explorations

an introduction to astronomy

9th edition

Thomas T. Arny
Stephen E. Schneider

Mc Graw Hill Education

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An Introduction to Astronomy

Ninth Edition

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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 six 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), Draco (the Dragon), and faint Camelopardalis (the Giraffe). The brightest stars in Ursa Major and Ursa Minor form two well-known asterisms: the Big and Little Dippers.

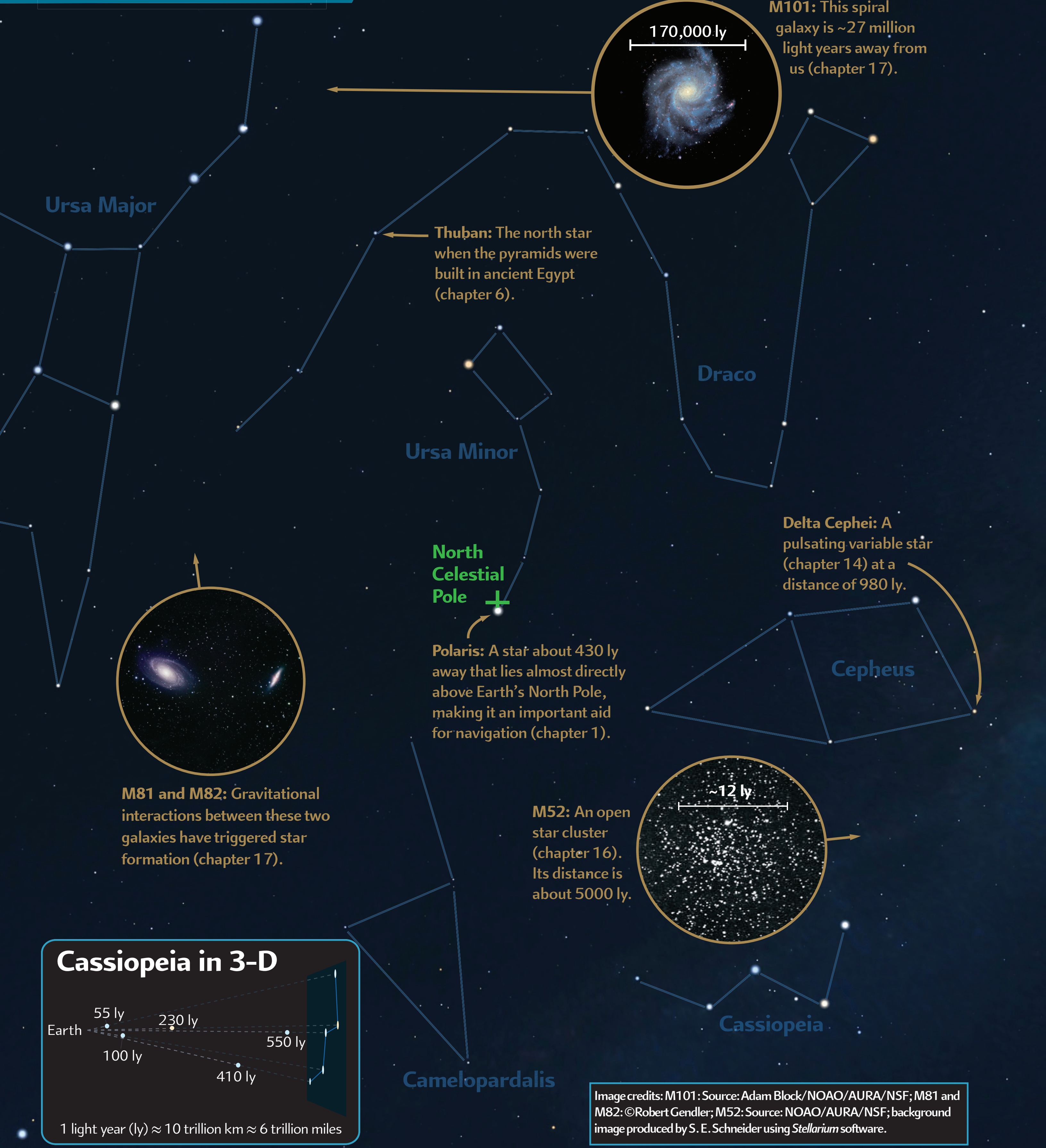


Image credits: M101: Source: Adam Block/NOAO/AURA/NSF; M81 and M82: ©Robert Gendler; M52: Source: NOAO/AURA/NSF; background image produced by S. E. Schneider using *Stellarium* software.

LOOKING UP #2
Ursa Major

Circling in the northern sky is the well-known Big Dipper, part of the constellation Ursa Major. The Big Dipper is 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.

Polaris

Little Dipper

Ursa Minor

Draco

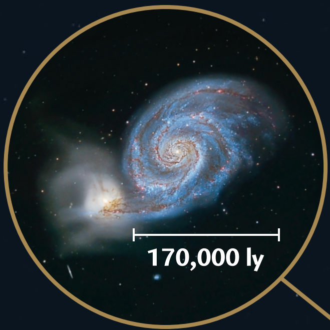
Over the course of a night, stars appear to rotate counterclockwise around the star Polaris, which remains nearly stationary because it lies almost directly above Earth's North Pole. Polaris is not especially bright, but you can easily find Polaris by extending a line from the two stars at the end of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

Location of the Hubble Deep Field (chapter 17)

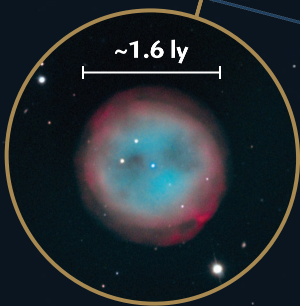
Pointer stars

Big Dipper

Ursa Major



M51—The Whirlpool Galaxy: This interacting galaxy looks like a dim patch of light with a small telescope. M51 is ~37 million ly away (chapter 17).



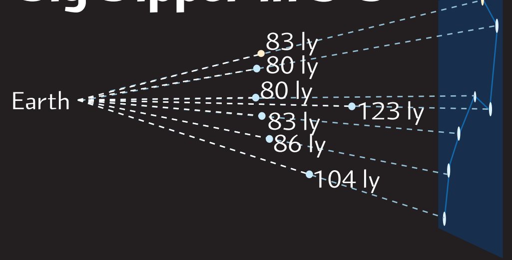
M97—The Owl: This planetary nebula (chapter 14) is ~2500 ly away.

Boötes

Leo Minor

Mizar and Alcor: If you look closely, you may notice that the middle star in the "handle" is actually two stars. 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 two stars) has a faint companion that 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



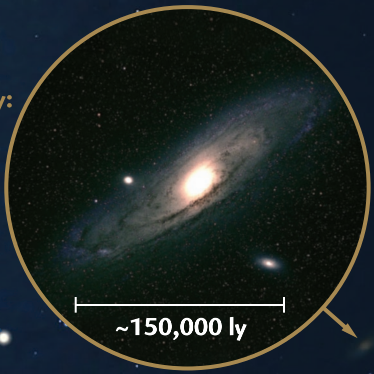
1 light year (ly) ≈ 10 trillion km ≈ 6 trillion miles

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, and through binoculars or a small telescope its shape and extent become apparent.

M31—The Andromeda Galaxy: The largest galaxy in the group to which the Milky Way Galaxy belongs (chapter 17).



Andromeda

Cassiopeia

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).

Aries

Perseus

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

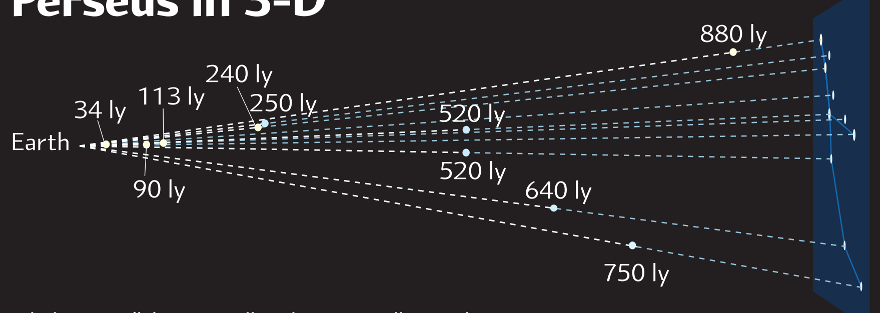
California Nebula: An emission nebula (chapter 16) with a shape like the state of California.

Image credits: M31: Courtesy of George Greaney; The Double Cluster: ©Neil Fleming; background image produced by S. E. Schneider using *Stellarium* software.

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

Auriga

Perseus in 3-D



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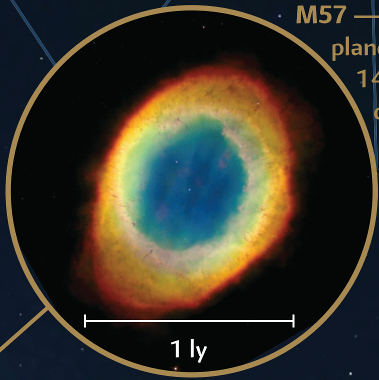
LOOKING UP #4

Summer Triangle

The Summer Triangle consists of the three bright stars Deneb, Vega, and Altair, the brightest stars in the constellations Cygnus (the swan), Lyra (the lyre), and Aquila (the eagle), 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.



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.

Epsilon Lyrae: A double, double star

Vega

Lyra

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.

Cygnus

Vulpecula

M27—Dumbbell Nebula: Another planetary nebula (chapter 14), the Dumbbell is about 1200 ly distant and is about 2.5 ly in diameter.

Sagitta

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.

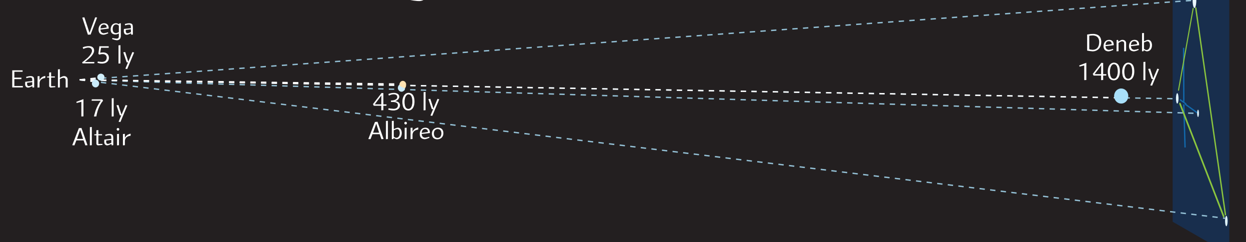
Altair

Delphinus

Aquila

Image credits: M57: Source: H. Bond et al., Hubble Heritage Team (STScI/AURA), NASA; M27: Source: ESO/I. Appenzeller, W. Seifert, O. Stahl, with recoloring; Albireo: Courtesy of Randy Brewer; background image produced by S. E. Schneider using *Stellarium* software.

The Summer Triangle in 3-D



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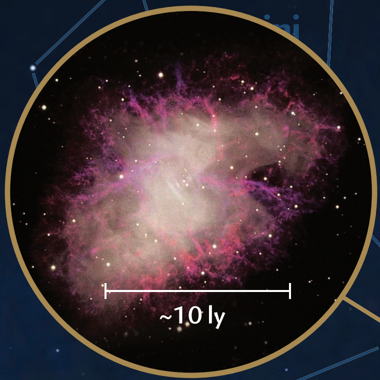
LOOKING UP #5

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.

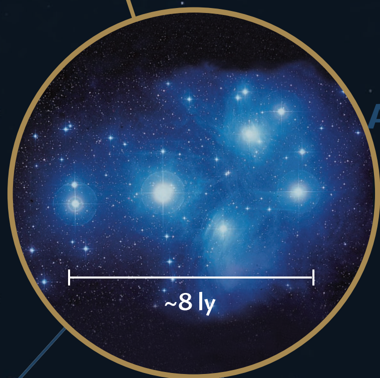


M1—Crab Nebula: The Crab Nebula is the remnant of a star that blew up in the year 1054 as a supernova. At its center is a pulsar (chapter 15). It is about 6500 ly away from us.

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.

Aldebaran: 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.

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



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.

