "permanent" matter. They should not be viewed as assemblages of stars, gas, and dust moving 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



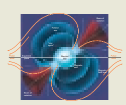
◀ **DISCOVERY Boxes** Exploring a wide variety of interesting topics, *Discovery* boxes provide the reader with insight into how scientific knowledge evolves and emphasizes the process of science.

CHAPTER REVIEW

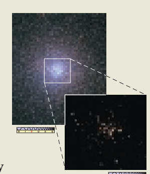
SUMMARY

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.

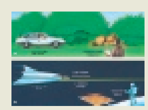


LO3 A neutron star that is a member of a binary system can draw matter from its companion, forming an accretion disk, which is usually a strong source of X-rays. As gas builds up on the star's surface, it eventually becomes hot enough to fuse hydrogen. When hydrogen burning starts on a neutron star, 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

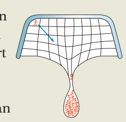


explosions involve the violent merger of neutron stars in a distant binary system, or the recollapse and subsequent violent explosion following a "failed" supernova in a very massive star.

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.

Instructor Resources

MasteringAstronomy™

www.masteringastronomy.com

MasteringAstronomy is the most widely used and most advanced astronomy tutorial and assessment system in the world. By capturing the step-by-step work of students nationally, MasteringAstronomy has established an unparalleled database of learning challenges and patterns. Using this student data, a team of astronomy education researchers has refined every activity and problem. The result is a library of activities of unique educational effectiveness and assessment accuracy. MasteringAstronomy provides students with two learning systems in one: a dynamic self-study area and the ability to participate in online assignments.

MasteringAstronomy, now easier to use than ever, provides instructors with a fast and effective way to assign uncompromising, wide-ranging online homework assignments of just the right difficulty and duration. The tutorials coach 90 percent of students to the correct answer with specific wrong-answer feedback. The powerful post-diagnostics allow instructors to assess the progress of their class as a whole or to quickly identify individual student's areas of difficulty. Tutorials built around text content and all the end-of-chapter problems from the text are also available.

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 Mastering-Astronomy 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.

Instructor Resource DVD This DVD provides virtually every electronic asset you'll need in and out of the classroom. The DVD is organized by chapter and contains all text illustrations, tables, and photos in jpeg and PowerPoint® formats, as well as animations, videos, and self-guided tutorials from the self-study section of MasteringAstronomy.
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Learner-Centered Astronomy Teaching: Strategies for ASTRO 101

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

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

techniques to the task of teaching astronomy to predominantly nonscience students.
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Peer Instruction for Astronomy
Paul Green, Harvard Smithsonian Center for Astrophysics
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handbook covering timekeeping and positional measurements on the celestial sphere; the Sun, Moon, and other bodies of the solar system; telescopes and other equipment for observing and imaging the sky; and stars, nebulae, and galaxies. Throughout, succinct fundamental principles and practical tips guide the reader into the night sky. The appendices Units and Notation, Astronomical Constants, Symbols and Abbreviations, and Useful Addresses complete what has long been the only essential reference for the stargazer.
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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
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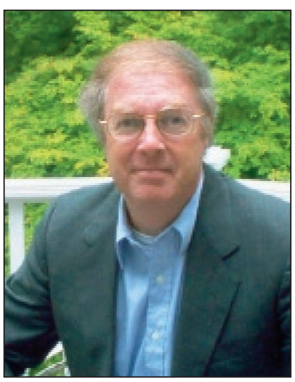

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Astronomy

A Beginner's Guide to the Universe

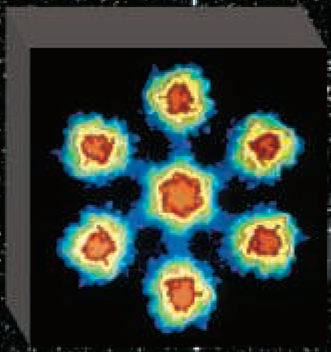
PART 1

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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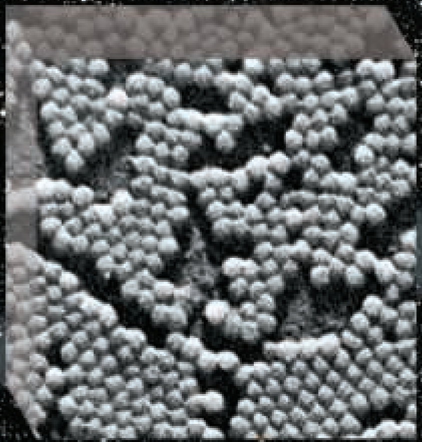

