Arny + Schneider

EXPLORATIONS

AN INTRODUCTION TO ASTRONOMY

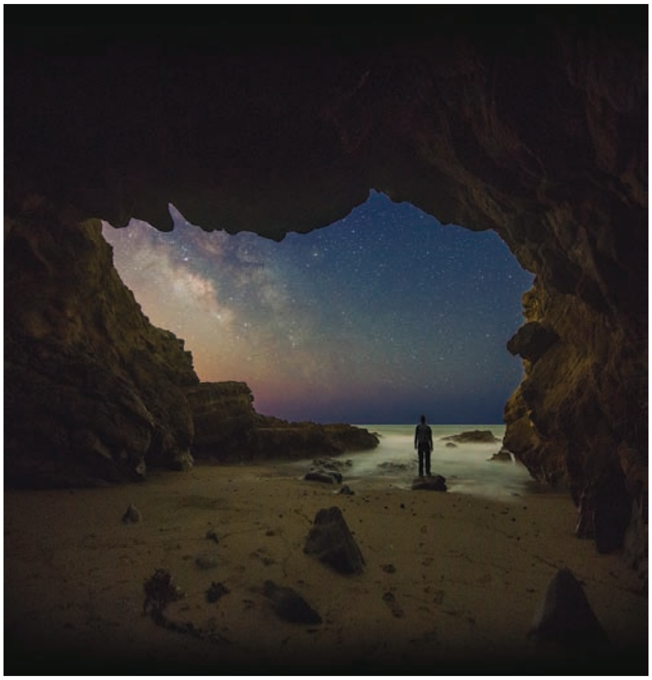
Eighth Edition

McGraw Hill Education

Explorations

An Introduction to Astronomy

Eighth Edition



Thomas T. Arny & Stephen E. Schneider

The nine “Looking Up” figures on the following pages explore a variety of the amazing objects that can be spotted in the night sky. Brief descriptions of each also list the chapter where you can learn more about them.

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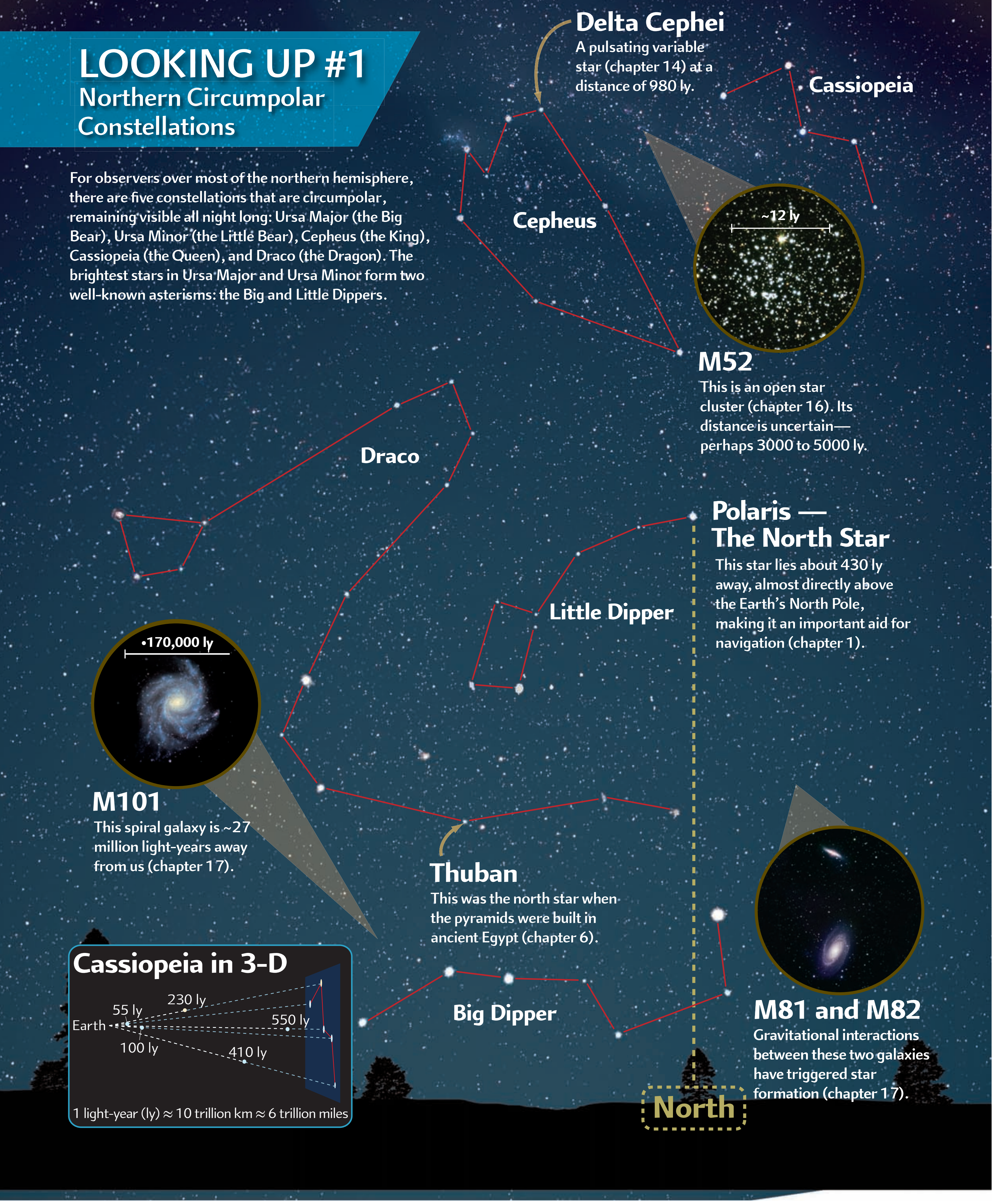
LOOKING UP #1

Northern Circumpolar Constellations

For observers over most of the northern hemisphere, there are five constellations that are circumpolar, remaining visible all night long: Ursa Major (the Big Bear), Ursa Minor (the Little Bear), Cepheus (the King), Cassiopeia (the Queen), and Draco (the Dragon). The brightest stars in Ursa Major and Ursa Minor form two well-known asterisms: the Big and Little Dippers.



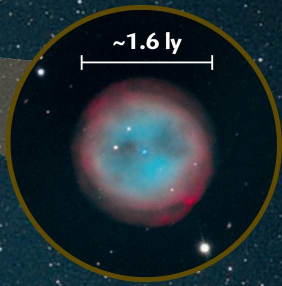
LOOKING UP #2
Ursa Major

Circling in the northern sky is the Big Dipper, part of the well-known constellation Ursa Major, the Big Bear. The Big Dipper is technically not a constellation, but just an asterism—a star grouping. It is easy to see in the early evening looking north from mid-March through mid-September. The Big Dipper can help you find the North Star, and with a telescope on a dark, clear night, you can find several other intriguing objects as shown below.

Pointer stars

Big Dipper

Over the course of a night, stars appear to rotate counterclockwise around the star Polaris, which remains nearly stationary because it lies almost directly above Earth's North Pole. Polaris is not especially bright, but you can easily find Polaris by extending a line from the two stars at the end of the bowl of the Big Dipper, the pointer stars, as shown by the dashed yellow line (chapter 1).



M97 — The Owl

This planetary nebula (chapter 14) is ~2500 ly away.

Location of the Hubble Deep Field (chapter 17)

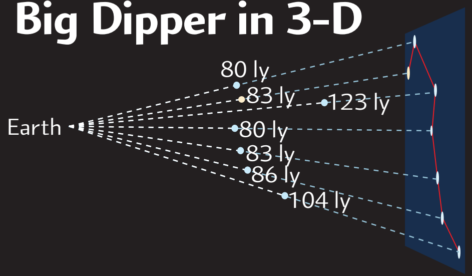
Polaris

Little Dipper

Mizar and Alcor

If you look closely at it, you may notice that the middle star in the "handle" is actually two stars—Mizar and Alcor. Despite appearing close together in the sky, they are probably not in orbit around each other. However, with a small telescope, you can see that Mizar (the brighter of the star pair) has a faint companion star. This companion does in fact orbit Mizar. Moreover, each of Mizar's stars is itself a binary star, making Mizar a quadruple system (chapter 13).

Big Dipper in 3-D



1 light-year (ly) ≈ 10 trillion km ≈ 6 trillion miles

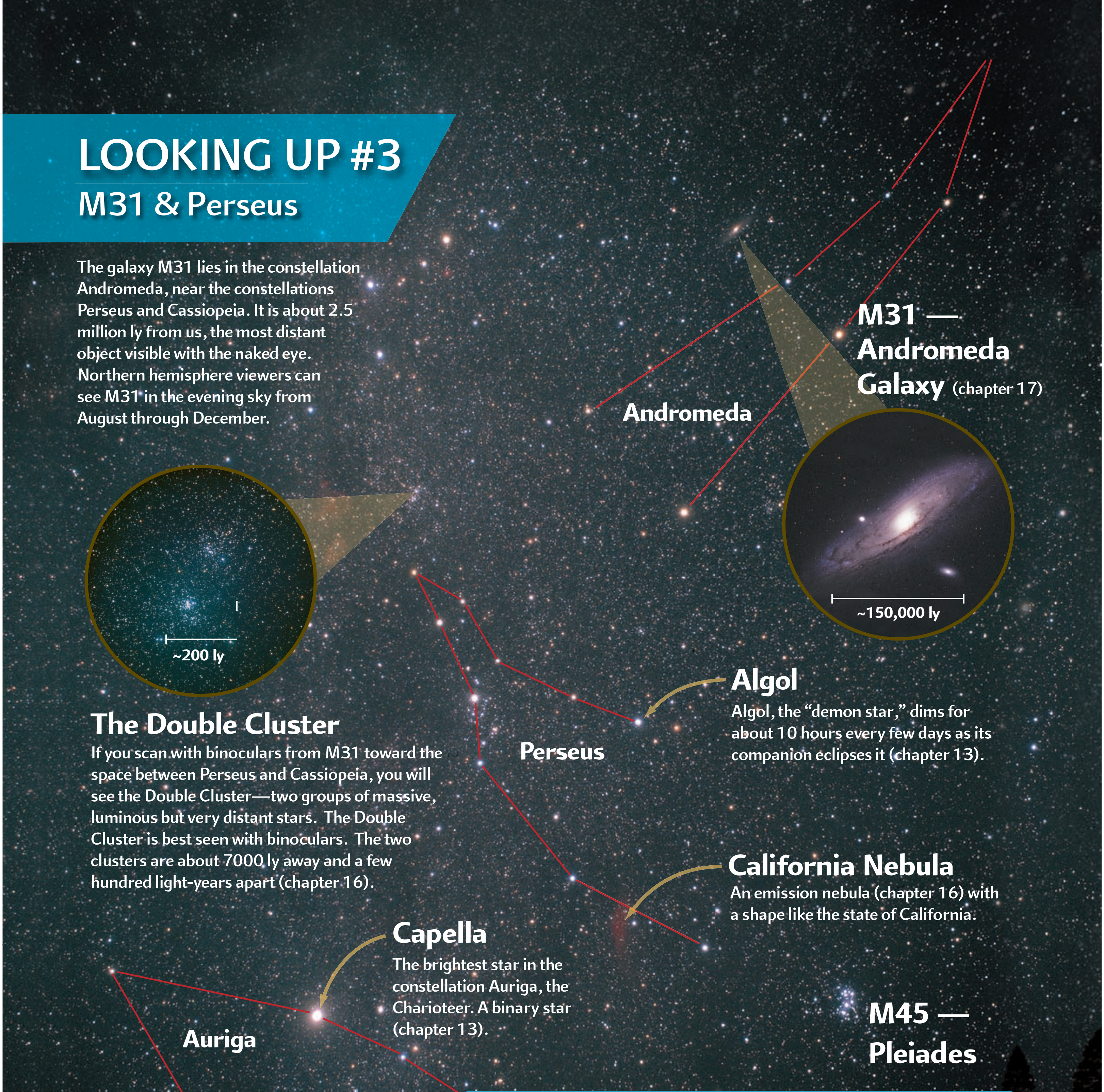
M51

The Whirlpool Galaxy can be seen as a dim patch of light with a small telescope. M51 is about 37 million ly away from Earth (chapter 17).

LOOKING UP #3

M31 & Perseus

The galaxy M31 lies in the constellation Andromeda, near the constellations Perseus and Cassiopeia. It is about 2.5 million ly from us, the most distant object visible with the naked eye. Northern hemisphere viewers can see M31 in the evening sky from August through December.



The Double Cluster

If you scan with binoculars from M31 toward the space between Perseus and Cassiopeia, you will see the Double Cluster—two groups of massive, luminous but very distant stars. The Double Cluster is best seen with binoculars. The two clusters are about 7000 ly away and a few hundred light-years apart (chapter 16).