Auriga

Perseus

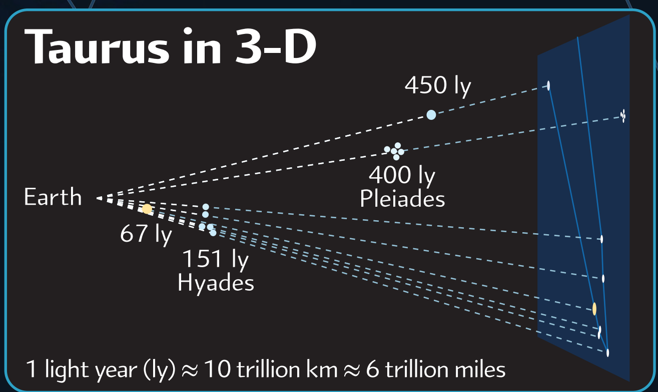
Taurus

Orion

Aries

Lepus

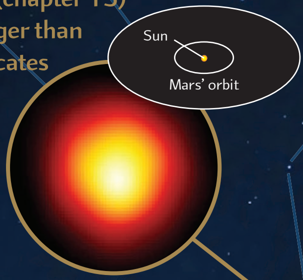
Cetus

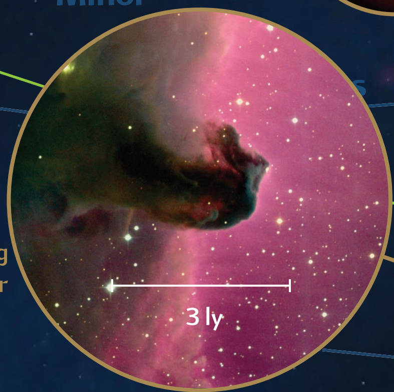


LOOKING UP #6
Orion

The constellation of Orion lies on the celestial equator, so it is visible from both hemispheres. 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. Orion is trailed by Canis Major (the large dog) which contains Sirius, the brightest star in the sky other than the Sun.

Betelgeuse: 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.

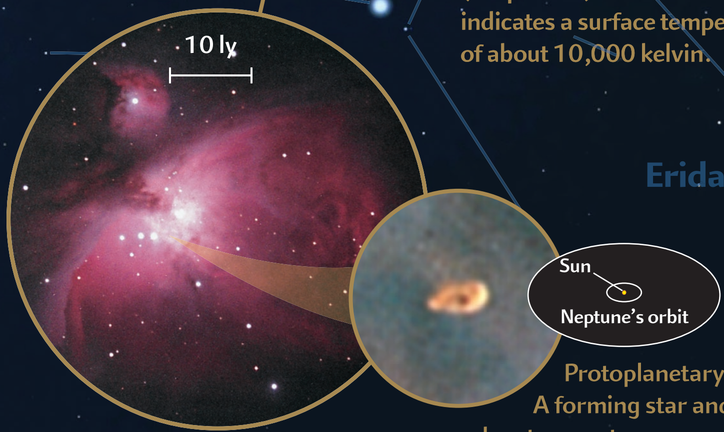




Horsehead Nebula: The horsehead shape is produced by dust in an interstellar cloud blocking background light (chapter

Sirius: The brightest star in the night sky, about 8.6 ly distant. It is orbited by a white dwarf (chapter 15) visible with a telescope.

Rigel: A blue supergiant star (chapter 13). Its blue color indicates a surface temperature of about 10,000 kelvin.

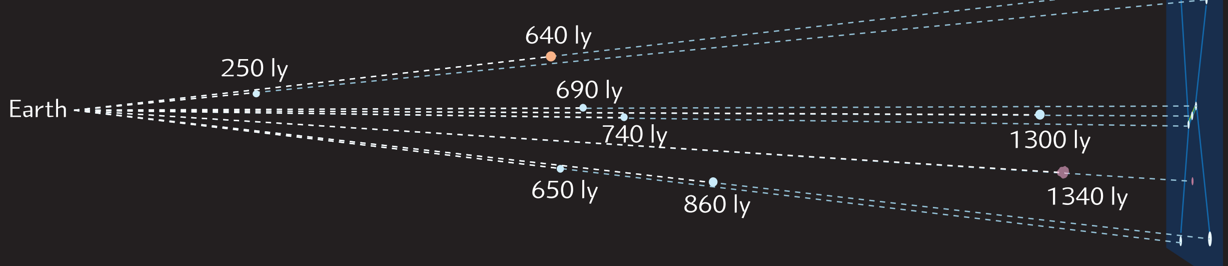


M42—Orion Nebula: An active star-forming region rich with dust and gas (chapter 14).

Protoplanetary disk: A forming star and planetary system; our early Solar System may have looked like this (chapter 8).

Image credits: Betelgeuse: Source: A. Dupree (CFA), NASA, ESA; Horsehead Nebula: Source: N.A.Sharp/NOAO/AURA/NSF; M42: Courtesy of Carol B. Ivers; Protoplanetary disk: Source: C.R. O'Dell/Rice University; NASA/ESA; background image produced by S. E. Schneider using *Stellarium* software

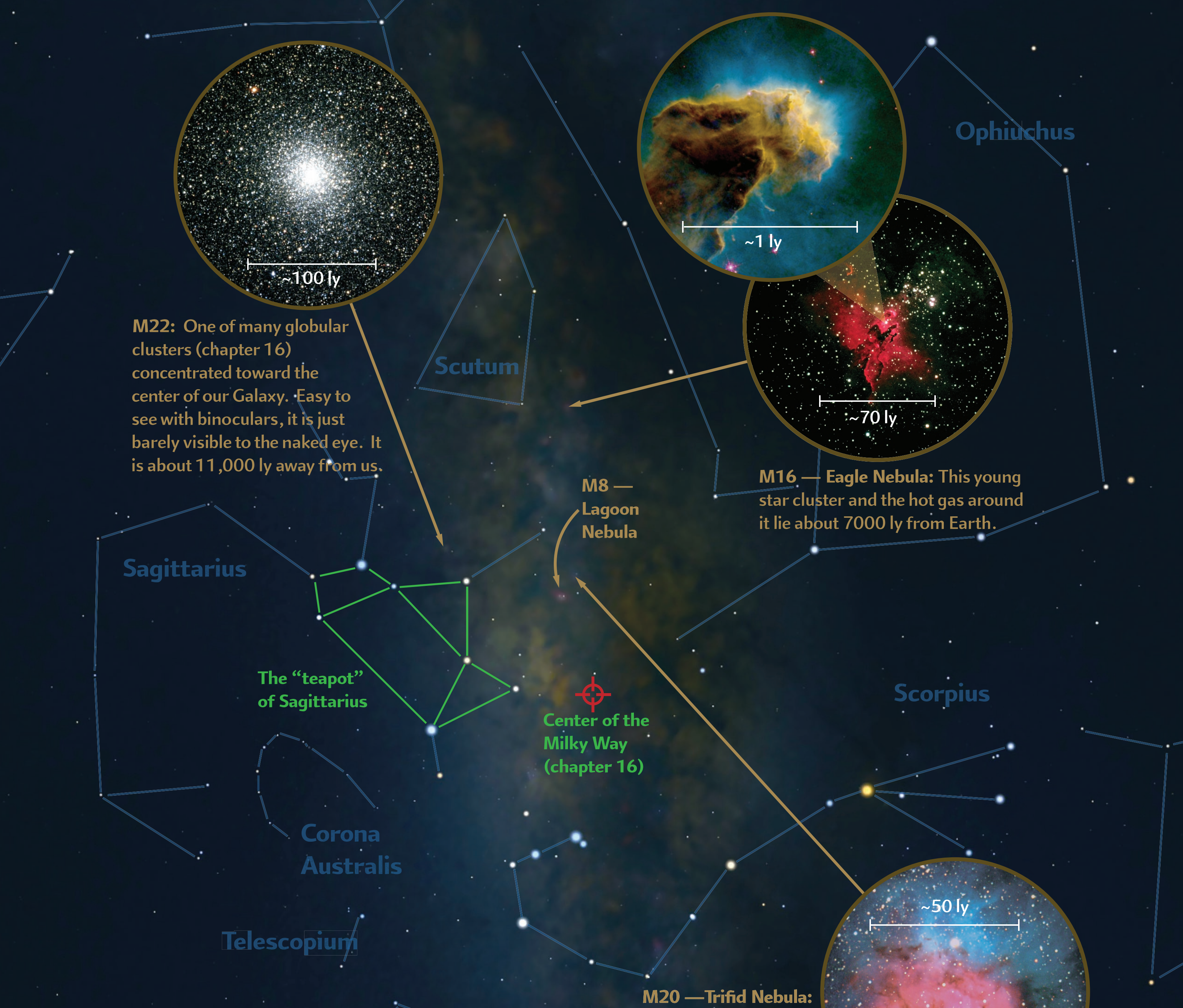
Orion in 3-D



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

LOOKING UP #7
Sagittarius

Sagittarius marks the direction to the center of the Milky Way. It can be identified by the “teapot” shape of its brighter stars, 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).

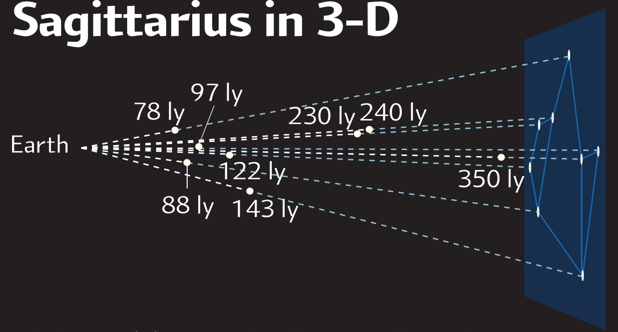


M22: One of many globular clusters (chapter 16) concentrated toward the center of our Galaxy. Easy to see with binoculars, it is just barely visible to the naked eye. It is about 11,000 ly away from us.

M16 — Eagle Nebula: This young star cluster and the hot gas around it lie about 7000 ly from Earth.

M20 —Trifid Nebula: The name Trifid was given because of the dark streaks that divide it into thirds. The distance of this nebula is ~5000 ly, but uncertain, making its size uncertain too.

Sagittarius in 3-D



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

Image credits: M22: Source: N.A. Sharp, REU program/ NOAO/AURA/NSF; M16: Source: Bill Schoening/ NOAO/AURA/NSF; M16 close-up: Source: NASA, HST, J. Hester & P. Scowen (ASU); M20: ©Jason Ware; background image produced by S. E. Schneider using *Stellarium* software.

LOOKING UP #8

Centaurus and Crux, The Southern Cross

These constellations contain many intriguing objects—the nearest star and one of the most massive known. They 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 United States).

Scorpius

Norma

Lupus

Omega Centauri: The largest globular cluster (chapter 16) in the Milky Way, ~16,000 ly distant and containing millions of stars.

Centaurus A: This active galaxy (chapter 17), ~11 million ly distant, is one of the brightest radio sources in the sky.

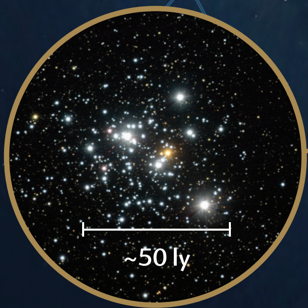
Proxiima Centauri: This dim star is the nearest star to the Sun, 4.22 ly distant (chapter 13).

Alpha Centauri

Centaurus

Circinus

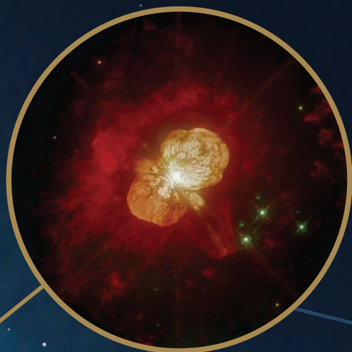
Crux



NGC 4755—the Jewel Box: An open star cluster (chapter 16) ~500 ly from us.

The Coal Sack: An interstellar dust cloud (chapter 16)

Musca



Eta Carina: 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.