Cells ~10^{-5} m

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Humans ~2 m

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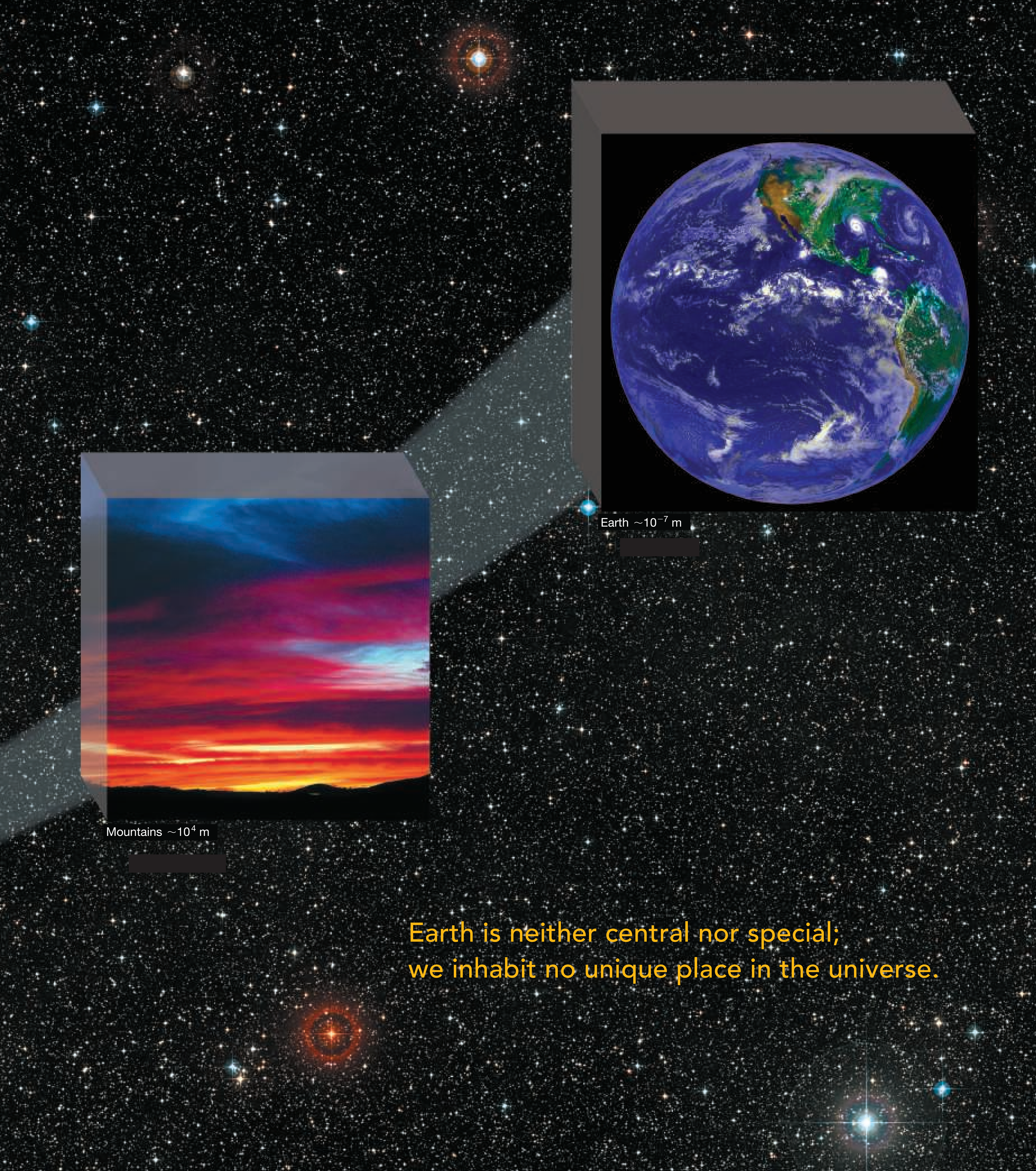


Earth is neither central nor special;
we inhabit no unique place in the universe.