Algol

Algol, the "demon star," dims for about 10 hours every few days as its companion eclipses it (chapter 13).

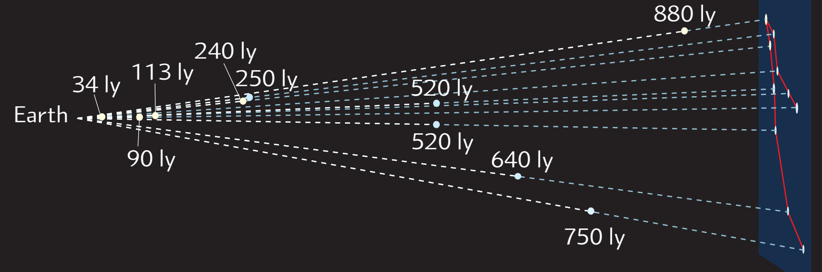
California Nebula

An emission nebula (chapter 16) with a shape like the state of California.

Capella

The brightest star in the constellation Auriga, the Charioteer. A binary star (chapter 13).

Perseus in 3-D



1 light-year (ly) ≈ 10 trillion km ≈ 6 trillion miles

LOOKING UP #4

Summer Triangle

The Summer Triangle consists of the three bright stars Deneb, Vega, and Altair, the brightest stars in the constellations Cygnus, Lyra, and Aquila, respectively. They rise in the east shortly after sunset in late June and are visible throughout the northern summer and into late October (when they set in the west in the early evening). Vega looks the brightest to us, but Deneb produces the most light, only looking dimmer because it is so much farther from us.

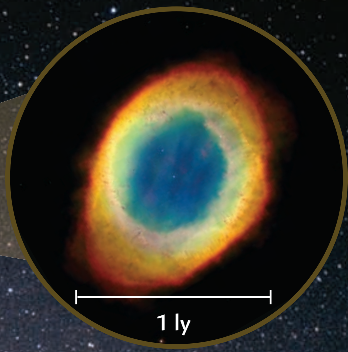
Vega

Lyra

Epsilon Lyra

A double, double star

Cygnus



M57 — Ring Nebula

This planetary nebula (chapter 14) is about 2300 ly distant. From its observed expansion rate it is estimated to be 7000 years old.

Deneb

Deneb is a blue supergiant (chapter 13), one of the most luminous stars we can see, Deneb emits ~50,000 times more light than the Sun.

Altair

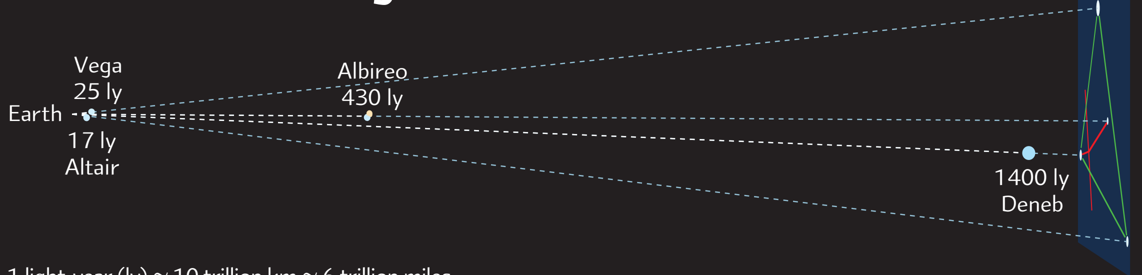
Albireo

Through a small telescope this star pair shows a strong color contrast between the orange red giant and blue main-sequence star (chapter 13). These stars may orbit each other every few hundred thousand years, but they are far enough apart that they may not be in orbit.

M27 — Dumbbell Nebula

Another planetary nebula (chapter 14), the Dumbbell is about 1200 ly distant and is about 2.5 ly in diameter.

The Summer Triangle in 3-D



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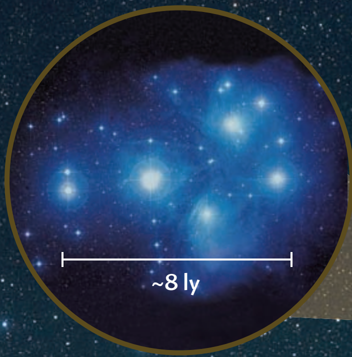
LOOKING UP #5

Taurus

Taurus, the Bull, is one of the constellations of the zodiac and one of the creatures hunted by Orion in mythology. Taurus is visible in the evening sky from November through March. The brightest star in Taurus is Aldebaran, the eye of the bull. The nebula and two star clusters highlighted below have been critical in the history of astronomy for understanding the distances and fates of stars.

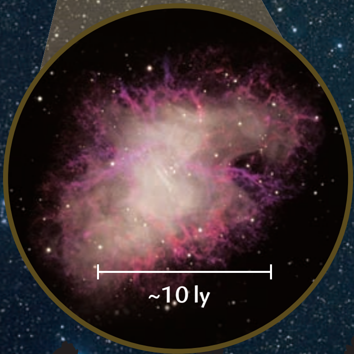


M45 — Pleiades

This open star cluster (chapter 16) is easy to see with the naked eye and looks like a tiny dipper. It is about 400 ly from Earth.

Aldebaran

Aldebaran is a red giant star (chapter 13). It is about 67 ly away from Earth and has a diameter about 45 times larger than the Sun's. Although it appears to be part of the Hyades, it is less than half as distant.



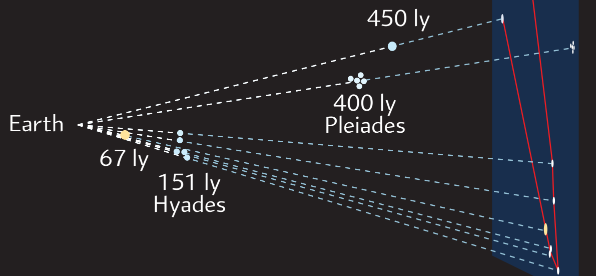
M1 — Crab Nebula

The Crab Nebula is the remnant of a star that blew up in the year A.D. 1054 as a supernova. At its center is a pulsar (chapter 15). It is about 6500 ly away from us.

T Tauri

T Tauri is an erratically varying pre-main-sequence star, prototype of a class of forming stars (chapter 14). It is about 600 ly distant.

Taurus in 3-D



1 light-year (ly) ≈ 10 trillion km ≈ 6 trillion miles

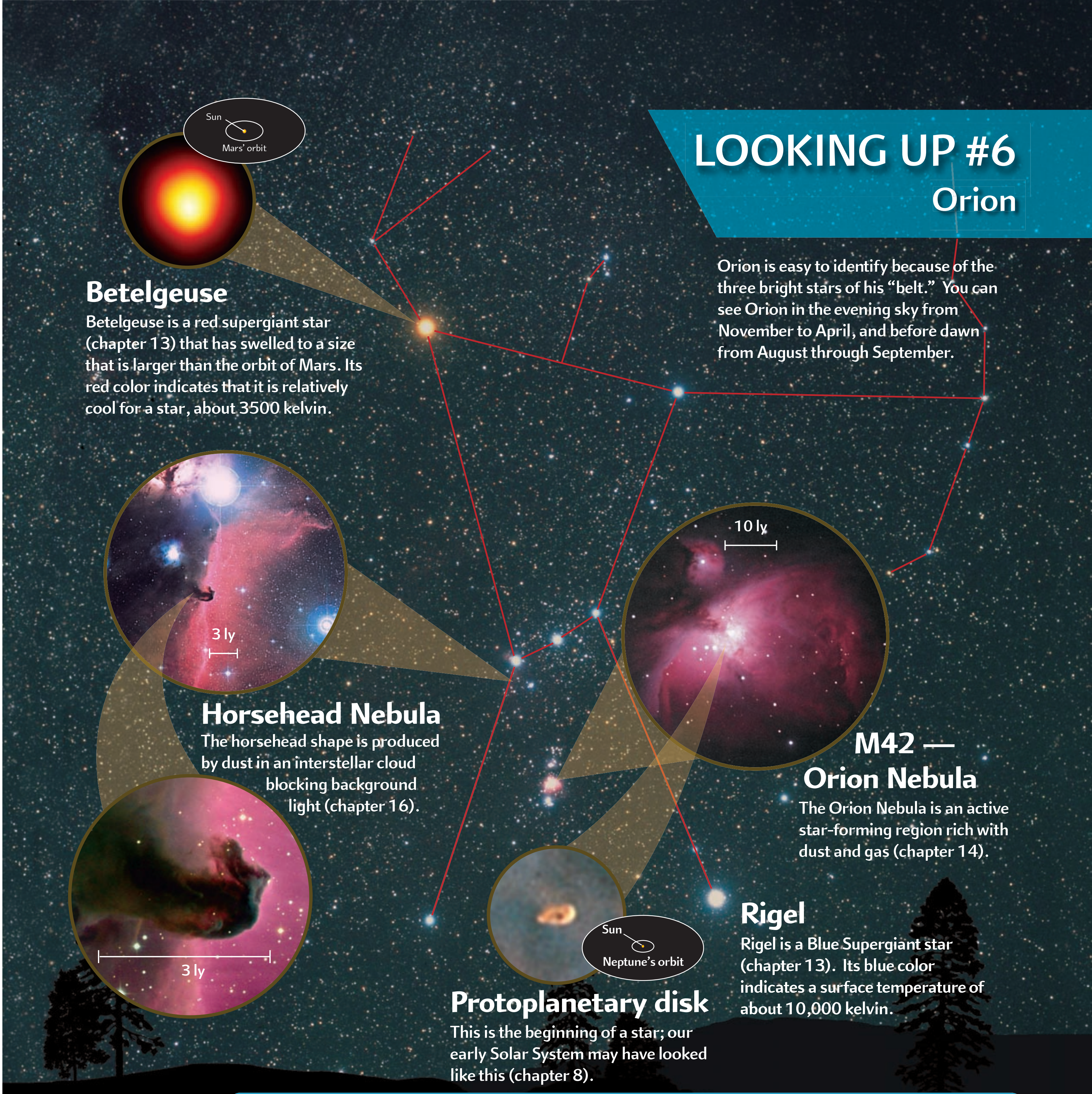
Hyades

The "V" in Taurus is another nearby star cluster, measured to be 151 ly away by the *Hipparcos* satellite (chapter 13). It is easy to see its many stars with binoculars.

LOOKING UP #6

Orion

Orion is easy to identify because of the three bright stars of his "belt." You can see Orion in the evening sky from November to April, and before dawn from August through September.



Betelgeuse

Betelgeuse is a red supergiant star (chapter 13) that has swelled to a size that is larger than the orbit of Mars. Its red color indicates that it is relatively cool for a star, about 3500 kelvin.

Horsehead Nebula

The horsehead shape is produced by dust in an interstellar cloud blocking background light (chapter 16).

M42 — Orion Nebula

The Orion Nebula is an active star-forming region rich with dust and gas (chapter 14).

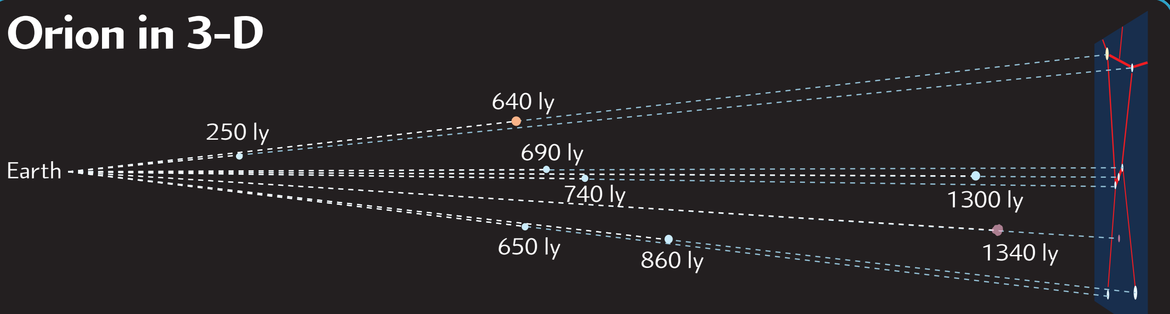
Rigel

Rigel is a Blue Supergiant star (chapter 13). Its blue color indicates a surface temperature of about 10,000 kelvin.

Protoplanetary disk

This is the beginning of a star; our early Solar System may have looked like this (chapter 8).