Carina

Vela

Southern Cross in 3-D

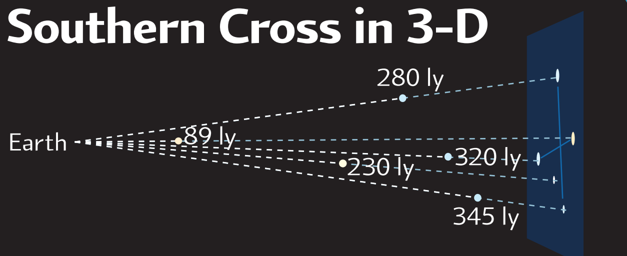


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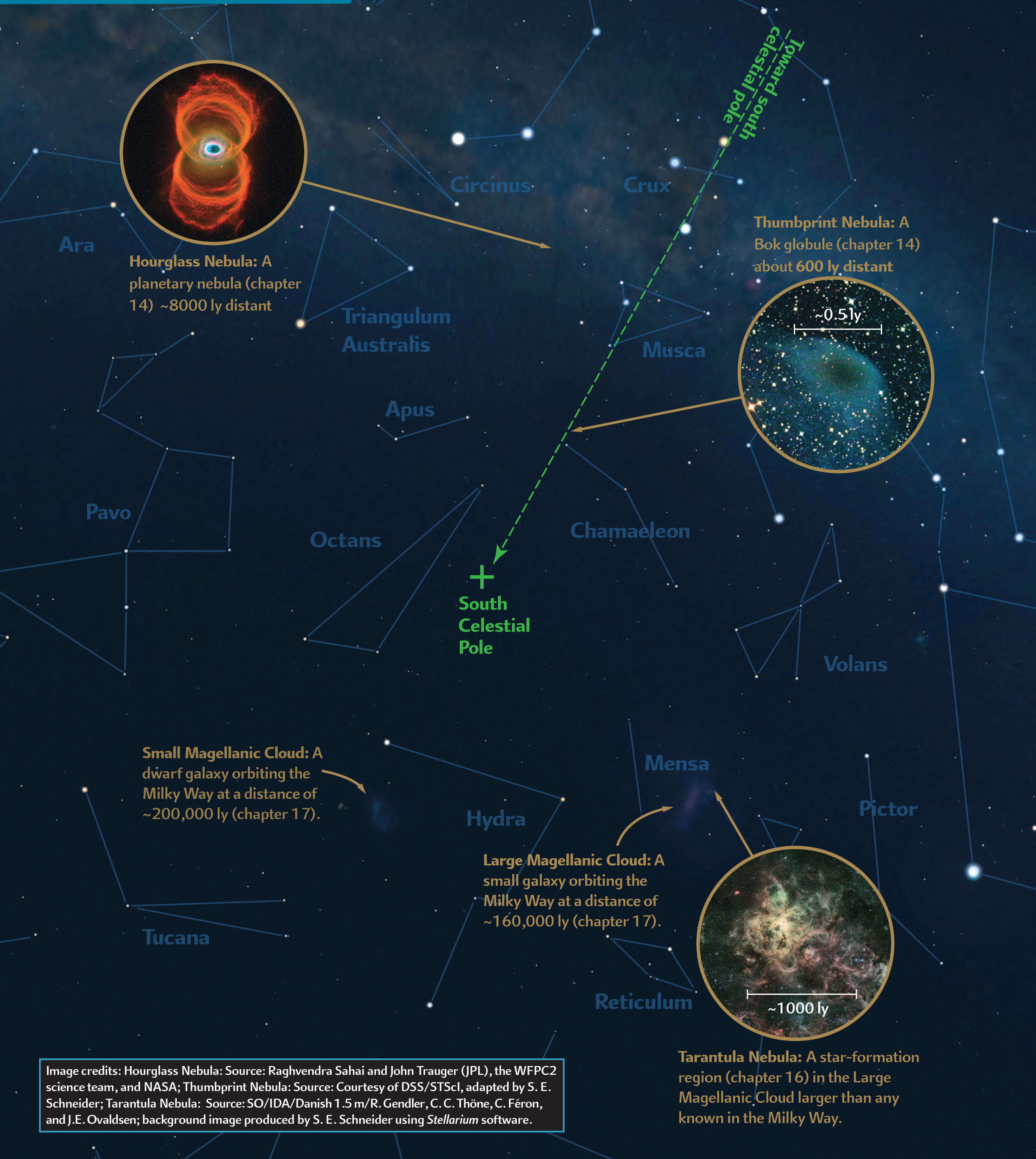
Image credits: Omega Centauri: Al Kelly; Centaurus A: Source: ESO; NGC 4755: Courtesy of Research School of Astronomy and Astrophysics, the Australian National University; Eta Carina: Source: NASA, ESA, and J. Hester (Arizona State University); background image produced by S. E. Schneider using *Stellarium* software.

LOOKING UP #9

Southern Circumpolar Constellations

The south celestial pole lies in the constellation Octans, named after a navigational instrument. The stars in this region are dim, but the bright stars of Crux (the Southern Cross) point approximately toward the pole. Observers in much of the Southern Hemisphere can see the Magellanic Clouds circling the south celestial pole throughout the night.



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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 experiences. 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. You can even learn how planets get their internal structure by examining 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, you will gain a better understanding of how science works.

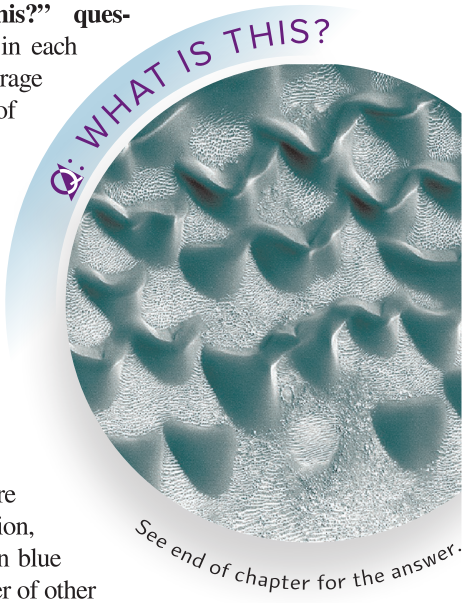
Seeing a clear night sky spangled with stars is a wondrous experience. And yet the beauty and sense of wonder can be enriched even more by an appreciation of the complex processes that make the Universe work. We hope this book will similarly increase your appreciation of our Universe's wonders.

A READER'S GUIDE TO *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, and take advantage of them to deepen your understanding as you read.

Learning Objectives are presented at the start of each chapter. These identify the most important skills that you 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, you are presented with a mystery photo of an astronomical object and asked to guess what it is. After reading the chapter, have you figured out what the picture shows? 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."



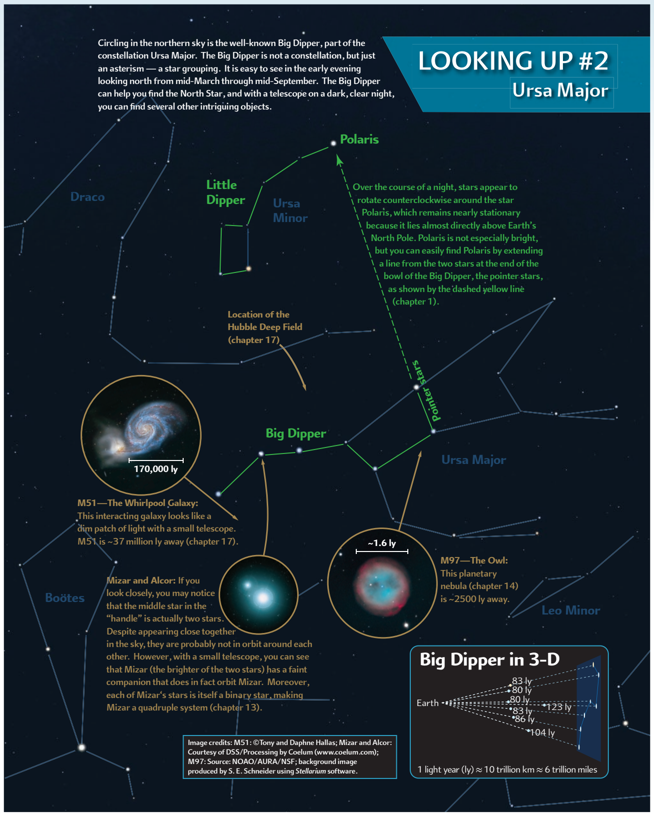
Concepts and Skills to Review are listed at the start of each chapter to provide quick pointers to earlier material that is critical for understanding the content of the chapter. If any look unfamiliar, you should review them before reading the chapter.

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 an image of several 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/arny9e) to help you 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 HTML5, allowing users to manipulate parameters and gain a better understanding of topics such as Blackbody Radiation, The Bohr Model, Retrograde Motion, and the H-R Diagram by watching the effect of these manipulations.

Projects are indicated by a their own icon, and are easy activities that you can carry out to better understand a wide variety of astronomical ideas and connect them with what is visible in the sky. Most of the Projects are based on the free open source planetarium program *Stellarium,* which can be downloaded from *stellarium.org*. The Projects also include some hands-on activities. All are described in detail online.

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, and stars and 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 can be used for projects such as plotting the changing location of the Moon and planets, or the paths of meteors. The chart also shows the positions of many of the best star clusters, nebulas, and galaxies for viewing through a small telescope.

The **Cosmic Periodic Table** on the back side of the foldout graphically illustrates a wide variety of essential information about the atomic elements critical to understanding their role in the cosmos: how the elements were created; their cosmic abundance; the temperature at which they condense; the amount of nuclear energy available from each through fission or fusion; and their radioactive properties. These properties are linked to the formation and evolution of planets, stars, and the Universe itself.

NOTES TO THE INSTRUCTOR

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 you might choose to skip. We also cover some essential background material 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 intimidating to many readers, we begin these discussions by introducing the essence of the calculation in everyday language so that the basic idea can be understood independent of 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. A perpetual challenge for astronomers is illustrating objects of fantastically different sizes and vast separations. We have also put considerable effort into refining figures to help readers keep in mind relative size differences while still keeping the illustration clear. This is based on decades of work with students and discovering points of confusion as they studied and interpreted these figures.

New to the Ninth Edition

In this ninth edition of *Explorations,* we continue to update the art and text throughout the book in response to readers' comments and suggestions. One of the best aspects of McGraw-Hill's electronic resources for students is that we can find the links back to text and figures related to questions that students are having difficulty answering. We have closely examined these materials and worked on making sure the wording and imagery is as clear as possible. In addition to changes for clarity, there are several places where we have made more extensive revisions in response to recent research and requests for extra detail. These include the following:

- The latest results and analysis of exoplanets based on *Kepler* and other observations continue to change our views about planets and planetary systems. This is a rapidly expanding subject with exciting new results that we have attempted to distill to the most important and solid results in Chapter 8. The growing understanding of planetary systems has touched many aspects of the Solar System chapters as well.
- Fascinating new discoveries such as the interstellar asteroid 'Oumuamua and gravitational waves from merging black holes and neutron stars by LIGO have each received new coverage.
- The demonstration that merging neutron stars are the likely source for the rapid-process chemical elements has led us to revisit the discussion of the origins of the elements. This appears in multiple places throughout the text (red giants, planetary nebula phase, supernova explosions), and we have expanded the "Cosmic Periodic Table," to indicate the latest thinking about how the elements each formed.
- We have compiled many "Projects" that can be carried out by students on their own, or used in class to illustrate ideas in lecture. Most of these use the planetarium program *Stellarium* to link a topic to what is actually visible in the sky. Some are based on activities we have used with our own students. The Projects are indicated by a new icon in the text, and details of each are described online.
- The foldout star chart has been updated to show the positions of Messier objects and a selection of brighter southern objects suitable for binoculars or a small telescope. The Moon and planet finder tables now show dates of partial eclipses in addition to total eclipses.

Detailed Revisions

Some of the changes may be of particular interest for the instructor who previously used the eighth edition. The following list calls attention to new figures and revised text that may be useful in updating lecture presentations and class notes:

- chapter 1: Better image of annular eclipse. Modifications to illustration of lunar orbit precession for clarity. Updated table of upcoming eclipses.
- essay 1: New examples of star charts based on the new foldout star-chart and Stellarium. New image of 2016 transit of Mercury.
- essay 2: Added new section on gravitational waves along with a figure illustrating the LIGO detection.
- chapter 5: Added mention of neutron-star mergers as possible source of gamma ray bursts to "Extending Our Reach" box. Reorganized discussion of atmospheric refraction.
- chapter 6: Revised discussions of the greenhouse effect and the origin of the atmosphere.