0

Charting the Heavens

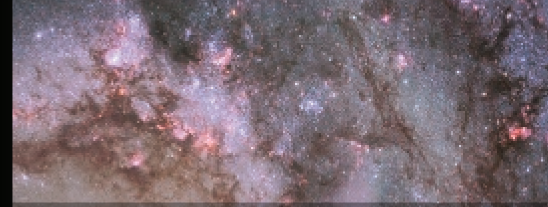
The Foundations of Astronomy

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.

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)



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.

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Visit www.masteringastronomy.com for quizzes, animations, videos, interactive figures, and self-guided tutorials.

0.1 The "Obvious" View

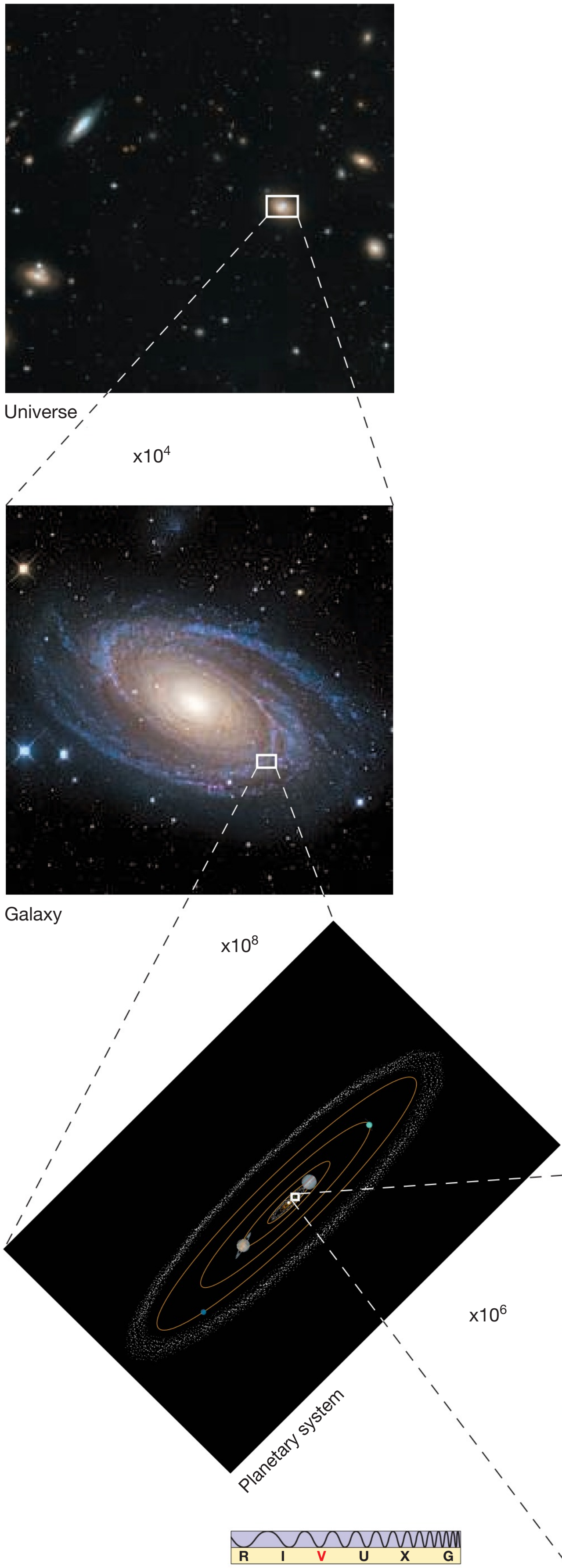
Our Place in Space

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.