Orion in 3-D



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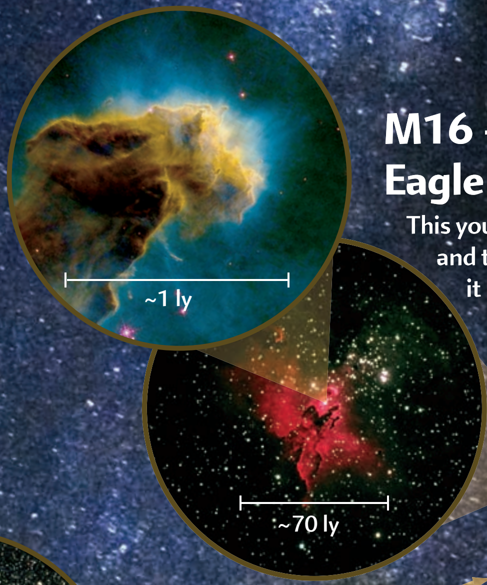
LOOKING UP #7

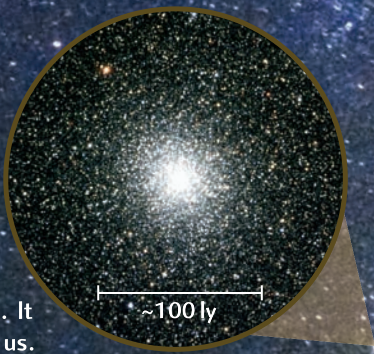
Sagittarius

Sagittarius marks the direction to the center of the Milky Way. It can be identified by its “teapot” shape, with the Milky Way seeming to rise like steam from the spout. From northern latitudes, the constellation is best seen July to September, when it is above the southern horizonin the evening. Many star-forming nebulae are visible in this region (chapter 16).



M16 — Eagle Nebula

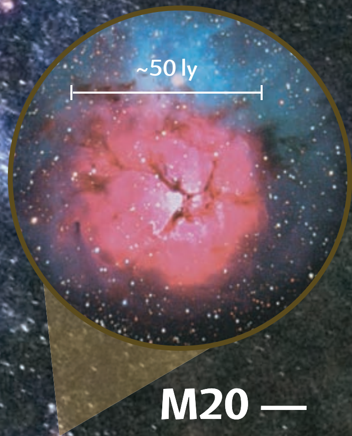
This young star cluster and the hot gas around it lie about 7000 ly from Earth.



M22

M22 is one of many globular clusters (chapter 16) concentrated toward the center of our Galaxy. Easy to see with binoculars, it is just barely visible to the naked eye. It is about 11,000 ly away from us.

M17 — Swan Nebula



M20 — Trifid Nebula

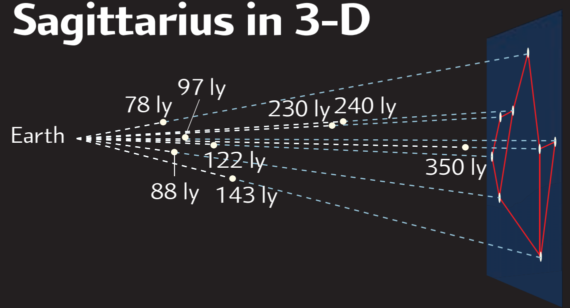
The name Trifid was given because of the dark streaks that divide it into thirds. The distance of this nebula is uncertain, approximately 5000 ly away, making its size uncertain too.

M8 — Lagoon Nebula

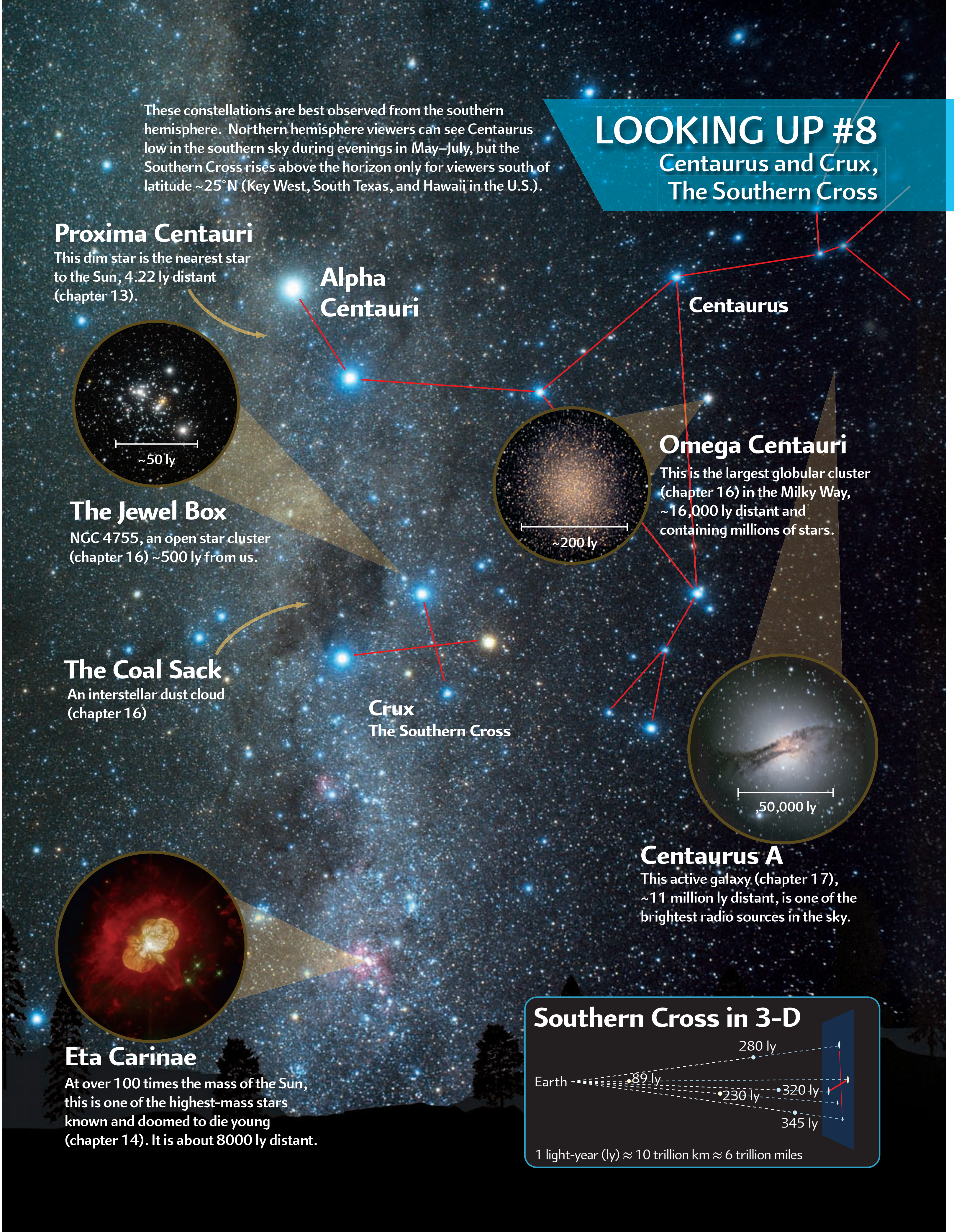
Center of the Milky Way

(chapter 16)

Sagittarius in 3-D



1 light year (ly) ≈ 10 trillion km ≈ 6 trillion miles



LOOKING UP #8
Centaurus and Crux,
The Southern Cross
These constellations are best observed from the southern hemisphere. Northern hemisphere viewers can see Centaurus low in the southern sky during evenings in May–July, but the Southern Cross rises above the horizon only for viewers south of latitude ~25°N (Key West, South Texas, and Hawaii in the U.S.).
Proxima Centauri
This dim star is the nearest star to the Sun, 4.22 ly distant (chapter 13).
Alpha Centauri
Centaurus
~50 ly
The Jewel Box
NGC 4755, an open star cluster (chapter 16) ~500 ly from us.
~200 ly
Omega Centauri
This is the largest globular cluster (chapter 16) in the Milky Way, ~16,000 ly distant and containing millions of stars.
The Coal Sack
An interstellar dust cloud (chapter 16)
Crux
The Southern Cross
50,000 ly
Centaurus A
This active galaxy (chapter 17), ~11 million ly distant, is one of the brightest radio sources in the sky.
Eta Carinae
At over 100 times the mass of the Sun, this is one of the highest-mass stars known and doomed to die young (chapter 14). It is about 8000 ly distant.
Southern Cross in 3-D
280 ly
Earth
89 ly
320 ly
230 ly
345 ly
1 light-year (ly) ≈ 10 trillion km ≈ 6 trillion miles

LOOKING UP #9
Southern Circumpolar Constellations

Most of the constellations in this part of the sky are dim, but observers in much of the southern hemisphere can see the Magellanic Clouds circling the south celestial pole throughout the night.

Explorations

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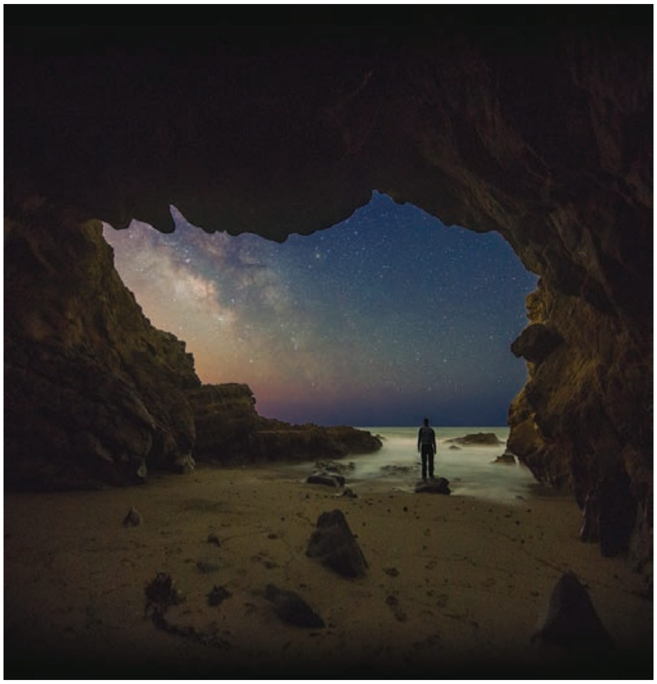
Eighth Edition



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EXPLORATIONS: AN INTRODUCTION TO ASTRONOMY, EIGHTH EDITION

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Brief Contents

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Preface

Our motivations for writing *Explorations: An Introduction to Astronomy* are many, both personal and pedagogic. Perhaps foremost among these is a desire to share with students our own sense of wonder about the Universe.

That sense of wonder grows deeper when we begin to understand why things happen. Many astronomy books today seem to simply say, “This is how it is.” We want instead to offer explanations that draw as much as possible on simple, everyday effects that students can see around them in the world. For example, why do some stars pulsate? A simple analogy of steam building up pressure under the lid of a pan offers a model of this phenomenon that is easy to understand and reasonably accurate. We have also tried to link complex physical processes to simple everyday experiences. Another example of this is that you can see the effects of differentiation in a previously-melted box of chocolate chip ice cream. When we can thus link physical principles to everyday observations, many of the more abstract and remote ideas become more familiar. Throughout the book we have made heavy use of analogies, along with carefully designed illustrations to make those analogies more concrete.

Knowing the facts about astronomical objects is important, but it is equally important to understand how astronomers deduce those facts. Thus, an additional aim throughout this text is to explain *how* astronomers have come to their understanding of our Universe. New observations can force astronomers to revise their ideas of how a given process occurs. As part of showing how scientists arrive at their ideas, we have set many of the modern discoveries in their historical context to illustrate that science is a dynamic process and subject to controversy—many ideas are not immediately accepted, even if they ultimately prove to be “correct.” We hope that by seeing the arguments for and against various ideas, students will have a better understanding of how science works.

If we had attempted to make this textbook completely comprehensive, it would have been very long and overwhelming in detail. It is challenging to keep *Explorations* to a reasonable size because reviewers tend to suggest things that we should include, but rarely suggest things to omit. To solve this problem, we cover some topics, such as timekeeping and astrobiology, in essays that the instructor might choose to skip. We also cover some background topics in later chapters, in the astronomical context where they are most often encountered. This makes it possible to jump directly to some of the later chapters without having to work through the details of all the earlier chapters.

Some astronomy textbooks maintain brevity by omitting most of the mathematics, but we feel that math is essential for understanding many of the methods used by astronomers. We have therefore included the essential mathematics in a number of places. However, because math is so intimidating to so many readers, we begin these discussions by introducing the essence of the calculation in everyday language so that the basic idea can be understood without understanding the mathematics. For example, Wien’s law relates the temperature of a hot object to its color by means of a mathematical law, but illustrations of the law can be seen in everyday life, as when we estimate how hot an electric stove burner is by the color of its glow. Where we do present the mathematics, we work through it step by step, explaining where terms must be cross-multiplied and so forth.