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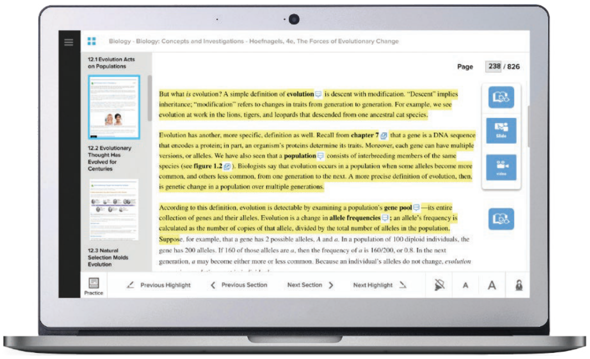

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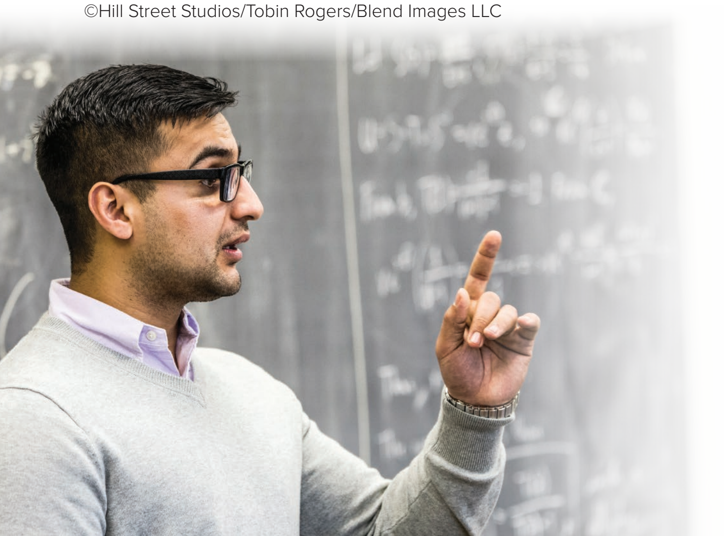

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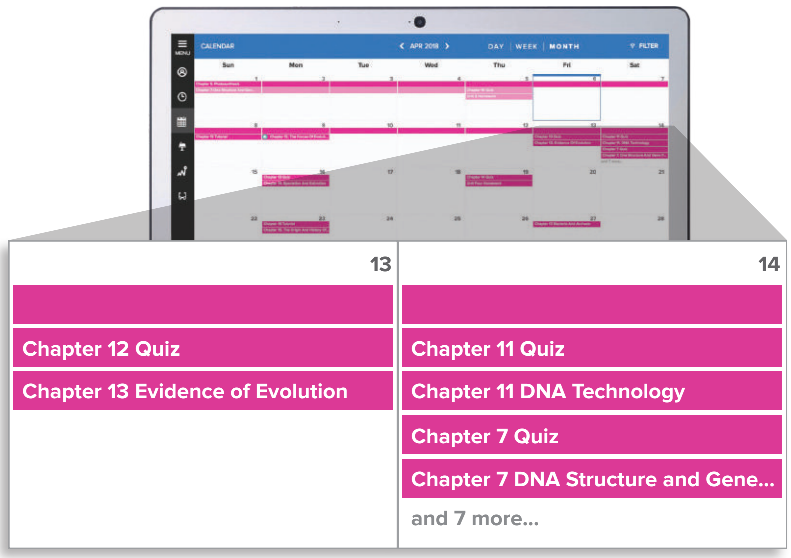

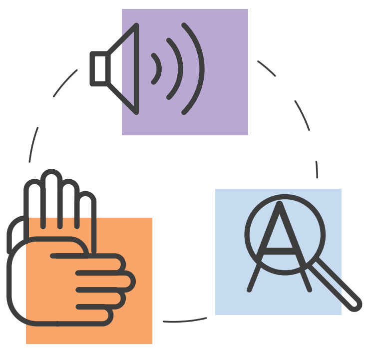

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- chapter 7: Revised discussion of tides.
- chapter 8: Haumea and Makemake included in figures and text when discussing dwarf planets. Mentions of Bode's rule are now further de-emphasized since findings that it does not appear to apply to other planetary systems. Extensive revisions to section on other planetary systems, including several new figures illustrating exoplanets. Updated figure showing all exoplanetary systems with at least five planets now also shows where heating from star is similar to Earth's. Added ALMA image of dust disk around HL Tau.
- chapter 9: Added *Messenger* images and discussion of Mercury's spider troughs, volcanic vents, and "hollows." Noted recent hypotheses about major collisions contributing to planetary magnetic fields and importance of magnetic fields for retaining an atmosphere. Revised diagrams of the orbits of Mercury and Venus and expanded discussion of resonances in their orbits. Updated discussion of Mars's polar caps and complex climate history. Added images of Victoria Crater and comparison of the three types of Martian rovers to date. Updated images and discussion of *Curiosity's* mission. Added consideration of exoplanet properties to section comparing terrestrial planets.
- chapter 10: Added *Juno* image of Jupiter's polar region. Expanded discussion of tidal heating of Io
- chapter 11: Added *Dawn* image of Vesta's south pole. New "Extending our reach" box on the interstellar asteroid 'Oumuamua. Added new figure and discussion of the possibility of a planet orbiting in the outer Solar System.
- chapter 12: Revised description of modeling of Sun's internal structure. New image of Super-Kamiokande, and expanded discussion of solar neutrinos and the new physics they revealed. Updates to graphics on magnetic field interaction with charged particles, solar wind termination, and solar cycle. Revised discussion of links of solar cycle with Earth's climate and added information about Annie Maunder's contribution.
- chapter 13: Revised explanation of absolute magnitudes. Reorganized section on stellar spectra to clarify how temperature affects which elements' lines are seen, and trimmed some of the early history of spectral classification.
- chapter 14: Added diagram showing convection regions for different mass stars and added to discussion of causes of convection and effects on stellar evolution. Added discussion of "dredge up" in red giants and the importance for enriching interstellar clouds with carbon and other elements. Revised figure and discussion of shell burning in high-mass stars and updated discussion of contributions of type II supernova explosions to heavy element production.
- chapter 15: Expanded discussion of type Ia supernova explosions and the elements they produce. Abbreviated discussion of early models of pulsars and clarified discussion of effects of angular momentum conservation and generation of electromagnetic beaming. Added "Science at Work" box about observation of merging neutron stars and the detection of heavy elements it produced.
- chapter 16: Revised discussion of effects of interstellar clouds on starlight, emphasizing complementarity of scattering, dimming, and reddening. Updated figure showing stellar orbits at Galactic center.
- chapter 17: Expanded discussion of causes of spiral structure. Added side-by-side comparison of optical and radio neutral hydrogen images of M81. Revised discussion of determining galaxy distances to explain some of the observational challenges. Updated discussion and illustration of evolutionary effects of galaxy mergers.
- chapter 18: Revised discussion and figure explaining the cosmic horizon. Expanded discussion of CMB fluctuations and their connection to the amount of dark and normal matter present in the Universe.
- essay 4: Added genetic "family tree" and discussion of archaea's central role in the evolution of life on Earth.

If you find mistakes or have suggestions about how to make this book better, please contact us by email: Tom Arny at tarny@theriver.com and Steve Schneider at schneider@astro.umass.edu. We always appreciate your comments and thank you for taking the time to contact us.

ACKNOWLEDGMENTS

Many people have played an important role in bringing this book into being. We are also very grateful to many people at McGraw-Hill, but especially Megan Platt, Laura Bies, David Hash, Thomas Scaife, and Lorraine Buczek.

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REVIEWERS OF THIS AND PREVIOUS EDITIONS

Special thanks and appreciation go out to reviewers of this and previous editions, especially Kirsten Bernabee at *Idaho State University* and Scott Hildreth at *Cabot College*.

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Eric Thuma, Macomb Community College

Those who contributed to the eighth edition and earlier are too numerous to mention individually, but their contributions, constructive suggestions, new ideas, and invaluable advice played an important role in the development of this edition and its supplements.

PREVIEW

The Cosmic Landscape

Astronomy is the study of the heavens, the realm extending from beyond 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 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 gain some familiarity with its features and to appreciate its vast scale.

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

P.1 EARTH, OUR HOME

We begin with 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 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.

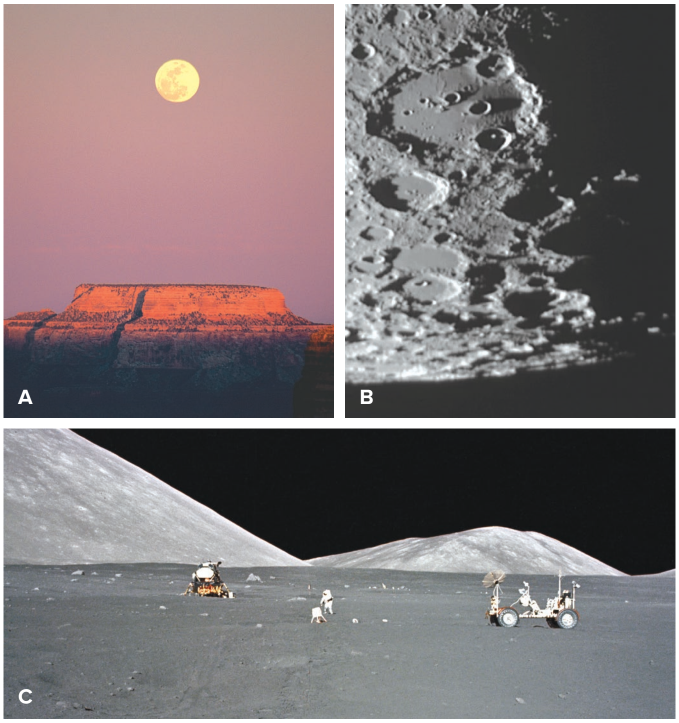

FIGURE P.2
The Moon as seen (A) with the unaided eye and (B) through a small telescope, and (C) *Apollo 17* astronauts on the surface. a: ©Vol. 74 PhotoDisc/Getty; b: Courtesy of Dr. F.A. Ringwald; c: Source: NASA

P.2 THE MOON

The Moon is our nearest neighbor in space, a **satellite** that orbits Earth some quarter million miles (384,000 km) away. Held in tow by 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 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 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 (fig. P.2C).

P.3 THE PLANETS

Beyond the Moon, circling the Sun as 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 at night as bright points of light, much like stars.

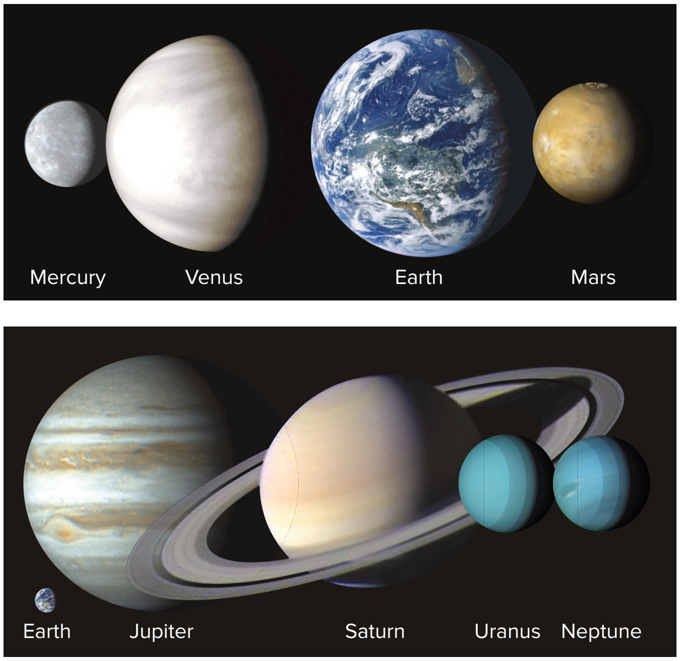

FIGURE P.3
The eight planets. *Top panel:* the four inner planets are shown to their correct relative size. *Lower panel:* the outer planets are shown to their correct relative size, with Earth for comparison. Top: (Mercury): Source: NASA/John Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington; (Venus): Source: NASA/JPL/USGS; (Earth): Source: NASA Goddard Space Flight Center; (Mars): Source: NASA/JPL/MSSS. Bottom: Source: NASA/JPL, adapted by S. E. Schneider.

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 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 Earth. As best we can tell, none has given rise to life other than Earth, 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. Mercury is only about 1/18th as massive, but Jupiter is more than 300 times more massive. In fact, Jupiter outweighs all of the other planets combined. However, all are dwarfed by the star they orbit: the Sun.

P.4 THE SUN

The Sun is a **star,** a huge ball of gas more than 100 times the diameter of Earth and more than 300,000 times more massive: if the Sun were the size of a volleyball, 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 differs from the planets in more than just size, of course: 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.