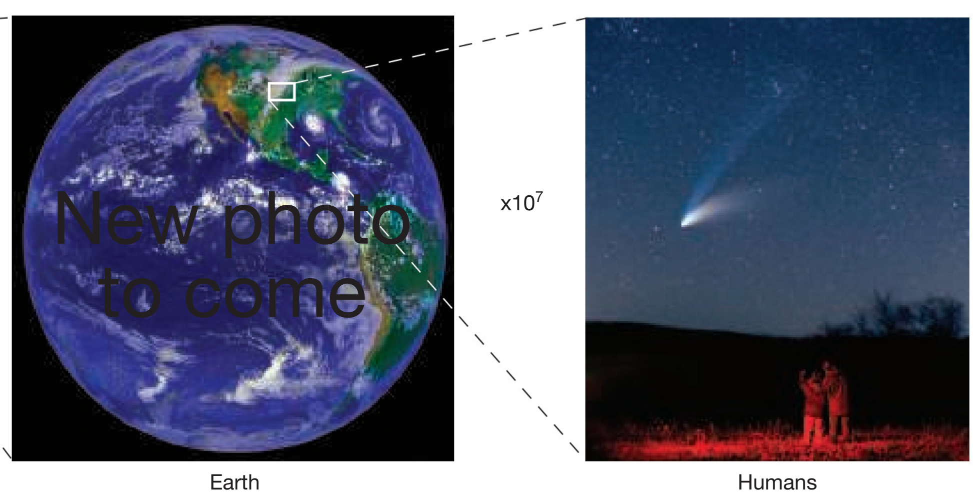
Today, our scientific understanding of the cosmos extends as far as we can see, spanning the vast reaches of intergalactic space. But the modern view of the universe depicted here is in many ways the "punch line" of the story presented in this text. It is the culmination of countless scientific discoveries, 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

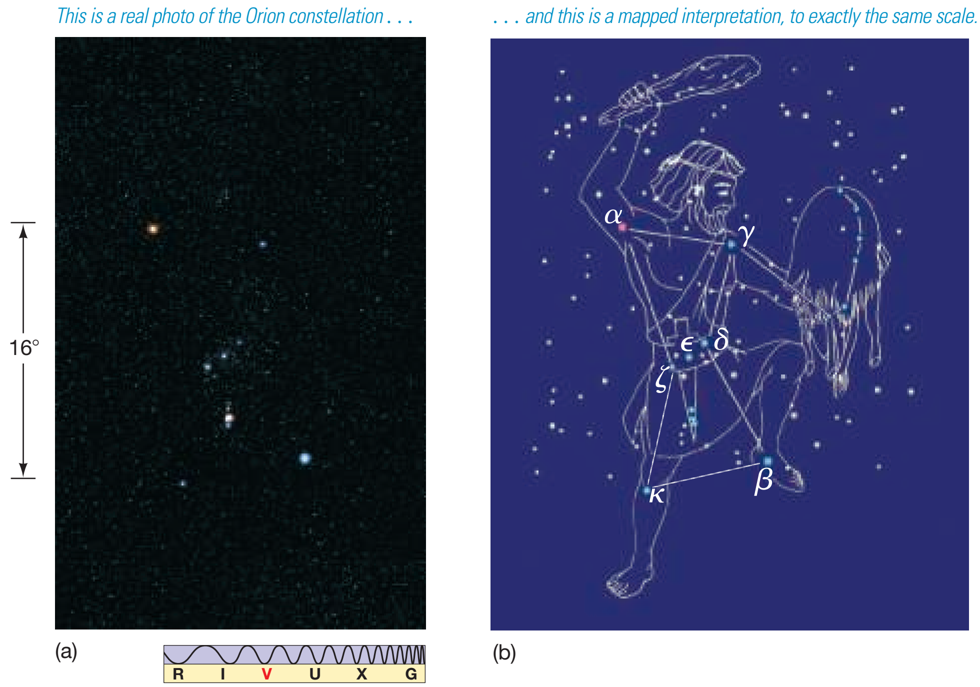
Between sunset and sunrise on a clear night, we can see some 3000 points of light. Include the view from the opposite side of Earth, and nearly 6000 stars are visible to the unaided eye. A natural human tendency is to see patterns and relationships between objects even when no true connection exists, 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)*