Because astronomical concepts often depend on a visual understanding of objects and phenomena, we pay very close attention to the figures. We have refined the illustrations to clarify the presentation, often making small changes to aid the viewer’s ability to focus in on essential features while avoiding misconceptions. For example, we have converted all global maps of the planets to Mollweide projections. While no projection can perfectly represent a spherical surface, this one maintains equal areas and the consistent presentation helps the reader to compare features. We work very closely with the McGraw-Hill team throughout the design, layout, and composition process in an effort to make the book easier to read. For example, we often adjust figure labels and sizes to make sure they complement the text and fit very close to the spot where their content is discussed. This helps the reader to connect words, logic, images, and geometry.

NEW TO THE EIGHTH EDITION

In this eighth edition of *Explorations,* we have updated the art and text throughout the book in response to readers’ comments and suggestions. Following are some of the highlights of these changes:

- Major update to Essay 1 (“Backyard Astronomy”) with detailed advice on small telescopes and astrophotography.
- Major update to Chapter 8 (“Survey of Solar Systems”) with latest results and analysis of exoplanets based on *Kepler* findings.
- Major update to Chapter 11 (“Small Bodies Orbiting the Sun”) with latest images of Ceres, Pluto, and Comet Churyumov-Gerasimenko from the *Dawn, New Horizons,* and *Rosetta* spacecraft.
- The latest images and science results from planetary spacecraft and space telescopes, including *Hubble, Spitzer, Chandra, Messenger, Curiosity, Solar Dynamics Observatory, Fermi,* and others.
- New “Looking Up” icons in margins call attention to objects discussed in the text that are displayed in the Looking Up illustrations at the beginning of the book. Most of these objects can be seen in the night sky by eye, or with binoculars or a small telescope.

- New and updated images and art in every chapter not only add to the book's visual appeal but enhances student learning with clear, accurate representations that reflect the most current data in the field.

Detailed Revisions

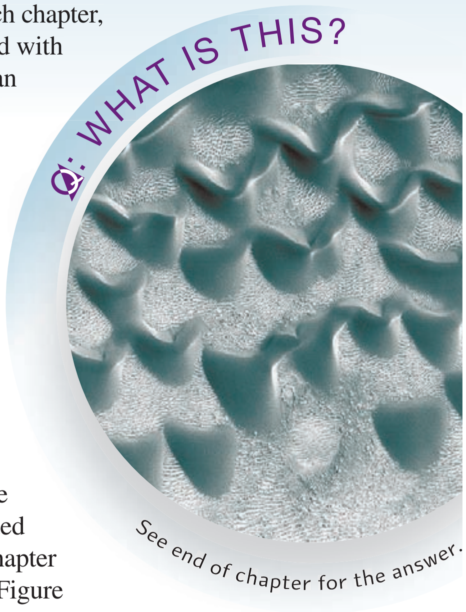
- Chapter 1: Revised illustration of the zodiac to make clearer that it is part of the celestial sphere. Improved illustration of lunar phases with new images. Updated table of upcoming eclipses.
- Chapter 2: Rearranged section 1 to present early Greek astronomical findings in historical order. New figure and discussion of how Earth's curvature can be seen when looking across the surface of the ocean. Illustration of greatest elongations of Mercury and Venus moved here from essay 1 because of its importance to development of Copernican model. Added discussion and figure of orbital eccentricity. Added photos of Venus's phases. New Extending Our Reach box on astrology.
- Chapter 3: Added discussion and figure about Cavendish's experiment to measure value of the gravitational constant. Revised illustration of escape velocity to stress idea that it is based on an initial velocity (as opposed to a rocket that may apply thrust continuously).
- Chapter 4: New figure to illustrate relationship of frequency and wavelength in everyday experience. New infrared image of dog illustrating use of false colors to display "heat." New images of M31 to illustrate differences across wavebands. New figure of Sun with sunspots to illustrate Stefan-Boltzmann equation.
- Chapter 5: New images of M31 as it appears with different resolution and integration time. Added images of large radio telescopes.
- Chapter 6: Improved seismic wave illustration. New image of aurora from the International Space Station. Added graph of carbon dioxide and global temperatures since 1890.
- Chapter 7: New image of crater wall from the *Lunar Reconnaissance Orbiter*. Updated illustration and discussion of the formation of maria. New images of lunar rilles. Updated illustration of lunar interior based on recent reanalyses. New Astronomy by the Numbers box on the Moon's distance from the Earth in the past.
- Chapter 8: Reorganized chapter to introduce exoplanets and exoplanet systems after the Solar System, culminating with discussion of formation of planetary systems. Moved figure on the shape of small bodies here (from chapter 6). Exoplanet results are examined in much more detail. *Kepler* findings about multiple-planet systems, statistics of exoplanet sizes, and planet densities are explored. Added new images of protoplanetary disks, and expanded discussion of migrating planets and the possible early evolution of the Solar System.
- Chapter 9: New topographic map of Mercury based on *Messenger* data. Figure and discussion of radar evidence of ice at Mercury's poles. Expanded coverage of Mars *Curiosity* results. New images of Phobos and Deimos.
- Chapter 10: Expanded discussion of Jupiter's atmospheric circulation, and infrared images of the belts and zones. New *Hubble* image of Jupiter's aurora. Added image of Galilean satellites seen through small telescope. New images and discussion of several interesting smaller satellites—Amalthea, Hyperion, Iapetus, and Enceladus. New images of major storm on Saturn and its polar vortex.
- Chapter 11: New *Dawn* image of Ceres, with comparison to the Moon and asteroids. First results on Pluto from *New Horizons*. New images and discussion of Comet Churyumov–Gerasimenko from early *Rosetta* results. New image of meteor from ISS, and of Chelyabinsk meteor and damage. Added image of Tunguska site.
- Chapter 12: New *Solar Dynamics Observatory* image of Sun. New diagram of *Voyager* findings about outer limits of the solar wind.
- Chapter 13: Section 2 is now split in half. The new section 2 now covers luminosity, inverse-square law, standard candles, and magnitudes. Section 3 focuses on determining stars' temperatures and radii. Added mention of new spectral type *Y*. Added discussion and figure about proper motion.
- Chapter 14: Added H-R diagram overviewing evolution of low- and high-mass stars. New *Hubble* image of Eagle nebula. Revised several illustrations of stellar interiors.
- Chapter 15: New X ray/optical images of type Ia supernova remnants.
- Chapter 16: New *Spitzer* image of Milky Way. Updated discussion of Galactic center, with new images and diagrams, including gamma-ray "bubbles" detected by *Fermi*. Revised discussion of future of Milky Way and added illustrations.
- Chapter 17: Expanded explanation of galaxy types. Added side-by-side comparison of optical and radio neutral hydrogen images of M81.
- Chapter 18: Added illustration from millennium simulation of growth of structure in the Universe. Revised presentation within section 1 to more strongly motivate need for modern model of expanding Universe. Latest *Planck* results for composition of the Universe. New table showing relationship of distances, times, and redshift for current cosmological parameters.
- Revised and updated the Moon and planet finder on the foldout chart.

FEATURES OF *EXPLORATIONS*

Explorations has been designed with a number of special features to help you better comprehend the many wide-ranging aspects of astronomy. Familiarize yourself with these features, then before you begin reading a chapter scan through to see what features and figures are present. This overview of the chapter will help deepen your understanding as you read.

Learning Objectives are presented at the start of each chapter. These identify the most important skills that the reader should gain upon completing the chapter. Use this as a checklist for successful completion of a chapter, as well as for identifying topics to reread or to seek further help about.

"What Is This?" questions are presented in each chapter to encourage deeper examination of photos and figures. At the beginning of each chapter, readers are presented with a mystery photo of an astronomical object and asked to guess what it is. After reading the chapter, they should have some idea of what is shown in the photo. In addition, there are questions in blue boxes about a number of other figures and images. The answers to these questions are provided at the end of each chapter under the heading "Figure Question Answers."



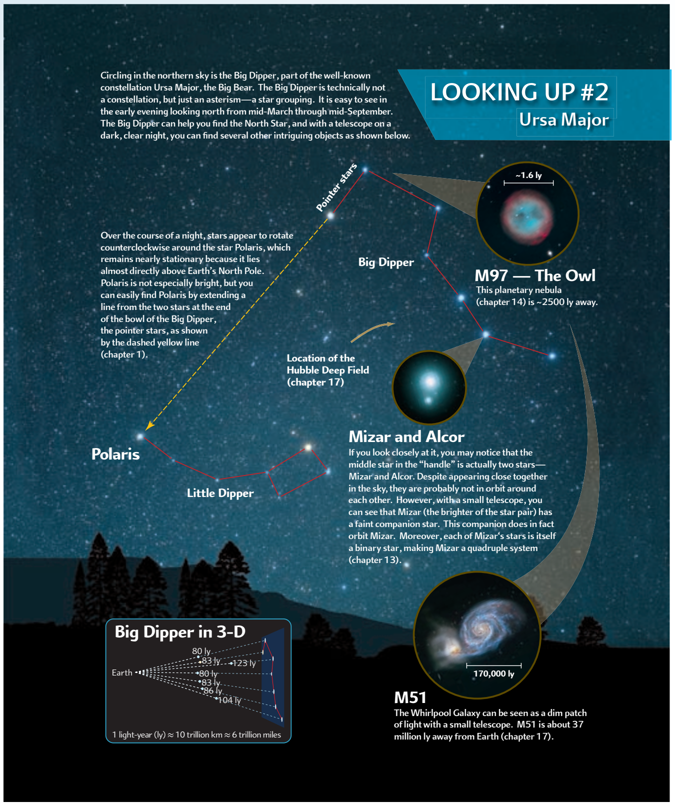
Concepts and Skills to Review are listed at the start of each chapter to provide quick pointers to earlier material that is critical for understanding the content of the chapter. If any look unfamiliar, you should review them before reading the chapter.

Astronomy by the Numbers boxes work through the details of some mathematical derivations and provide worked examples of typical calculations. Read these to gain a greater command of the mathematics behind the discussion in the text.

Extending Our Reach boxes present recent and advanced subjects that are not central to the main material in the text. These can be included for a deeper coverage of the topic.

Science at Work boxes discuss ideas, sometimes controversial, that illustrate how scientists examine new hypotheses.

Looking Up figures, each a full-page art piece, are located at the start of the book. These nine images of the night sky designed to show students how some of the astronomical objects discussed in the text connect with the real sky that they can see overhead at night. The figures cover nine especially interesting regions, ranging from the North Pole to the South Pole. In particular, they show where a variety of the frequently mentioned and important astronomical objects can be seen, many with binoculars or a small telescope. Each Looking Up figure presents a photograph of one or more constellations in which nebulas, star clusters, and other interesting objects are identified and illustrated, with references to the relevant chapter. These latter illustrations include scale factors to help students visualize how even immense objects many light-years across can appear as mere dots in the sky.



Along with the illustrated objects, most of the Looking Up features include a small insert to show how one of the constellation's stars are arranged in space.

When objects appearing in these figures are discussed in the text, Looking Up icons can be found in the margin. These point the reader to the appropriate Looking Up figure. We hope this connection to the night sky helps readers maintain or regain that sense of amazement when they view the sky.

Online Media are available on the *Explorations* website(www.mhhe.com/arny8e) to help students gain a better grasp of key concepts. Icons have been placed near figures and selections where students can gain additional understanding through Animations and Interactives. The Interactives are programmed in Flash, allowing users to manipulate parameters and gain a better understanding of topics such as Blackbody Radiation, The Bohr Model, a Solar System Builder, Retrograde Motion, Cosmology, and the H-R Diagram by watching the effect of these manipulations.

Summary boxes at the end of each chapter give a brief review of the material covered. You also may want to read the summary *before* reading the chapter to get a general idea of the most important topics.

End-of-Chapter Questions are keyed to the relevant section numbers to help make connections between readings and problem solving. Use these cross references to delve back into the chapter if you are struggling with any of the questions.

When you finish a reading assignment, try to answer the "Questions for Review" for the sections you covered. They are short and are designed to help you see if you have assimilated the basic factual material in each section. Try to do this without looking back into the chapter, but if you can't remember, look it up rather than skip over the question. You might find it helpful to write out short answers to the questions.

Having worked your way through the material, go back and try to work through the other questions. "Thought Questions" challenge you to think more deeply about the readings. If you can't answer these on your own, talk them through with other students or your instructor. Then try some of the mathematical "Problems" and see if you can work through the material on your own. You may want to refer to the "Astronomy by the numbers" boxes in the chapter for ideas how to do these calculations. Finally, you can use the multiple-choice "Test Yourself" questions for a quick check of your understanding.

The **Appendix** contains a brief introduction to working with scientific notation and solving simple equations. It also contains 11 tables with important numbers and astronomical data, bringing together information about Solar System objects, other stars, and other galaxies so you can easily compare their properties.