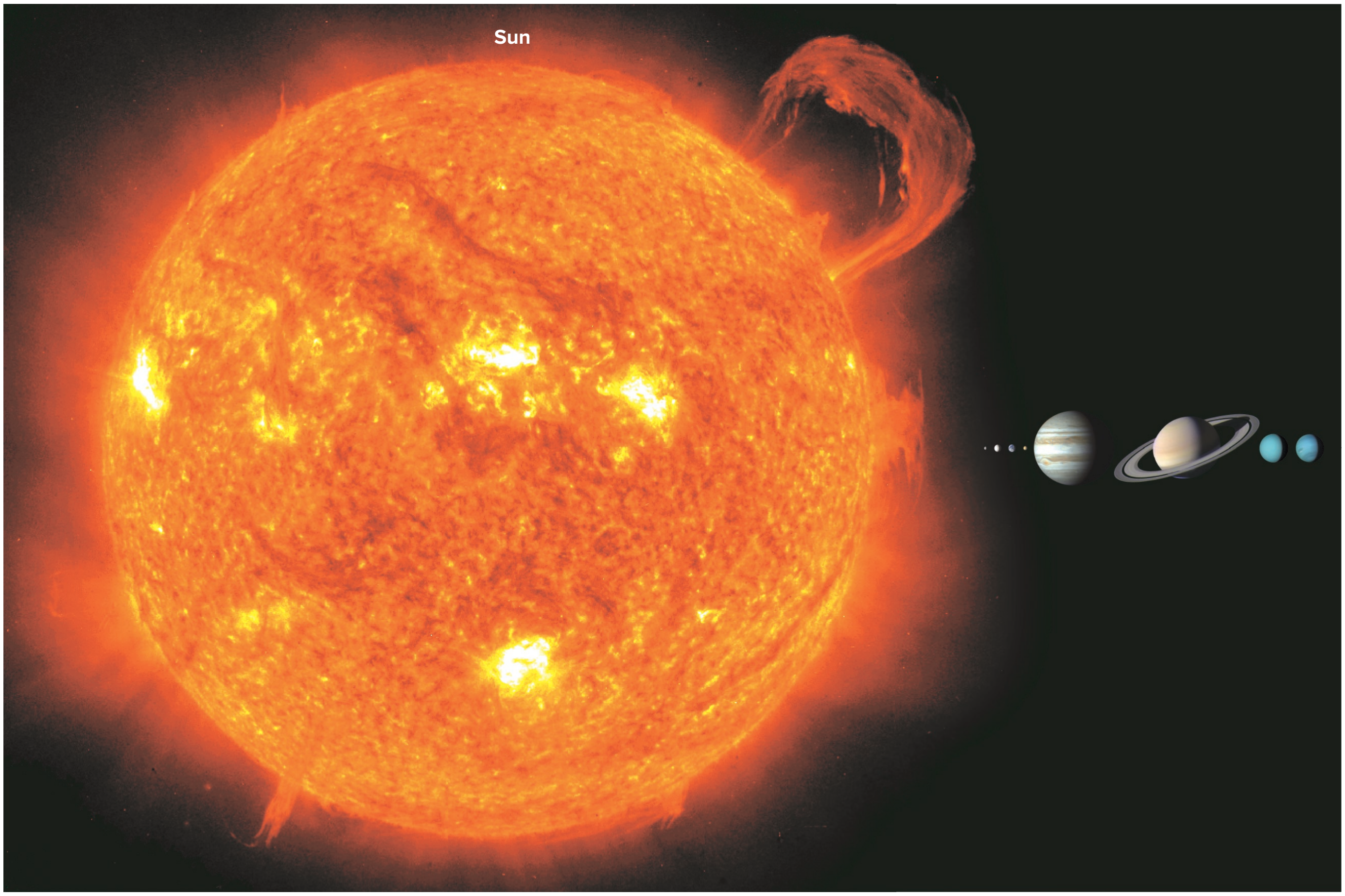

FIGURE P.4
The Sun and the eight planets shown to the same scale. If separations were shown to the same scale, Earth would be about 30 feet away, and Neptune 1000 feet away. The image of the Sun was made through a filter that shows hot helium gas near its surface. Source: SOHO, NASA/ESA

P.5 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 the planets and other 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 millions 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 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 home to uncounted icy bodies, large and small. Astronomers have so far identified four dwarf planets in the Kuiper belt: Pluto, the slightly more massive Eris, Haumea, and Makemake. There are probably dozens more dwarf planets, 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 plunging close enough to the Sun that their ices boil away.

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). The smaller bodies have more irregular orbits, some extending thousands of times farther out.

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, Earth's radius and mass are convenient units for measuring the sizes of other planets. Likewise, Earth's distance from the Sun is a good unit for measuring the scale of the Solar System.

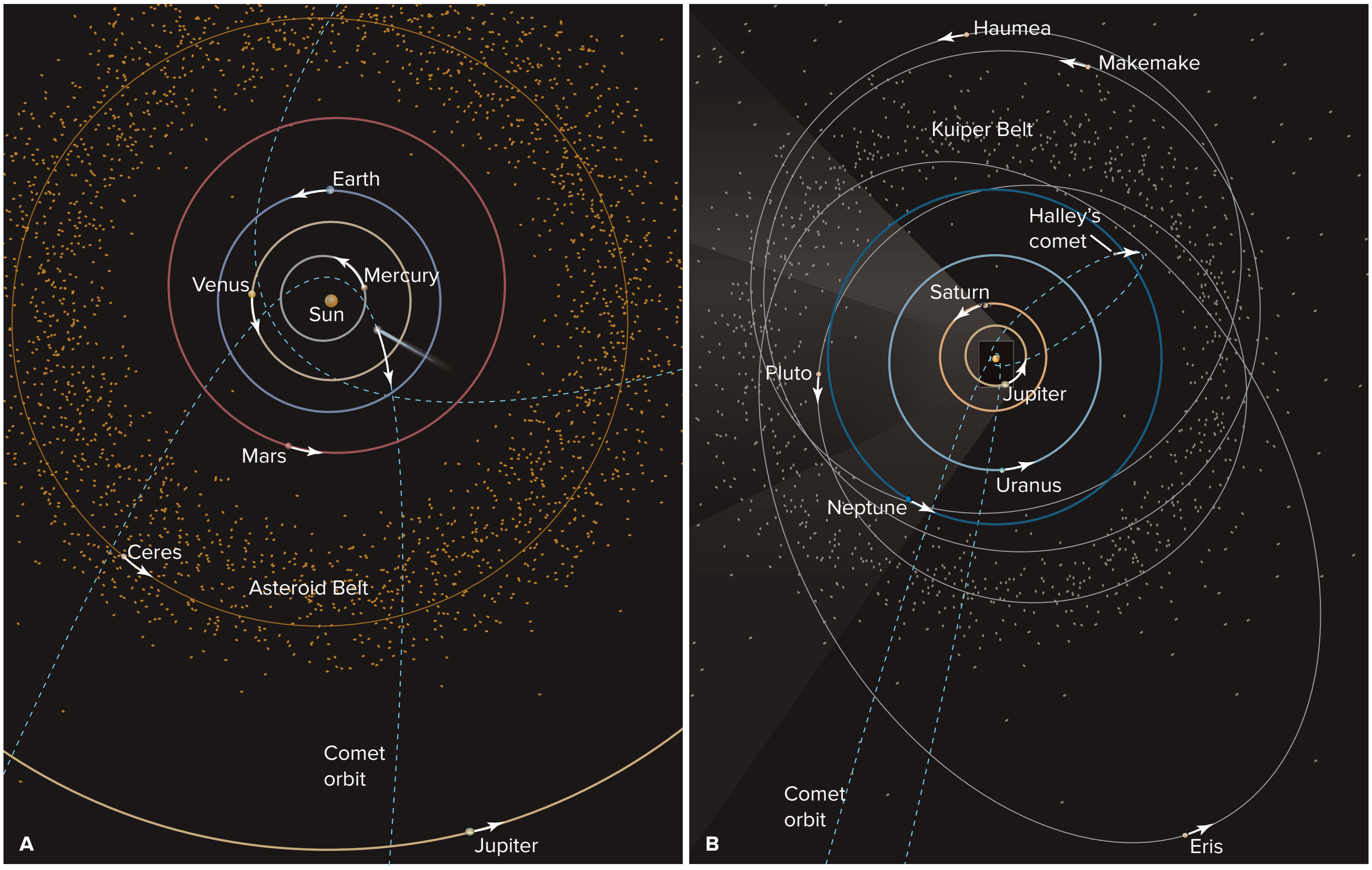

FIGURE P.5
Sketch of the positions and orbits of the planets and a variety of smaller bodies in our Solar System on March 20, 2011. The orbits of the five recognized dwarf planets, Halley's comet, and another typical comet are also shown. The approximate location of small bodies in the asteroid belt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

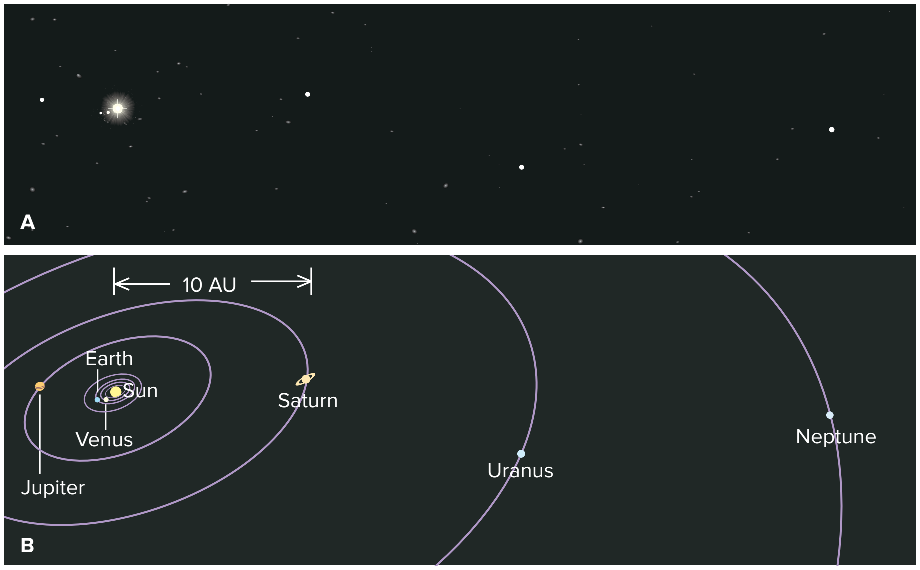

FIGURE P.6
(A) This view of the Solar System is based on a series of real images made by the *Voyager 1* spacecraft. The spacecraft was about 40 AU from the Sun and about 20 AU above Neptune's orbit. The images of the planets (mere dots because of their immense distance) and the Sun have been made bigger 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. a: Source: NASA/JPL images

P.6 ASTRONOMICAL SIZES

The **astronomical unit,** abbreviated as **AU,** is the average distance from Earth to the Sun.* This translates into about 93 million miles or 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.

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. Expressing a distance in this fashion implies that we are assuming 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, this works out to be about 6 trillion miles or 10 trillion kilometers.

Working with extremely large numbers like trillions is cumbersome, so astronomers use a more concise way to write them called **scientific notation** in which we write numbers using ten to an exponent, or power. Thus, we write $100 = 10 \times 10 = 10^2$, 1 million (1,000,000) as $10 \times 10 \times 10 \times 10 \times 10 \times 10 = 10^6$, and 1 trillion (1,000,000,000,000) as 10^{12}. 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 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.

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

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:

$$3.16 \times 10^7 \text{ seconds} \times 1.86 \times 10^5 \text{ miles/second}$$
$$= 3.16 \times 1.86 \times 10^{12} \text{ seconds} \times \text{miles/second}$$
$$= 5.88 \times 10^{12} \text{ miles,}$$

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!

One reason to use scientific notation is that multiplying and dividing becomes much 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.

P.7 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.