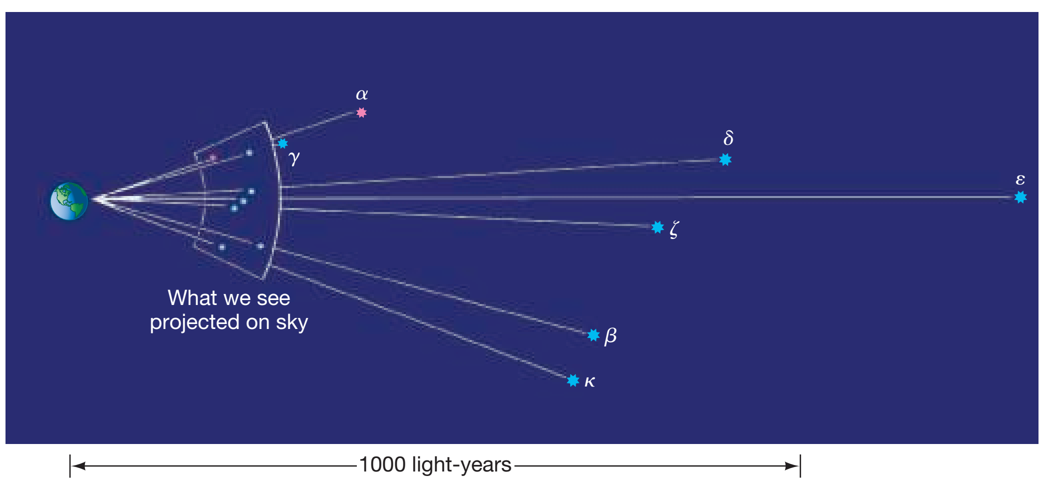
Pleiades, the seven daughters of the giant Atlas. According to Greek mythology, the gods placed the Pleiades among the stars to protect them from Orion, who still stalks them nightly across the sky. Many other constellations have similarly fabulous connections with ancient cultures.

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

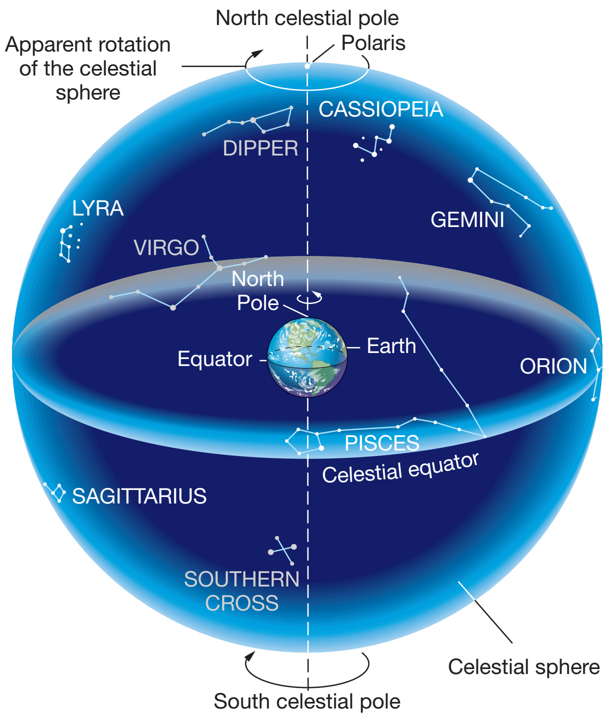
Over the course of a night, the constellations appear to move across the sky from east to west. However, ancient sky-watchers noted that the *relative* positions of stars (to each other) remained unchanged as this nightly march took place. It was natural for early astronomers to conclude that the stars 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.)

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



▲ **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?

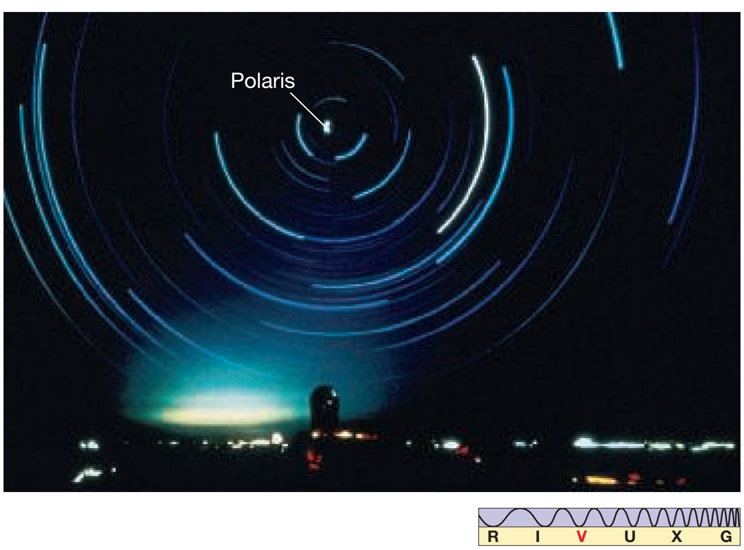
description of the heavens, astronomers still use the idea as a convenient fiction that helps us visualize the positions of stars in the sky. The point where Earth's rotation axis (the line through the center around which the planet rotates) intersects the celestial sphere in the Northern Hemisphere 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.