The **Glossary** provides short definitions of all the key terms in the text. If you encounter words or terms as you read that you don't know, look them up in the glossary. If they are not included there, check the index or a dictionary or encyclopedia.

The **Foldout Star Chart** at the back of the book is useful for studying the sky and figuring out where the Moon and planets are located in any month. The chart is useful for projects such as plotting the changing location of the Moon and planets, or the paths of meteors.

Seeing a clear night sky spangled with stars is a wondrous experience. And yet the beauty and sense of wonder can be enriched even more by an appreciation of the complex processes that make the Universe work. We hope this book will similarly increase your appreciation of our Universe's wonders.

If you find mistakes or have suggestions about how to make this book better, please contact one of us. Write T. Arny at P.O. Box 545, Patagonia, AZ 85624, or by email at tarny@theriver.com; or S. Schneider at Department of Astronomy, University of Massachusetts, Lederle Tower, Amherst, MA 01003, or by email at schneider@astro.umass.edu.

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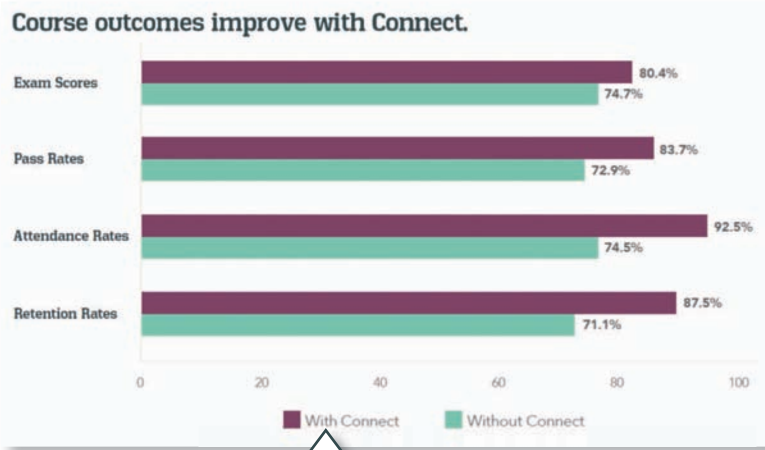

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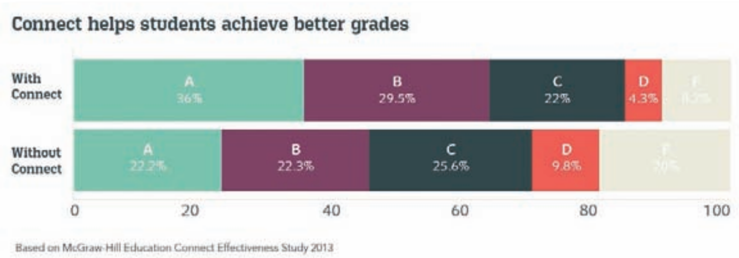

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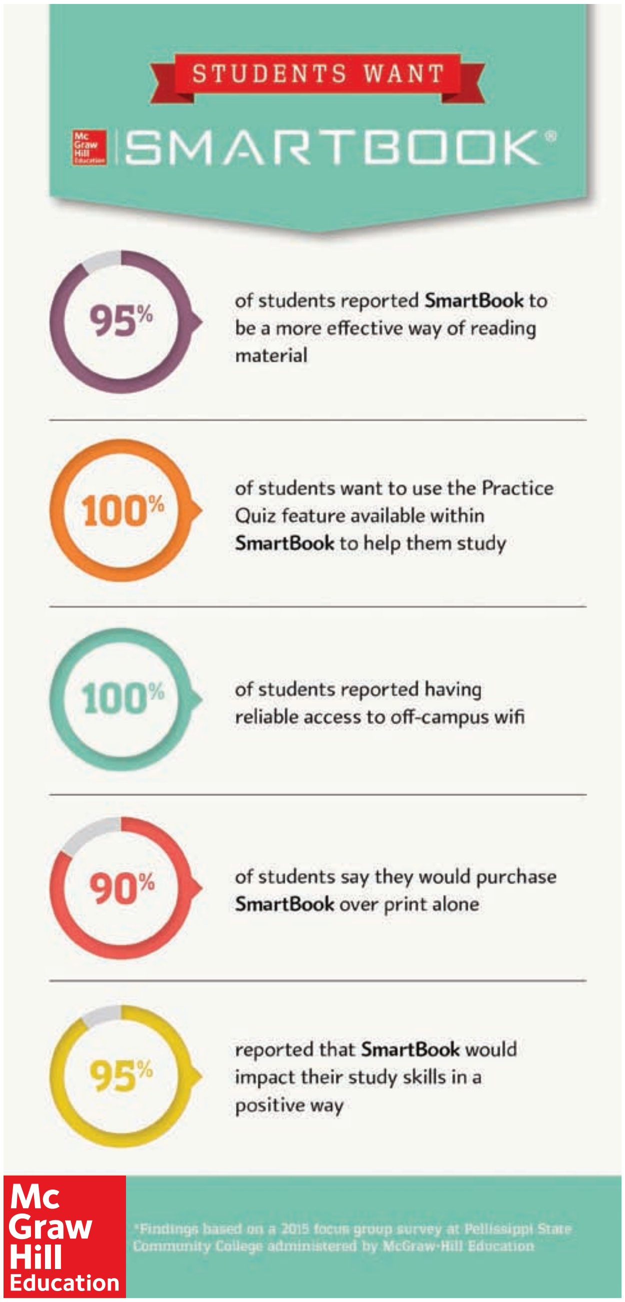

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PREVIEW

The Cosmic Landscape

Astronomy is the study of the heavens, the realm extending from beyond the Earth's atmosphere to the most distant reaches of the Universe. Within this vast space we find an amazing diversity of planets, stars, and galaxies. It is amazing that creatures as tiny as ourselves not only can contemplate but also can understand such diversity and immensity. But even more amazing are the objects themselves: planets with dead volcanos whose summits dwarf Mount Everest, stars a hundred times the diameter of the Sun, and galaxies—slowly whirling clouds of stars—so vast that they make the Earth seem like a grain of sand in comparison. All this is the cosmic landscape in which we live, a landscape we will explore briefly here to familiarize ourselves with its features and to gain an appreciation for its vast scale.

FIGURE P.1
The planet Earth, our home, with blue oceans, white clouds, and multihued continents.

THE EARTH, OUR HOME

We begin with the Earth, our home **planet** (fig. P.1). This spinning sphere of rock and iron circling the Sun is huge by human standards, but it is one of the smaller bodies in the cosmic landscape. Nevertheless, it is an appropriate place to start because, as the base from which we view the Universe, it influences what we can see. We cannot travel from object to object in our quest to understand the Universe. Instead, we are like children who know their neighborhood well but for whom the larger world is still a mystery, known only from books and television.

Just as children use knowledge of their neighborhood to build their image of the world, so astronomers use their knowledge of Earth as a guide to more exotic worlds. For example, we can deduce from the glowing lava of an erupting volcano and the boiling water shooting from a geyser that the interior of our planet is hot. That heat creates motion inside the Earth, much like the way heat makes soup in a pot bubble and churn. Although the motions inside Earth are far slower than those we see in bubbling soup, over millions of years they buckle the seemingly firm rock of our planet's crust to heave up mountains and volcanoes. Deeper inside Earth, similar motions generate magnetic forces that extend through the surface and into space. On Earth's surface these forces tug on the needle of a compass so that it points approximately north–south. High in our atmosphere, these same magnetic forces shape the northern lights.

Looking outward to our planetary neighbors, we find landscapes on Venus and Mars that bear evidence of many of the same processes that sculpt our planet and create its diversity. Likewise, when we look at the atmospheres of other planets, we see many of the same features that occur in our atmosphere. For example, winds in the thin envelope of gas that shelters us swirl around our planet much as similar winds sweep the alien landscapes of Venus and Mars.

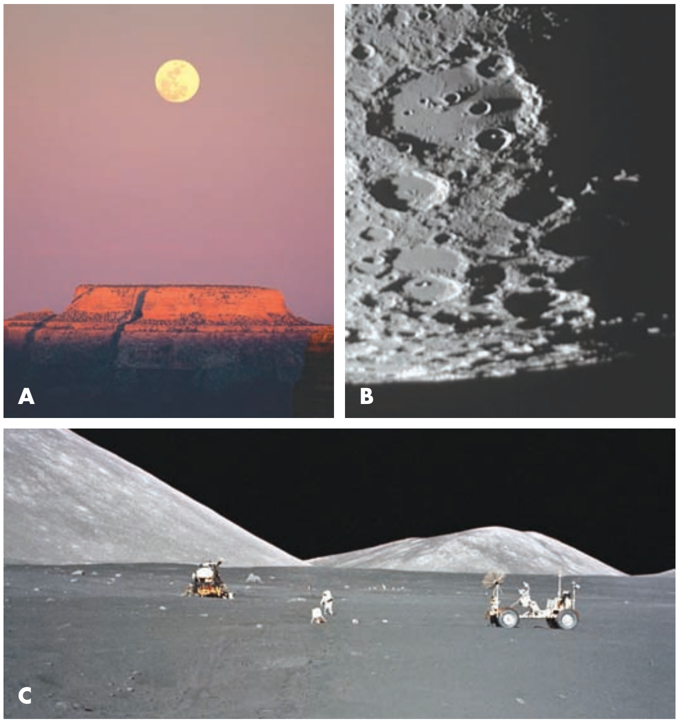

FIGURE P.2
The Moon as seen (A) with the unaided eye and (B) through a small telescope, and (C) *Apollo 17* astronauts on the surface.

THE MOON

The Moon is our nearest neighbor in space, a **satellite** that orbits the Earth some quarter million miles (384,000 km) away. Held in tow by the Earth's gravity, the Moon is much smaller than Earth—only about one-quarter our planet's diameter.

With the naked eye (fig. P.2A), and certainly with a pair of binoculars or small telescope (fig. P.2B), we can clearly see that the Moon's surface is totally unlike Earth's. Instead of white whirling clouds, green-covered hills, and blue oceans, we see an airless, pitted ball of rock that shows us the same face night after night.

Why are the Earth and Moon so different? Their differences arise in large part from the great disparity in their masses. The Moon's mass is only about 1/80th the Earth's, and it was therefore unable to retain an atmosphere. Without wind and rain, there has been relatively little erosion of the Moon's surface. Because of its smaller bulk, the Moon was also less able to retain heat. Without that strong internal heat, the crustal motions that are so important in shaping Earth are absent on the Moon. In fact, the Moon has changed so little for billions of years that its surface provides important clues to what Earth was like when it was young. In addition to this scientific importance, the Moon has symbolic significance for us—it is the farthest place from Earth that humans have traveled to (fig. P.2C).

THE PLANETS

Beyond the Moon, circling the Sun as the Earth does, are seven other planets, sister bodies of Earth. In the order of their average distance from the Sun, working outward, the eight planets are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. These worlds have dramatically different sizes and landscapes. For example:

- Ancient craters blasted out by asteroid impacts scar the airless surface of Mercury.
- Dense clouds of sulfuric acid droplets completely shroud Venus.
- White clouds, blue oceans, green jungles, and red deserts tint Earth.
- Huge canyons and deserts spread across the ruddy face of Mars, but long ago there may have been lakes or even oceans.
- Immense atmospheric storms sweep across Jupiter—one storm almost as big as the whole Earth has lasted for centuries.
- Trillions of icy fragments orbit our second largest planet Saturn, forming its bright rings.
- Dark rings girdle Uranus, its spin tipped by some cosmic catastrophe in its distant past.
- Choking methane clouds whirl in the deep blue atmosphere of Neptune.

Figure P.3 shows pictures of these eight distinctive bodies and reveals something of their relative size and appearance. Mercury, Venus, Mars, Jupiter, and Saturn are visible to the naked eye

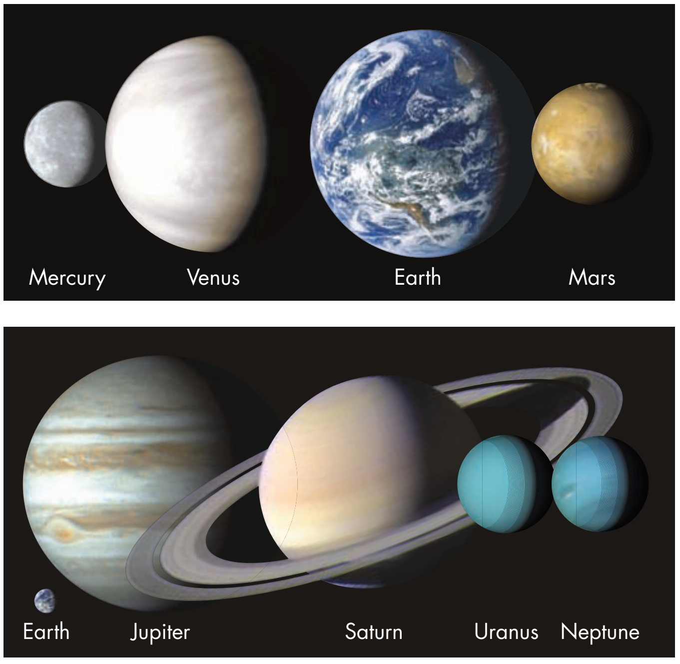

FIGURE P.3
The eight planets. *Top panel:* the four inner planets are shown to their correct relative size. *Lower panel:* the outer planets are shown to their correct relative size, with Earth for comparison.