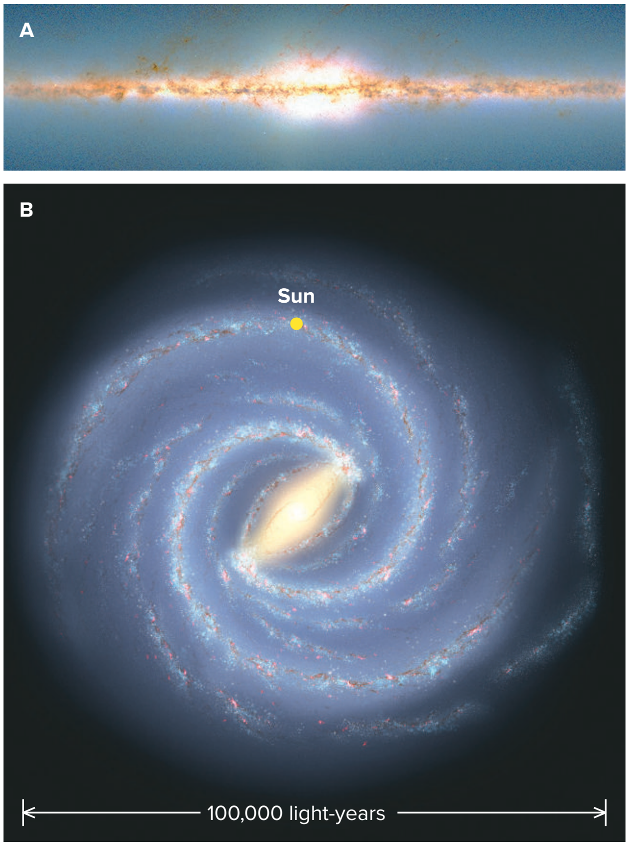

FIGURE P.7
The Milky Way Galaxy. (A) A side view made by plotting stars in the 2MASS star catalog. (B) The approximate structure of the Milky Way if it were seen from above, as mapped out by the Spitzer Space Telescope. a: Source: 2MASS/UMass/IPAC-Caltech/NASA/NSF, b: Source: NASA/JPL-Caltech

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. Source: NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI)

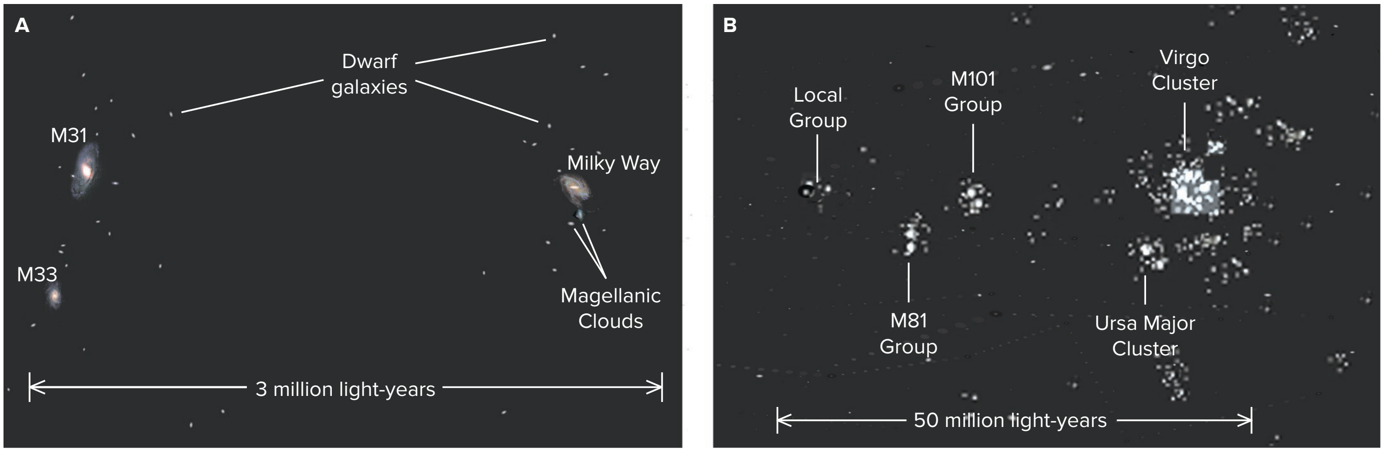

FIGURE P.9
(A) A sketch of the central region of the Local Group. (B) A sketch of the Virgo Supercluster. Only a few of the clusters of galaxies are labeled. The names of the galaxies M31, M33, M81, and M101 are from a list of galaxies and other astronomical objects that was compiled in the late 1700s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

P.8 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 see what lies beyond. But regardless of our uncertainty about the 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.

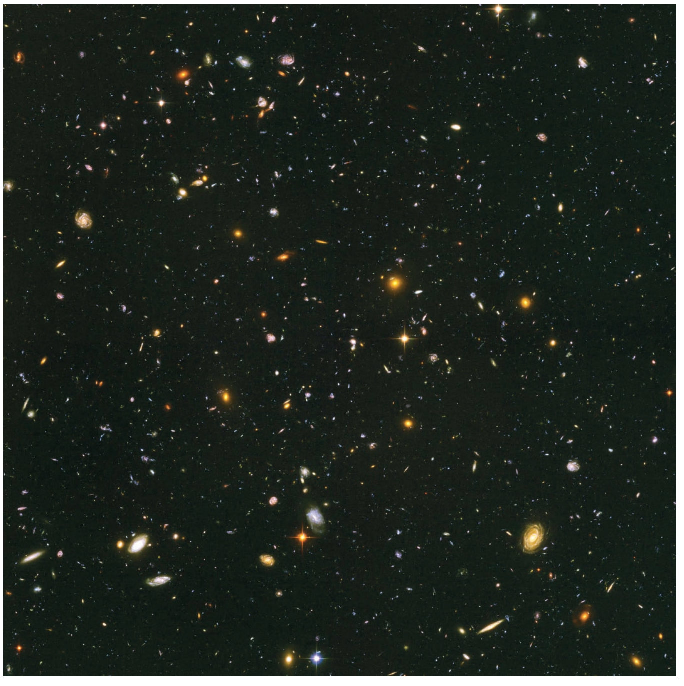

FIGURE P.10
A portion of the deepest image ever made with the Hubble Space Telescope. Virtually every one of the thousands of dots in the image is a galaxy—some near the edge of the visible Universe are seen when they were just beginning to form. A grain of sand held at arm's length would cover the tiny area imaged here. Source: S. Bechwith & the HUDF Working Group (STScI), HST, ESA, NASA

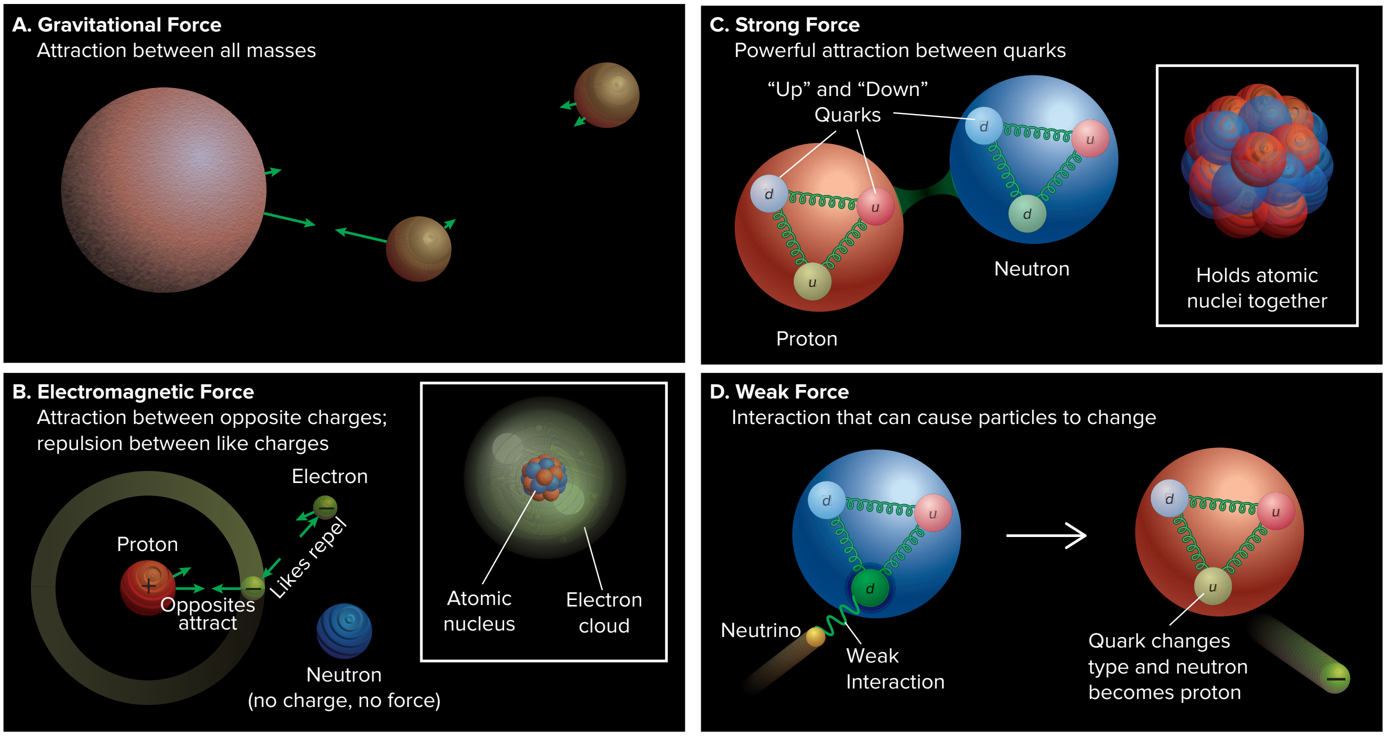

FIGURE P.11
The four fundamental forces. (A) The force of gravity is present between all objects with mass. The force, represented by green arrows in the figure, is always attractive, but grows weaker with distance. (B) The electromagnetic force arises between particles with an electric charge. It causes 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.

P.9 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, Earth's gravitational force makes the book fall. That same force spans the vast distance between 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, like all matter, it is far too weak to hold an atom together. Instead, the 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.

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.11B).

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. A neutron is "neutral" as its name suggests—it has no electric charge that would attract or repel protons, but its quarks do generate the strong force. 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.11D). 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.

P.10 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 matter in 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 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 sunlight. 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 event 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 ever 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 something like the footprints of an invisible creature: we can study the tracks to estimate its size and behavior, but we cannot observe it directly.

P.11 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 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 scientists

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

use the term *theory* formally, they do *not* mean that the ideas are unproven or tentative. Rather, a theory has achieved wide acceptance through successful testing. For example, scientists have subjected the quantum theory of atomic structure and the theory of relativity to numerous tests, and these theories have passed all such tests with high precision.

The scientific method as usually described is an idealization of a much more complex process. In practice, scientists move back and forth between a variety of stages involving the gathering of data, the analysis of the data, and reformulating questions, all informed by interactions with the scientific community and society at large. A working description of the scientific method is shown in figure P.12.

Astronomers face a special difficulty in applying the scientific method because usually they cannot experiment with their subject matter directly: in virtually all cases, they can only passively observe. Nevertheless, they try—like all scientists—to use the scientific method. You will find some specific examples of this method in later chapters, where *Science at Work* boxes show how this process has led to new ideas and the revision of old ones.

Application of the scientific method is no guarantee that its results will be believed. For instance, we will see in chapter 2 that even before 300 B.C., the Greek philosopher Aristotle taught that Earth is a sphere. Yet despite the proofs he offered to support that hypothesis, many people continued to believe Earth to be flat. Today, too, some scientific hypotheses might be rejected despite their experimental verification, and others might be accepted though untrue. For example, one astronomer might find evidence supporting some hypothesis, but another astronomer might claim that the experiment was done incorrectly or the data were analyzed improperly. Therefore, throughout this book, whenever we discuss our knowledge of a given topic, we must keep in mind the fact that such knowledge is not always certain or even universally accepted. This is especially true of topics at the frontiers of our understanding, such as the nature of dark matter and dark energy or the eventual fate of the Universe. Therefore, keep in mind that some of what we discuss in this book will be proved wrong in the future. That is not a failing of science, however. It is its strength.

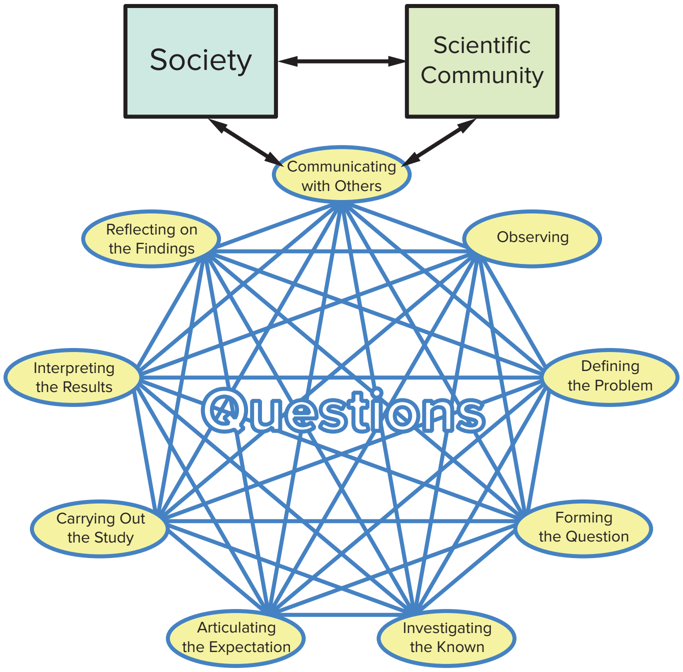

FIGURE P.12
A diagram illustrating the scientific method as described by scientists. The figure is based on interviews with scientists carried out by Reiff, Harwood, and Phillipson of Indiana University. Far from being a regular step-by-step procedure, the scientific method was described by scientists as a set of different activities and processes, which might be visited and revisited in a wide variety of orders as different questions arose. This is illustrated in the figure by lines connecting nine processes identified from the interviews.