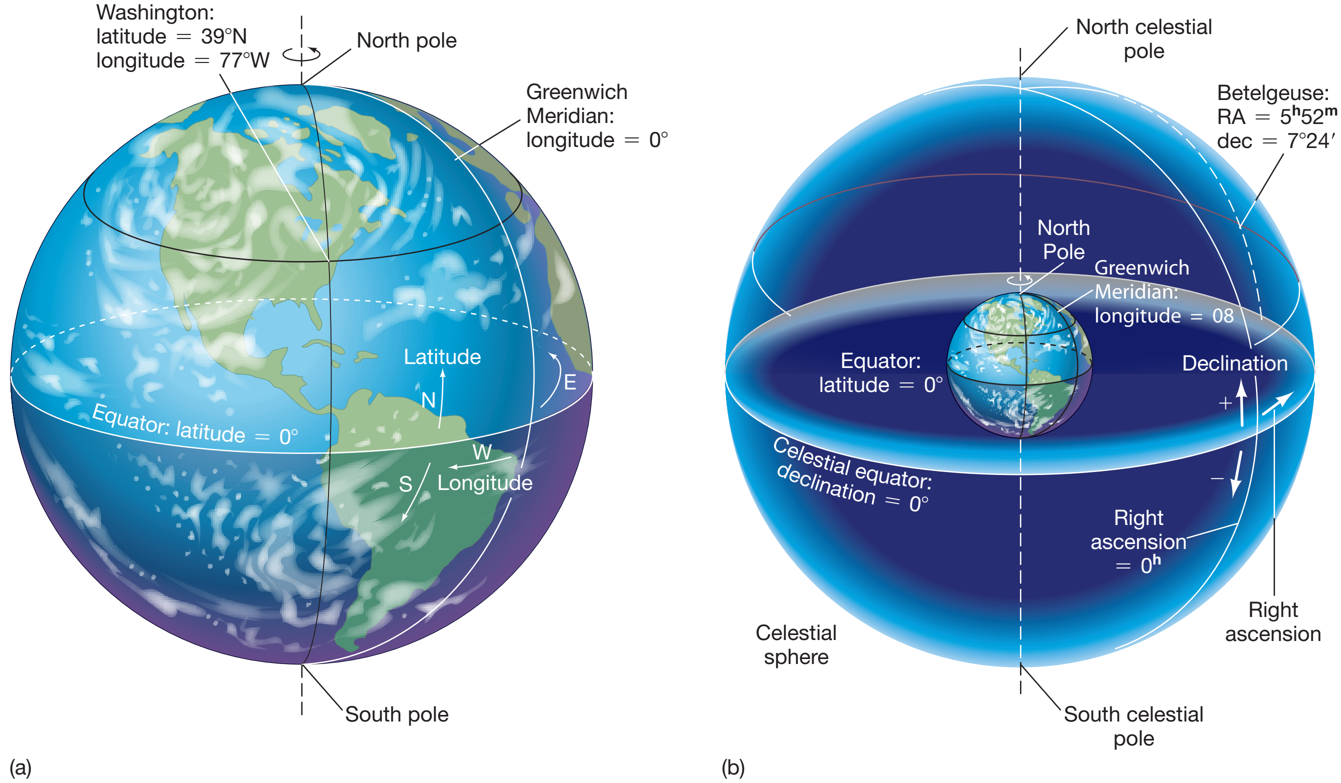
Declination (dec) is measured in *degrees* (°) north or south of the celestial equator, just as latitude is measured in degrees north or south of Earth's equator (see *More Precisely 0-1*). The celestial equator is at a declination of 0°, the north celestial pole is at +90°, and the south celestial pole 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.