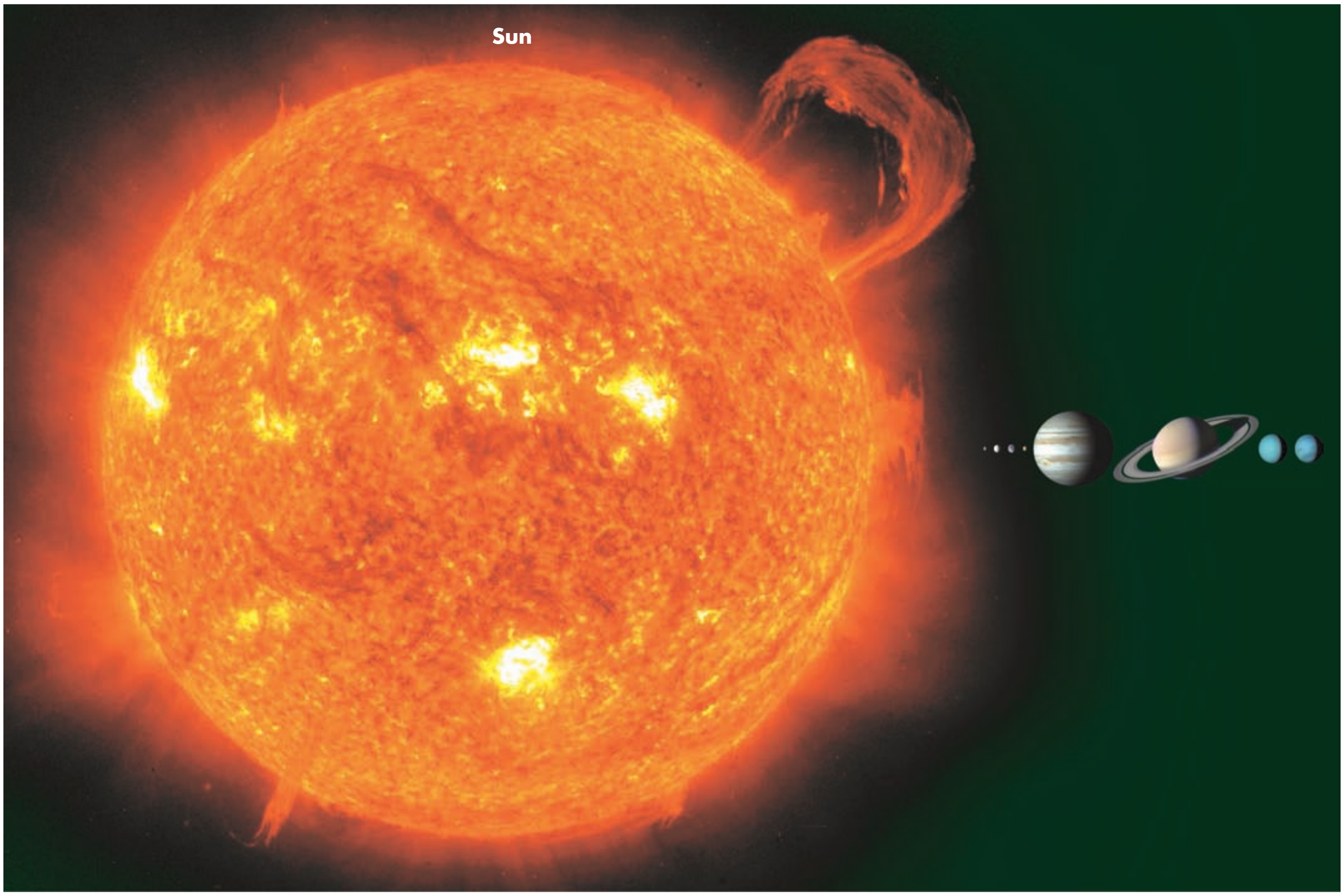

FIGURE P.4
The Sun and the eight planets shown to the same scale. If separations were shown to the same scale, Earth would be about 30 feet away, and Neptune 1000 feet away. The image of the Sun was made through a filter that shows hot helium gas near its surface.

at night as bright points of light, much like stars. But whereas stars do not noticeably change their positions relative to one another, the planets, because of their orbital motion around the Sun, move slowly and regularly against the pattern of the background stars. This regular motion gave the planets a special significance to people in ancient times who named these moving "stars" after gods and goddesses—a significance that has been carried forward to today in the names of many of the days of the week. Saturday gets its name from Saturn, while in Spanish, miércoles (Wednesday) gets its name from Mercury.

Imagine how strange it must have seemed hundreds of years ago when astronomers first argued that the Earth was a “planet,” one of those wandering stars seen in the night sky. Today with modern telescopes and spacecraft we can see that each planet is a unique, fascinating world. Some are airless while others have atmospheres so deep that they could swallow the Earth. As best we can tell, none other than Earth has given rise to life, but the characteristics of each planet offer us insights into our own planet’s history and how we might maintain its unique environment.

Earth is a midsize planet. Jupiter is more than 300 times more massive, outweighing all of the other planets combined. However, all are dwarfed by the star they orbit: the Sun.

THE SUN

The Sun is a **star,** a huge ball of gas more than 100 times the diameter of the Earth and more than 300,000 times more massive: if the Sun were the size of a volleyball, the Earth would be about the size of a pinhead, and Jupiter roughly the size of a nickel (fig. P.4). The Sun contains about 1000 times more matter than all of the planets combined.

The Sun, of course, differs from the planets in more than just size: it generates energy in its core by nuclear reactions that convert hydrogen into helium. From the core, the energy flows to the Sun’s surface, and from there it pours into space, illuminating and warming the planets.

The Sun’s energy output cannot last forever. It has been warming the planets for more than 4 billion years—long enough for life to arise on Earth and for intelligent creatures to evolve who can marvel at such wonders. Studies of other stars teach us that the Sun will run out of fuel in another 5 or 6 billion years, then finally fade away like a cooling ember. Thus, astronomy helps us not only to examine unusual objects at huge distances, but to look deep into the past and far into the future.

THE SOLAR SYSTEM

The Sun and the eight planets orbiting it are the nine most massive bodies in the **Solar System.** Many less massive objects orbit the Sun as well. Among the most massive of these are the dwarf planets, and there are millions of smaller objects such as the asteroids and comets. There are also many satellites orbiting these bodies, some nearly as massive as Mercury.

Most asteroids orbit between Mars and Jupiter in the so-called asteroid belt (fig. P.5A), home to the dwarf planet Ceres. Ceres is similar to a planet in that its own gravity has forced it into a round shape and it orbits the Sun, but its orbit is strewn with thousands of other objects whose total mass actually exceeds the mass of Ceres. Unlike the major planets, Ceres has not "cleared its orbit" of material comparable to its own mass, so by a definition adopted in 2006, it is called a dwarf planet. The other objects orbiting in this belt are too small to have pulled themselves into a round shape and are called asteroids.

Over the last few decades, astronomers have discovered a vast number of objects orbiting beyond Neptune in what is known as the Kuiper belt (fig. P.5B). This realm is the home to uncounted icy bodies, large and small. There are probably dozens of dwarf planets, along with Pluto and the slightly more massive Eris, but it is very difficult to perform observations to confirm that gravity has given them a round shape. Millions of small comets also orbit in the outermost fringes of the Solar System, but we see them only when their orbits are disturbed, sending them to boil their ices away in the inner Solar System.

If the paths that the planets follow around the Sun were visible, we would see that the Solar System is like a huge set of nested, nearly circular rings, centered approximately on the Sun and extending about 3 billion miles outward to Neptune's orbit (fig. P.5B).

It is hard to imagine such immense distances measured in miles. In fact, using miles to measure the size of the Solar System is like using inches to measure the distance between New York and Tokyo. Whenever possible, astronomers try to use units appropriate to the scale of what they are measuring. For example, as we shall see in later chapters, the Earth's radius and mass are convenient units for measuring the sizes of other planets. Likewise, the Earth's distance from the Sun is a good unit for measuring the scale of the Solar System.

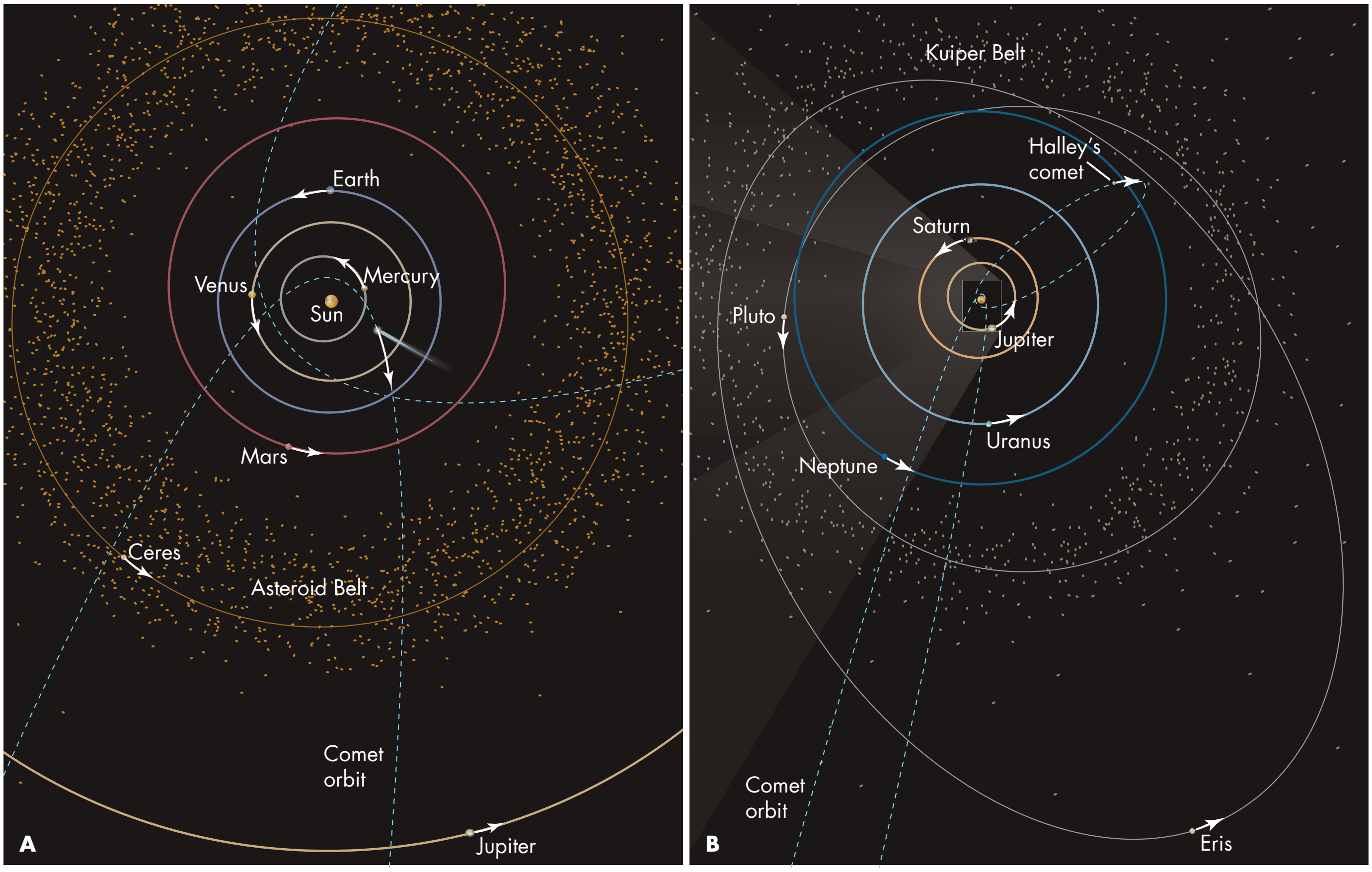

FIGURE P.5
Sketch of the positions and orbits of the planets and a variety of smaller bodies in our Solar System on March 20, 2011. The orbits of three of the largest "dwarf planets," Halley's comet, and another typical comet are also shown. The approximate location of small bodies in the asteroid belt and Kuiper belt are indicated. To show the orbits to scale, the (A) inner and (B) outer Solar System are shown separately.