SUMMARY

Earth is one of eight planets orbiting the Sun, and the Sun is one of several hundred billion stars that make up the Milky Way Galaxy. The Milky Way, two other similar-size galaxies, and dozens of smaller galaxies compose the Local Group, which in turn is part of the Local Supercluster of galaxies. Superclusters seem to be grouped into even larger systems that fill the visible Universe. We can speak with some certainty about the size and properties of objects in our immediate neighborhood, but the farther we move from Earth, the less certain we become.

Astronomers use the astronomical unit (AU) and light-year (ly) to measure the immense sizes and distances of astronomical systems. The AU is defined by the average distance between Earth and the Sun, and the light-year is defined as the distance light travels in a year, which is about 10 trillion kilometers. Using these units, we can see the immense scale of the Universe in figure P.13 and table P.1. The former shows a series of images to help you visualize how enormous the Universe is.

Matter is made up of atoms in which charged particles called electrons orbit a nucleus. The nucleus is itself composed of smaller particles called protons and neutrons. Four forces give the Universe its structure: the electromagnetic, strong, and weak forces on the scale of atoms, and gravity on the cosmic scale. The whole Universe appears to be governed by these forces, yet there is also growing evidence that most of the Universe is made of types of matter and energy that we have not yet been able to detect.

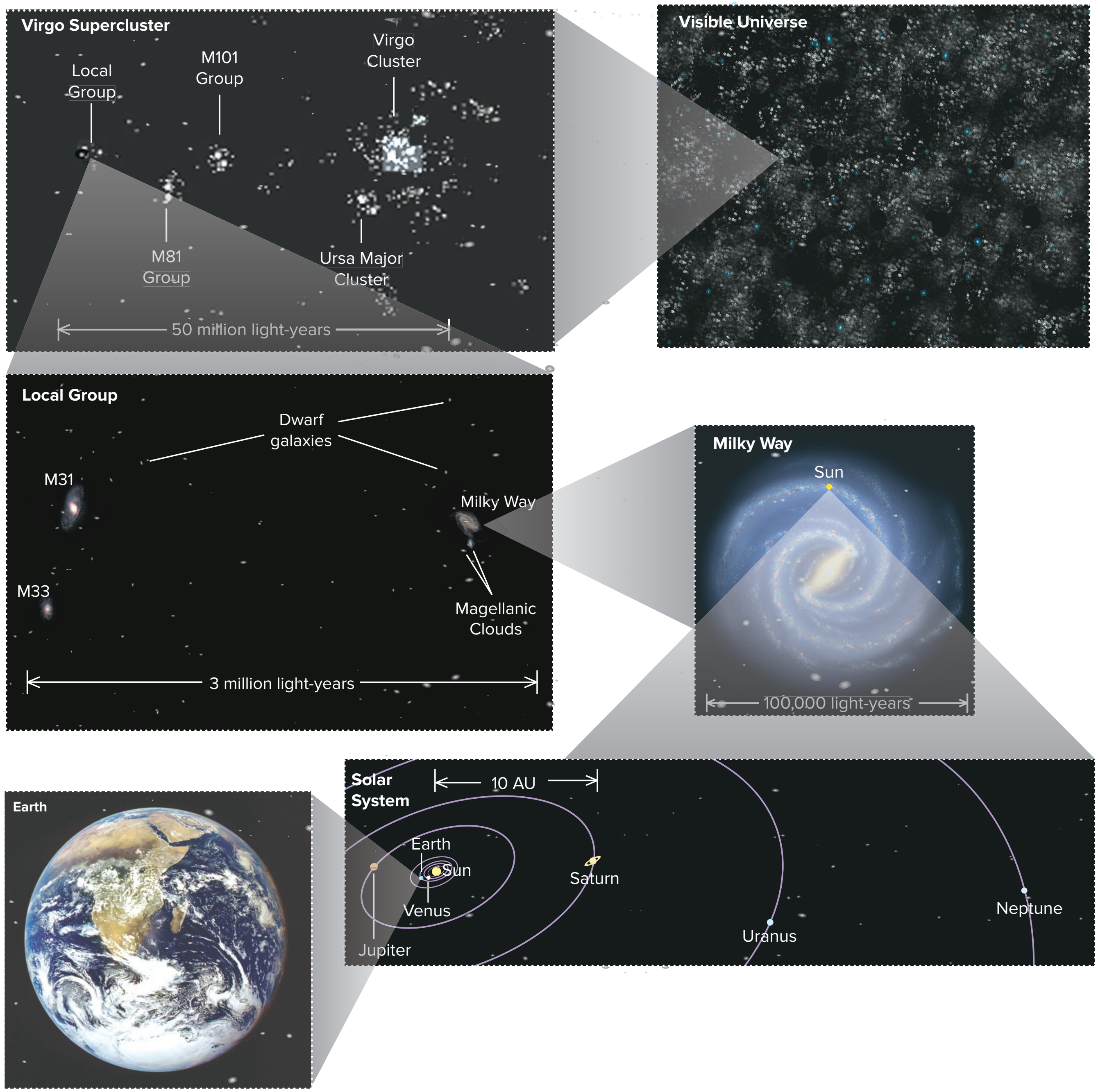

FIGURE P.13
Earth is but one of eight planets orbiting our star, the Sun. The Sun is but one of hundreds of billions of stars in our Galaxy, the Milky Way. The Milky Way is the second largest among many dozens of galaxies in our "Local Group." The Local Group is one of the smaller "clusters" of galaxies among hundreds of clusters that make up the "Virgo Supercluster." The Universe is filled with millions of other superclusters stretching to the limits of our vision. (Milky Way): Source: NASA/JPL-Caltech; (Earth): Source: NASA

Table P.1 The Scale of the Universe

Object	Approximate Radius
Earth	6400 km (~4000 miles)
Sun	700,000 km (~100 × radius of Earth)
Earth's orbit	150 million km (~200 × radius of the Sun) = 1 AU
Solar System to Neptune	30 AU (~6500 × radius of the Sun)
Milky Way Galaxy	50,000 ly (~10^8 × radius of Neptune's orbit)
Local Group	2.5 million ly (~50 × radius of the Milky Way)
Local Supercluster	50 million ly (~20 × radius of the Local Group)
Visible Universe	13.8 billion ly (~300 × radius of the Local Supercluster)

QUESTIONS FOR REVIEW

1. About how much bigger in radius is the Sun than Earth?
2. How big is an astronomical unit?
3. Roughly how big across is the Milky Way Galaxy?
4. How is a light-year defined?
5. What force holds together the different astronomical systems described in this section? What other forces exist in nature?
6. What particles make up an atom?
7. What force holds the electrons to an atom's nucleus?
8. What was the Big Bang? What are dark matter and dark energy?
9. What is meant by the scientific method?
10. What is the difference between a hypothesis and a theory?

THOUGHT QUESTIONS

1. To what systems, in increasing order of size, does Earth belong?
2. Propose a hypothesis about something you can experiment with in everyday life and try to verify or disprove the hypothesis. For example, what kind of surfaces will the little magnetic note holders people use on refrigerators stick to? Any smooth surface? Any metal surface?
3. If a new force were discovered, perhaps related somehow to dark energy or dark matter, how would this force and its effects need to "fit in" with the known four forces? Could it replace one of the existing forces as the explanation for some known phenomena? What kind of work would scientists need to do for this to happen? Apply this same logic to comment on what would be required to provide a scientific basis for ghosts or psychic powers.

PROBLEMS

1. The radius of the Sun is 7×10^5 kilometers, and that of Earth is about 6.4×10^3 kilometers. Use scientific notation to show that the Sun's radius is about 100 times Earth's radius.
2. Given that an astronomical unit is 1.5×10^8 kilometers and a light-year is about 10^{13} kilometers, how many AU are in a light-year?
3. What would be the circumference and diameter (circumference $= \pi \times$ diameter) of a ball that would represent the Moon if Earth were a volleyball? What kind of ball or object matches this size?
4. Calculate approximately how long it takes light to travel from the Sun to the dwarf planet Eris.
5. If the Milky Way were the diameter of a nickel (about 2 cm), how big would the Local Group be? How big would the Local Supercluster be? How big would the visible Universe be? The data in table P.1 may help you here.
6. Suppose two galaxies move away from each other at 6000 km/sec and are 300 million (3×10^8) light-years apart. If their speed has remained constant, how long has it taken them to move that far apart? Express your answer in years.
7. A typical bacterium has a diameter of about 10^{-6} meters. A hydrogen atom has a diameter of about 10^{-10} meters. How many times smaller than a bacterium is a hydrogen atom?
8. Using scientific notation, numerically evaluate the expression $[10^5 \times (10^2)^3]/[100 \times 10^4 \times (10^8)^{1/2}]$.
9. Using scientific notation, numerically evaluate the expression $(8 \times 10^6)^2/(2 \times 10^{-3})^3$.
10. Using scientific notation, numerically evaluate the expression $(3 \times 10^5)^2/(4 \times 10^4)^{1/2}$.

TEST YOURSELF

1. Judging from the lower part of figure P.3, about how much larger is Jupiter's diameter than Earth's?
   (a) 2 times
   (b) 5 times
   (c) 10 times
   (d) 25 times
   (e) 100 times
2. Ancients believed the planets to be special compared to stars because
   (a) the surface of each planet is very different from Earth's.
   (b) planets repeat the same paths on the sky each week.
   (c) over time the planets appear to move against background stars.
   (d) they could see Jupiter's moons and Saturn's rings.
3. The light-year is a unit of
   (a) time.
   (b) distance.
   (c) speed.
   (d) age.
   (e) weight.
4. You write your home address in the order of street, town, state, and so on. Suppose you were writing your cosmic address in a similar manner. Which of the following is the correct order?
   (a) Earth, Milky Way, Solar System, Local Group
   (b) Earth, Solar System, Local Group, Milky Way
   (c) Earth, Solar System, Milky Way, Local Group
   (d) Solar System, Earth, Local Group, Milky Way
   (e) Solar System, Local Group, Milky Way, Earth

5. Which of the following astronomical systems is/are held together by gravity?
   (a) The Sun
   (b) The Solar System
   (c) The Milky Way
   (d) The Local Group
   (e) All of them are.
6. Which of the following statements can be tested for correctness using the scientific method? (There may be more than one correct answer.)
   (a) An astronaut cannot survive on the Moon without life-support systems.
   (b) The Moon is an uglier place than Earth.
   (c) Electrons are charged particles.
   (d) The Sun's diameter is about 100 times larger than Earth's diameter.
   (e) The sky is sometimes blue.

KEY TERMS

astronomical unit (AU), 5
atom, 8
Big Bang, 9
dark energy, 9
dark matter, 9
electric charge, 8
electromagnetic force, 8
electron, 8
galaxy cluster, 7
gravity, 8
light-year (ly), 5
Local Group, 7
Milky Way Galaxy, 6
neutrino, 9
neutron, 8
nucleus, 8
planet, 1
proton, 8
quark, 9
satellite, 2
scientific method, 9
scientific notation, 5
Solar System, 4
star, 3
strong force, 9
Universe, 7
Virgo Supercluster, 7
weak force, 9

1

The Cycles of the Sky

Stonehenge was built more than 4000 years ago in England. The huge stones are aligned to mark the seasonal rising and setting points of the Sun on the horizon.

LEARNING OBJECTIVES

Upon completing this chapter you should be able to:

- Describe the motions of the Sun, Moon, and stars as they rise along the eastern horizon, move across the sky, and set along the western horizon.
- Recognize the kinds of fixed patterns of stars called constellations.
- Explain why different constellations are visible at different times of the year.
- Define the cycles of the Sun, Moon, and stars that are the basis for the day, month, and year.
- Describe how and why the shape of the lit portion of the Moon seen from Earth changes during the month.
- Relate the tilt of Earth's axis to the changes in the apparent daily path of the Sun during the course of the year.
- Explain why the tilt of Earth's axis leads to seasonal changes of temperature on Earth, and how the effects differ on different parts of Earth.
- Describe where, and how frequently, lunar and solar eclipses occur, and describe the visual phenomena associated with each.
- Explain why eclipses are rare, and why their dates gradually shift.