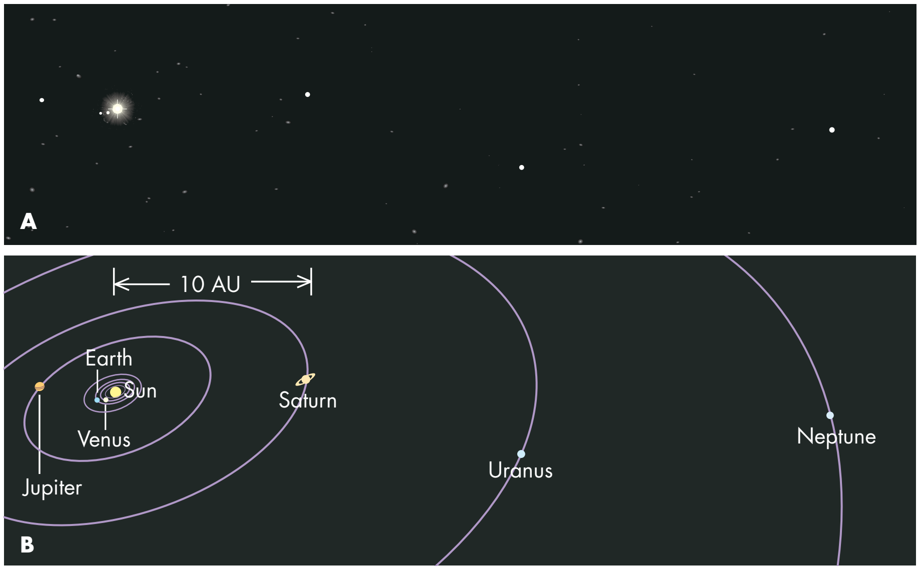

FIGURE P.6
(A) This view of the Solar System is based on a series of real images made by the *Voyager 1* spacecraft. The craft was about 40 AU from the Sun and about 20 AU above Neptune's orbit. The images of the planets (mere dots because of their immense distance) and the Sun have been made bigger and brighter in this view to allow you to see them more clearly. Mercury is lost in the Sun's glare and Mars happened to lie nearly in front of the Sun at the time the image was made, so it too is invisible. (B) A sketch of the orbits of the planets, showing where each was located at the time the image was made in February 1990.

ASTRONOMICAL SIZES

The **astronomical unit,** abbreviated as **AU,** is the average distance from the Earth to the Sun.* This translates into about 93 million miles (150 million kilometers). If we use the AU to measure the scale of the Solar System, Mercury is 0.4 AU from the Sun, while Neptune is about 30 AU (fig. P.6). The Solar System extends far beyond the planets. Some comets drift along orbits that stretch up to about 100,000 AU away from the Sun.

Figure P.6 shows a picture of the Solar System made by the spacecraft *Voyager 1* after it passed Neptune. Notice how *empty* space is. The *Voyager* spacecraft is presently the fastest-moving and most distant probe we have yet launched. Even at this speed, it would take tens of thousands of years to reach a nearby star. Rather than spacecraft, we use telescopes to extend our view beyond the Solar System. And to describe the distances to stars, we need a far larger unit of measure—the light-year.

*Because the Earth's orbit is an ellipse, which we will discuss further when we consider planetary orbits, the AU is technically defined slightly differently.

Measuring a distance in terms of a time may at first sound peculiar, but we do it often. We may say, for example, that our town is a 2-hour drive from the city, or our dorm is a 5-minute walk from the library, but expressing a distance in this fashion implies that we have a standard speed.

Astronomers are fortunate to have a superb speed standard: the speed of light in empty space, which is a constant of nature and equal to 299,792,458 meters per second (about 186,000 miles per second). Moving at this constant and universal speed, light in 1 year travels a distance defined to be 1 **light-year,** abbreviated as ly. As we show in the Astronomy by the Numbers box below, this works out to be about 6 trillion miles (10 trillion kilometers).

Working with extremely large numbers is cumbersome, so astronomers use a more concise way to write them called **scientific notation** (also called powers-of-ten notation) in which we write numbers using ten to an exponent, or power. Thus we write $100 = 10 \times 10 = 10^2$ and 1 million (1,000,000) as $10 \times 10 \times 10 \times 10 \times 10 \times 10 = 10^6$. Instead of writing out all the zeros, therefore, we use the exponent to tell us the number of zeros. A number like the speed of light (186,000 miles

ASTRONOMY *by the numbers* — THE SIZE OF A LIGHT-YEAR

To find how far light travels in a year, we multiply its speed by the travel time. One year is approximately 31,600,000 (or 3.16×10^7) seconds. Multiplying this time by the speed of light gives the distance light travels in one year:

$$3.16\times10^7 \text{ seconds} \times 1.86\times10^5 \text{ miles/second}$$
$$= 3.16 \times 1.86\times10^{12} \text{ seconds} \times \text{miles/second}$$
$$= 5.88\times10^{12} \text{ miles,}$$

or about 6 trillion miles (about 10^{13} kilometers). In these units, the star nearest the Sun is 4.2 light-years away.

Although we achieve a major convenience in adopting such a huge distance for our scale unit when describing distances to stars, we should not lose sight of how truly immense such distances are. For example, if we were to count off the miles in a light-year, one every second, it would take us about 186,000 years!

per second) may also be written in scientific notation, becoming 1.86×10^5 miles per second. Likewise, the astronomical unit (150 million kilometers) can be written as 1.5×10^8 km.

One reason to use scientific notation is that multiplying and dividing becomes enormously easier. For example, to multiply two powers of ten we just add the exponents, and to divide we subtract them. Thus $10^2 \times 10^5 = 10^7$, and $10^8/10^3 = 10^5$. More details on using scientific notation are given in the appendix.

With the ability to describe these enormous interstellar distances, we are prepared to move beyond the Solar System. In this vastly larger realm, the Sun is but one of a vast swarm of stars orbiting the center of our galaxy, the Milky Way.

THE MILKY WAY

The **Milky Way Galaxy** is a cloud of several hundred billion stars with a flattened shape like the Solar System (fig. P.7), but about 100,000 ly across. The Sun orbits 27,000 ly from the center of the Milky Way at some 150 miles per second (240 kilometers per second), but so vast is our galaxy that it still takes the Sun about 210 million years to complete one trip around this immense disk. The Milky Way's myriad stars come in many varieties, some hundreds of times larger than the Sun, others hundreds of times smaller. Some stars are much hotter than the Sun and shine a dazzling blue-white, while others are cooler and glow a deep red.

In the Milky Way, as in other galaxies, stars intermingle with immense clouds of gas and dust. These clouds, enormously larger than the Solar System, are the sites of stellar birth and death. Deep within their cold, dark gas, gravity draws their matter into dense clumps that eventually turn into new stars, lighting the gas and dust around them. Some stars eventually burn themselves out and explode, spraying matter outward to mix with the surrounding clouds. This matter from exploded stars is ultimately recycled into new stars (fig. P.8).

In this huge swarm of stars and clouds, the Solar System is all but lost—like a single grain of sand on a vast beach—forcing us again to grapple with the problem of scale. Stars are almost unimaginably remote: the nearest one to the Sun is over 25 trillion miles away, or about 4.2 light-years. Such distances are so immense that analogy is often the only way to grasp them. For example, if we think of the Sun as a pinhead, the nearest star would be another pinhead about 35 miles away and the space between them would be nearly empty.

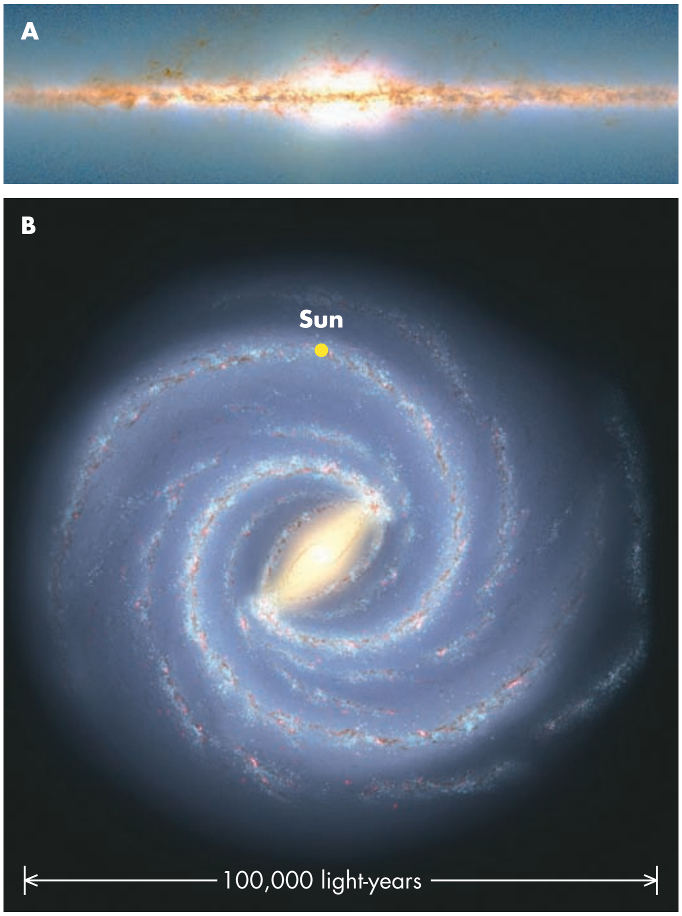

FIGURE P.7
The Milky Way Galaxy. (A) A side view made by plotting stars in the 2MASS star catalog. (B) The approximate structure of the Milky Way if it were seen from above, as mapped out by the Spitzer Space Telescope.

FIGURE P.8
An interstellar cloud in the Milky Way. Some stars are forming inside the dark cloud while other young stars heat the surrounding gas, making it glow. This Hubble Space Telescope image shows a region about 4 light-years across. At this scale the Solar System out to Neptune is about 100 times smaller than the period ending this sentence.

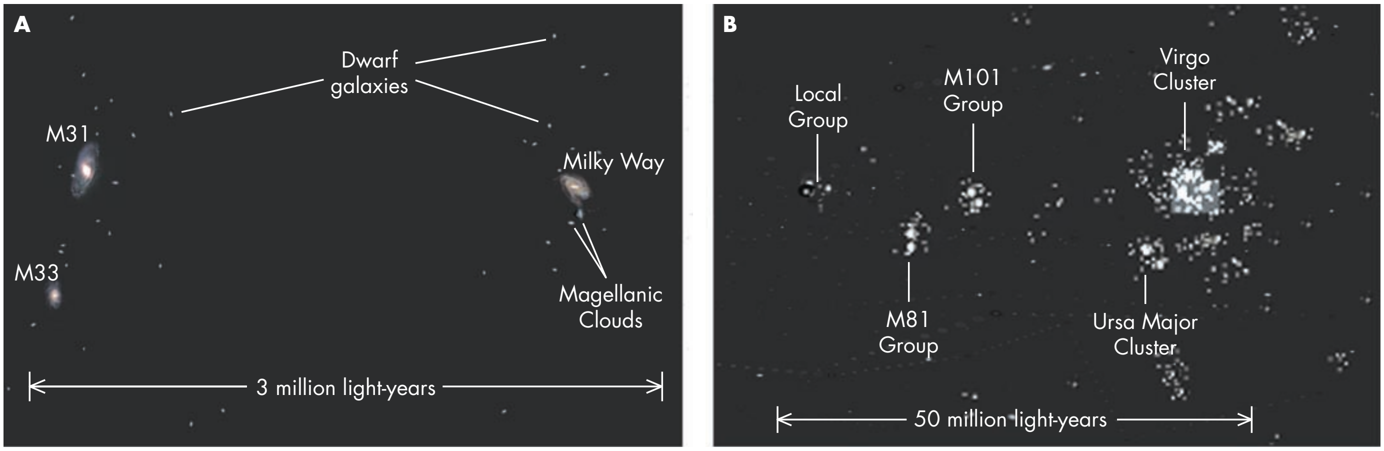

FIGURE P.9
(A) A sketch of the central region of the Local Group. (B) A sketch of the Virgo Supercluster. Only a few of the clusters of galaxies are labeled. The names of the galaxies M31, M33, M81, and M101 are from a list of galaxies and other astronomical objects that was compiled in the late 1700s by French astronomer Charles Messier ("*Mess-yay*").

GALAXY CLUSTERS AND THE UNIVERSE

Having gained some sense of scale for the Solar System and the Milky Way, we resume our exploration of the cosmic landscape, pushing out to the realm of other galaxies. Here we find that just as stars assemble into galaxies, so galaxies themselves assemble into **galaxy clusters.**

The cluster of galaxies to which the Milky Way belongs is called the **Local Group.** It is "local," of course, because it is the one we inhabit. It is termed a "group" because it is small as galaxy clusters go, containing just several dozen galaxies as members, but it is still a few million light-years in diameter. Despite such vast dimensions, the Local Group is itself part of a still larger assemblage of galaxies known as the **Virgo Supercluster.** Figure P.9 puts this in perspective.

Our supercluster consists of hundreds of galaxy groups and clusters, spread over some 100 million light-years, but it is perhaps itself part of an even larger structure known as the Great Attractor region, a cluster of superclusters, probably more than 300 million light-years across. Structures of such vast size are about the largest objects we can see before we take the final jump in scale to the **Universe** itself.

The visible Universe is the largest astronomical structure of which we have any knowledge. From the observations presently available to them, astronomers deduce that the Universe is about 13.8 billion years old. This limits the distance we can see, even in principle, to 13.8 billion light-years, a value we can use to describe the radius of the *visible* Universe. When we make an extremely deep photograph of the sky (fig. P.10), the light from the most distant visible galaxies takes nearly the age of the Universe to reach us, so we are seeing them when they first formed.

Although the visible Universe extends to 13.8 billion light-years from us, that does not mean the Universe ends there. Rather, it means we cannot yet see what lies beyond. But regardless of our uncertainty about the known Universe's size, we can observe that its structure is similar throughout the visible Universe. Small objects are clustered into larger systems, which are themselves clustered: planets around stars, stars in galaxies, galaxies in clusters, clusters in superclusters, and perhaps superclusters into even larger associations. Although astronomers do not yet understand completely how this orderly structure originated, they do know that gravity plays a crucial role.

FIGURE P.10
A portion of the deepest image ever made with the Hubble Space Telescope. Virtually every one of the thousands of dots in the image is a galaxy—some near the edge of the visible Universe are seen when they were just beginning to form. A grain of sand held at arm's length would cover the tiny area imaged here.

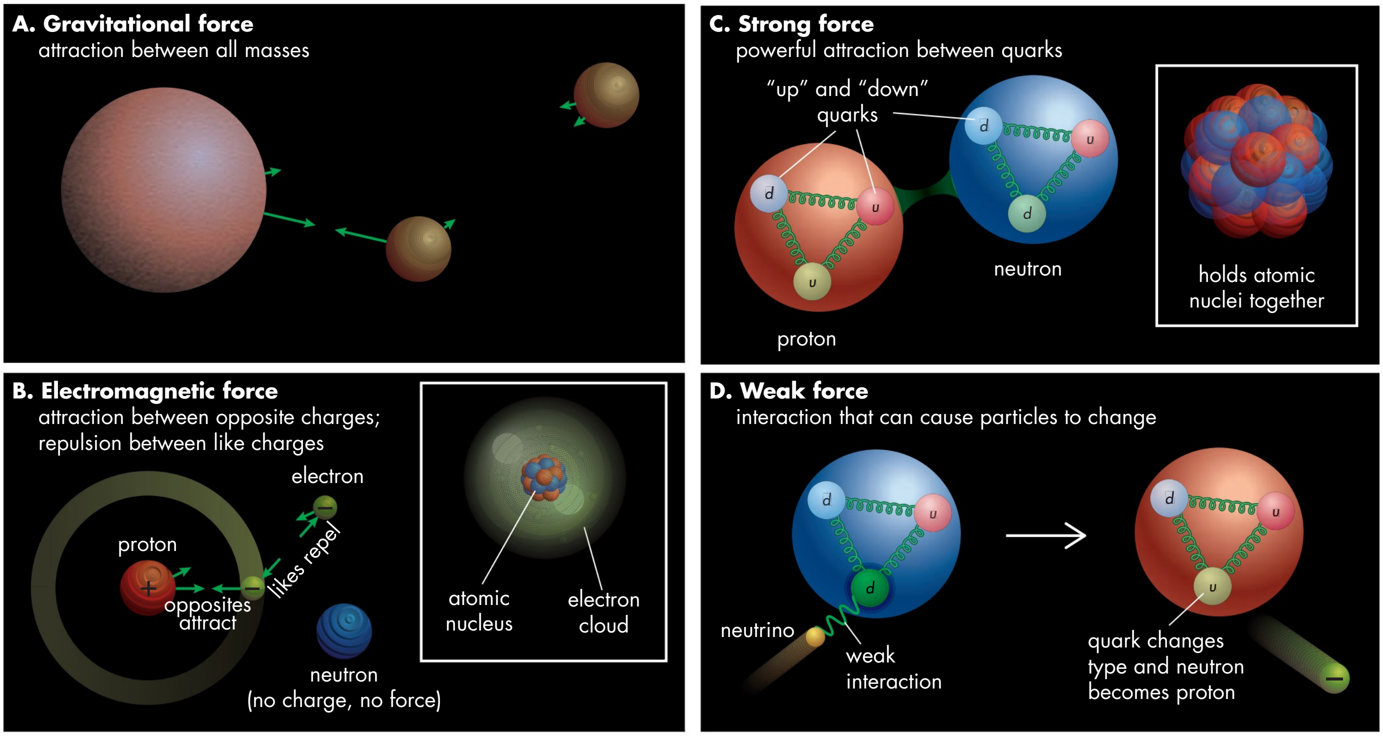

FIGURE P.11
The four fundamental forces. (A) The force of gravity is present between all objects with mass. The force, represented by green arrows in the figure, is always attractive, but grows weaker with distance. (B) The electromagnetic force arises between particles with an electric charge. It causes electrons (negative charge) to be attracted to protons (positive charge) to form atoms. The nucleus of an atom is made of protons and neutrons (with no electric charge). (C) Protons and neutrons are made of smaller particles called quarks, which are held together by the strong force. The strong attraction between quarks causes protons and neutrons to be attracted to each other, overcoming the electromagnetic repulsion between protons. (D) The weak force causes some particles to change into others as they interact. The weak force causes radioactive decay and plays a critical role in energy formation in stars.

FORCES AND MATTER

Gravity gives the Universe structure because it creates a force of attraction between *all* objects (fig. P.11A). You experience gravity's attraction in everyday life. For example, if you drop a book, the Earth's gravitational force makes the book fall. That same force spans the vast distance between the Earth and the Moon to hold our satellite in its orbit. Similarly, gravity holds our planet in its orbit around the Sun and the Sun in its orbit around the Milky Way.

Gravity may dominate the large-scale structure of the Universe, but other forces dominate on smaller scales. To understand these forces, we need to look at the small-scale structure of matter. Matter is composed of submicroscopic particles called **atoms.** Atoms are incredibly small. For example, a hydrogen atom is about one ten-billionth of a meter (10^{-10} m) in diameter. Ten million hydrogen atoms could be put in a line across the diameter of the period at the end of this sentence. But despite this tiny size, atoms themselves have structure. Every atom has a central core, called the **nucleus,** that is orbited by smaller particles called **electrons** (fig. P.11B). The nucleus is in turn composed of two other kinds of particles, called **protons** and **neutrons.**

Although the particles in an atom exert a gravitational attraction on one another, atoms are not held together by gravity. Instead, an electromagnetic force gives them their structure. That force arises because protons and electrons have a property called **electric charge.** A proton has a positive electric charge, and an electron has a negative electric charge. A neutron is "neutral" as its name suggests—it has no charge.

The **electromagnetic force** can either attract or repel, depending on the charges. Opposite charges attract, and like charges repel. Thus, two electrons (both negative) repel each other, while an electron and a proton (negative and positive) attract each other. That attraction is what holds the electrons in their orbits around the nucleus of an atom (fig. P.10B).

You can see the electric force at work in many ways. For example, the static electric charges generated when a clothes drier tumbles your laundry creates an attraction that may make clothes cling together. The crackling sound you hear as you pull fuzzy socks away from a shirt is the electric charges jumping and making tiny sparks.

The electric force is closely linked with the magnetic force that makes a compass work or holds the little magnets to the door of your refrigerator. In fact, the theory of relativity demonstrates that electric and magnetic forces are fundamentally the same, and scientists generally refer to them jointly as the electromagnetic force.

At yet a deeper level, protons and neutrons are made up of more basic particles called **quarks.** Quarks are attracted to each other by the **strong force,** which is so-named because its attraction can overcome the electromagnetic repulsion of like-charged particles. When protons and neutrons are very close to each other, the strong force between quarks can cause them to bind together, forming an atom's nucleus (fig. P.11C). Although the effects of the strong force cannot be seen directly in everyday life, without it the nuclei of atoms, and with them our familiar world, would disintegrate.

In addition, a fourth force, known as the **weak force***, operates on the subatomic scale and plays a role in radioactive decay (fig. P.10D). The weak force is so weak that interactions involving it are extremely rare. Their rareness is important in determining how long stars live. Stars would burn themselves out much more quickly, or would not shine at all, if the weak force were much stronger or weaker. Unlike the other forces, which produce attraction or repulsion between different kinds of matter, the weak force causes matter to change its form in fundamental ways. In fact, astronomers are beginning to suspect that the weak force plays a major role in shaping the kinds of matter that are present in the Universe.

The weak force earned its name because it is millions of times weaker than the electromagnetic and strong forces, but it is still trillions upon trillions of times stronger than gravity. Why then does gravity dominate the Universe? This genuinely weakest of the forces has the unique property that it always works in just one way, always pulling matter toward other matter. By contrast, the other forces sometimes push and sometimes pull, and the differently charged particles move about until the contrary forces cancel each other out. This leaves gravity as the only remaining force acting on the largest scales.

THE STILL-UNKNOWN UNIVERSE

Our quick trip from Earth outward has shown us a Universe of planets, stars, and galaxies. However, astronomers today have evidence that the bulk of the Universe must consist of something completely different. That evidence comes from many sources, the most convincing of which are the findings that stars within galaxies, and galaxies within clusters of galaxies, experience a far stronger gravitational force than can be explained by the directly observable matter. That is, both galaxies and galaxy clusters appear to contain huge amounts of what astronomers call **dark matter.**

Dark matter is so-named because it emits no as-yet-observed radiation. But from its gravitational effects, astronomers deduce that it outweighs luminous matter by a factor of about five to one. What is the dark matter? Astronomers do not know, but it may be made up of particles that interact only through the weak and gravitational forces. For example, there are billions of weakly interacting particles called **neutrinos** passing through your body each second. These were generated by the Universe in its early stages, by nuclear reactions in the Sun, and by other cosmic events. You do not sense these particles because normal matter is more transparent to them than a glass window is to light. Astronomers suspect that there may be particles much more massive than neutrinos that fill space, generating a much stronger gravitational pull than all of the stars in all of the galaxies that we can see.

On the largest scales, galaxies throughout the Universe are moving away from each other in a great cosmic expansion. This expansion began about 13.8 billion years ago in an unimaginable explosion called the **Big Bang** that created time and space and sent hot matter flying apart everywhere. During the last two decades, astronomers studying the expansion have discovered a great mystery—the rate of expansion is speeding up. Something is overcoming the gravitational attraction between galaxies, causing them to accelerate away from each other.

It is as if empty space contains a sort of energy that drives the expansion to grow faster. Because its nature is still unknown, astronomers have named it **dark energy.** If we compare the effective mass of dark energy and dark matter with the mass of the objects that we directly detect (such as stars, galaxies, and gas clouds), those luminous objects amount to a mere 1% of the Universe's total mass. What we see of the Universe is therefore much like the footprints of an invisible creature: a being who leaves tracks, but whose build and nature we do not yet know.

THE SCIENTIFIC METHOD

Our scientific understanding of the Universe has not come easily. It has grown out of the work of thousands of men and women over thousands of years. Their work is part of the broad field that we call science.

By "science" we mean the systematic study of things and the search for the underlying principles that govern them, be they living things, matter, or, in our case, the astronomical universe. An essential part of that study is the rigorous testing of ideas. We call the process of such testing the **scientific method.** In using the scientific method, a scientist typically proposes an idea—a hypothesis—about some property of the Universe and then tests that hypothesis by experiment. In fact, whether an idea is "scientific" depends to some extent on whether it can be verified by either a real or an imagined experiment. Ideally the experiment either confirms the hypothesis or refutes it. If refuted, the hypothesis is rejected. On the other hand, if the experiment confirms the hypothesis, the scientist may then go on to develop related hypotheses or perhaps to make predictions about some as-yet-undiscovered aspect of the subject.

Once a set of ideas has been thoroughly tested and verified, they may be incorporated into a theory or law. When

*The weak force is linked to the electromagnetic force, and their combination is known technically as the electroweak force.