We do not know when people of antiquity first began studying the heavens, but it was certainly many thousands of years ago. Astronomical observations are part of virtually every culture and include events that anyone who watches the sky can see, such as the rising of the Sun in the eastern sky and its setting toward the west, the changing appearance of the Moon throughout the month, and the beautiful and awe-inspiring occurrences of eclipses.

For many prehistoric people, observations of the heavens had more than just curiosity value. Because so many astronomical phenomena are cyclic—that is, they repeat day after day and year after year—they can serve as timekeepers. For example, when is it safe to set out on a sea voyage? When is it time to harvest crops? When will an eclipse occur? Moreover, the cyclic behavior of the heavens implies that many events seen in the sky are predictable. The desire to foretell these changes in the sky and on Earth probably motivated early cultures to study the heavens, and it may have led them to build monumental stone structures such as Stonehenge (chapter opening image).

Sadly, many of the astronomical phenomena well known to ancient people are not nearly so familiar to people living today, because the smog and bright lights of cities make it hard to see the sky and its rhythms. Perhaps more important, we no longer rely upon direct astronomical observations to tell us what season it is, when to plant, and so on. Therefore, if we are to appreciate the growth of astronomical ideas, we need to first understand what our distant ancestors knew and what we ourselves can learn by watching the sky over the course of a year.

In the following discussion, you might imagine yourself as a shepherd in the Middle East, a hunter-gatherer on the African plains, a trader sailing along the coast of the Mediterranean, or even a flight navigator in the early twentieth century. Whichever role you choose to assume, try to get out and actually look at the sky.

Concepts and Skills to Review

- The properties of Earth and Moon (P.1–2)
- The orbit of Earth (P.5)

1.1 The Celestial Sphere

One of nature's spectacles is the night sky seen from a clear, dark location with the stars scattered across the vault of the heavens (fig. 1.1*). Many of the patterns and motions of the stars have been all but forgotten in our hectic modern world, so our first goal is to familiarize ourselves with some general aspects of the sky at night.

Stars are at such huge distances that we cannot get any sense of their true three-dimensional arrangement in space when we view them. For purposes of naked-eye observations, we can therefore treat all stars as if they are at the same distance from Earth, and imagine that they lie on the inside of a gigantic dome that stretches overhead. This dome seems to stretch to where the sky meets the ground along a horizontal circle that we call the **horizon.**

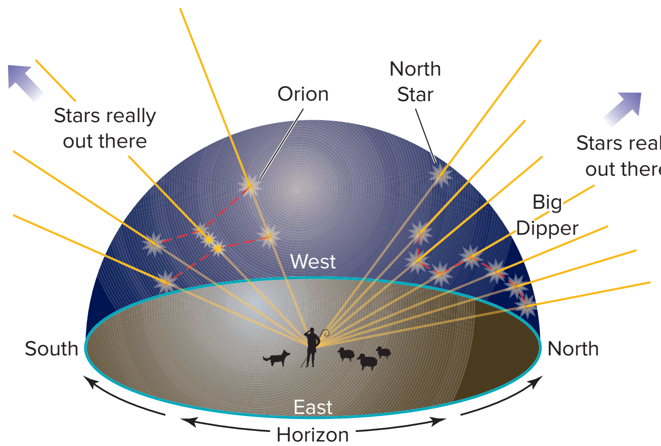

FIGURE 1.1
The stars appear to lie on a hemisphere over us that meets the ground at the horizon.

* In figure 1.1 and in many other figures throughout the book, distances and sizes of astronomical bodies are exaggerated for clarity.

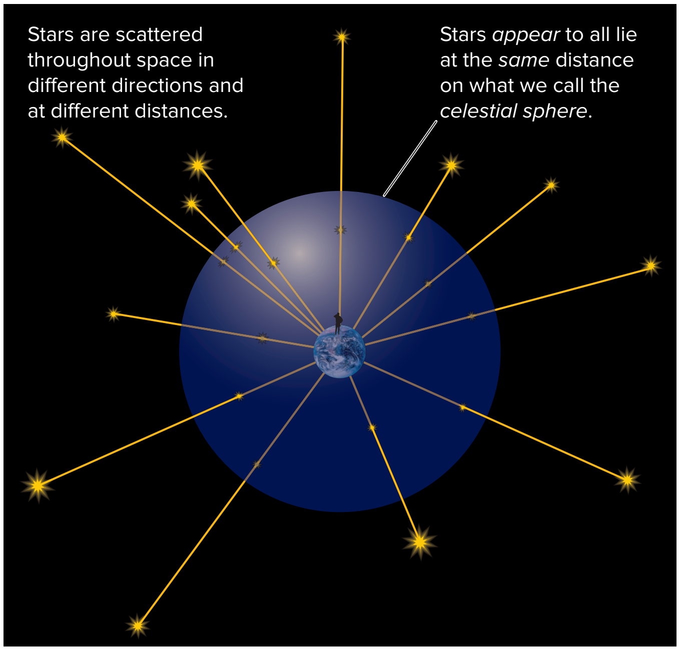

FIGURE 1.2
The stars are scattered through space at very different distances, but they *appear* to lie at the same distance from us on what we call the celestial sphere.

Astronomers picture the dome of the night sky as half of the **celestial sphere,** which surrounds Earth as depicted in figure 1.2. When we stand on Earth, the ground blocks our view of approximately half the celestial sphere. If you were suspended in space far from Earth, you would see the entire celestial sphere surrounding you.

In reality, the thousands of stars visible on a clear night are at vastly different distances from us. The nearest is about 4 light-years away, so for Earth at the size shown in figure 1.2, it would be about 6000 miles away. Other bright stars are thousands of times farther—millions of miles at the figure's scale!

Depicting the stars as though they lie on a celestial sphere is not physically accurate, but it serves as a useful **model** of the heavens—a way of simplifying the arrangement and motions of celestial bodies so they are easier to visualize. We use the term *model* to mean a representation of some aspect of the Universe that helps us to visualize it better. The celestial sphere represents a way of thinking about or picturing the location and motions of stars and planets for someone observing the sky from Earth.

The celestial sphere is the first of many models we will encounter that humans have used to describe the Universe. In later chapters, we will use models to enhance our understanding whenever the size or other properties of what we study fall outside the range of everyday experience. We will speak of models of atoms, models of stars, and models of the Universe itself.

Constellations

As human beings, we seek order in what we see. When ancient people looked at the night sky, they noticed that the stars form fixed patterns on the celestial sphere, what we today call **constellations.** Some of these constellations resemble animals if we use a little imagination. For example, the pattern of stars in Leo looks a little like a lion, whereas that of Cygnus looks like a swan in flight, as depicted in figure 1.3. However, you will discover, as you learn to identify the constellations, that many have shapes that bear little resemblance to their namesakes.

A

B

FIGURE 1.3
The two constellations Leo (A) and Cygnus (B) with figures sketched in to help you visualize the animals they represent. The background images are from the free sky-viewing program Stellarium (*www.stellarium.org*).

LOOKING UP

Some of the interesting celestial objects in and around Cygnus can be found in Looking Up #4.

All stars move through space, but as seen from Earth, their positions change very slowly, taking tens of thousands of years to make any noticeable shift. Thus, we see today virtually the same pattern of stars that was seen by ancient peoples. A shepherd who lived 5000 years ago in the Middle East would have no trouble recognizing the star patterns of the night sky we see and might even call them by the same names.

We do not know how all the constellation names were chosen. Most date back thousands of years to prehistoric times. It seems likely that some names served as mnemonic devices for keeping track of the seasons and for navigating. For example, the beginning of the stormy winter months, when sailing was dangerous and ships were often wrecked, was foretold by the Sun's appearance in the constellations Pisces and Aquarius, both water constellations. Likewise, the harvest time was indicated by the Sun's appearance in Virgo, a constellation often depicted as a goddess of agriculture and fertility.

Daily Motions of the Sun and Stars

Take a look at the night sky, and you will see stars rise along the eastern horizon, move across the sky, and set along the western horizon, just as the Sun does. You can verify this by watching the night sky for as little as 10 minutes. A star seen just above the eastern horizon will have risen noticeably higher, and stars near the western horizon will have sunk lower or disappeared (fig. 1.4A). Likewise, if you look at a constellation, you see its stars rise as a fixed pattern in the eastern sky, move across the sky, and set in the western sky.

In terms of our model of the heavens based on the celestial sphere, we can visualize the rising and setting of stars as a rotation of the celestial sphere around us (fig. 1.4B). Ancient peoples would have found it far easier to believe in that rotation than to believe that Earth moved. Thus, they attributed all celestial motion—that of the Sun, Moon, stars, and planets—to a vast sphere slowly turning overhead. Today we still say the Sun *rises* and *sets*, even though we know that it is Earth's rotation that makes the Sun, Moon, and stars rise and move westward across the sky each day. It is not the celestial sphere that spins but Earth.

If you look at the celestial sphere turning overhead, two points on it do not move. These points are defined as the north and south **celestial poles.** The celestial poles lie

Q: The stars appear to rotate counterclockwise around the north celestial pole. Which way does Earth rotate as viewed from above the North Pole?

PROJECT

Rising and Setting Sun and Stars

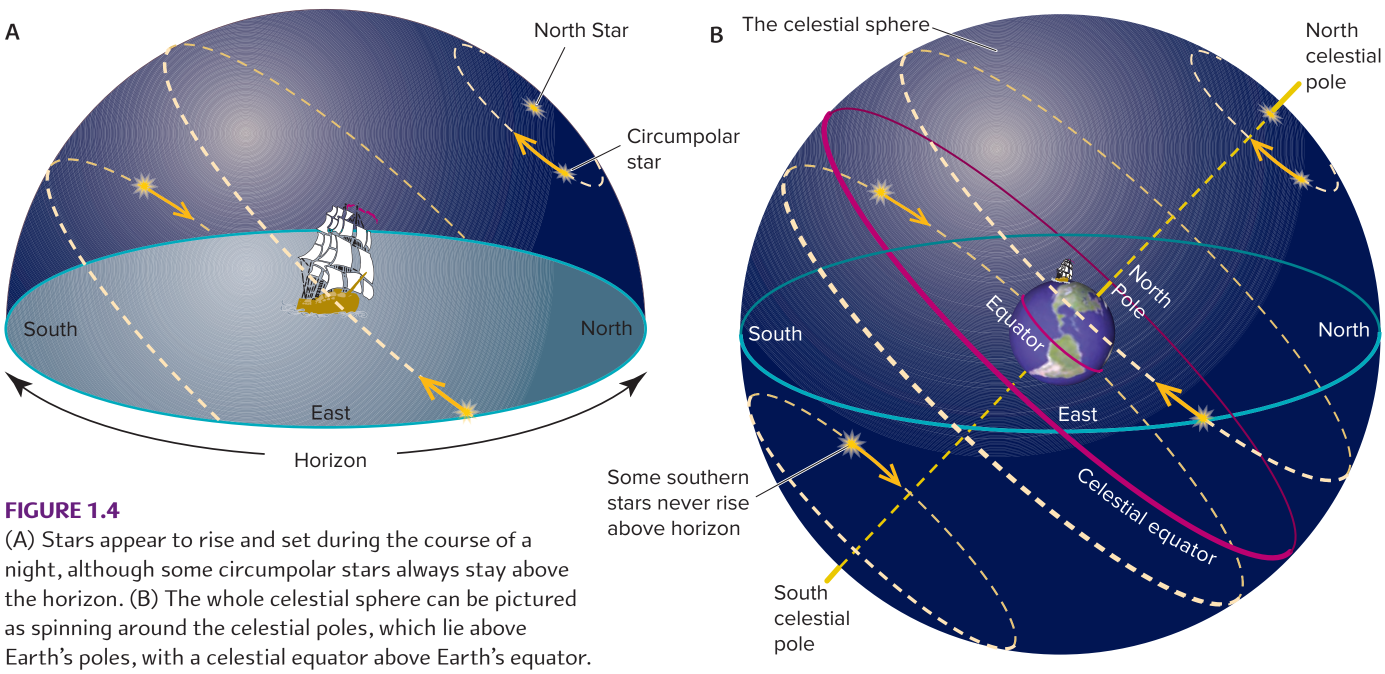

FIGURE 1.4
(A) Stars appear to rise and set during the course of a night, although some circumpolar stars always stay above the horizon. (B) The whole celestial sphere can be pictured as spinning around the celestial poles, which lie above Earth's poles, with a celestial equator above Earth's equator.

exactly above the North and South Poles of Earth, and just as our planet turns about its axis—a line running from its North to South Poles—so the celestial sphere appears to rotate around the celestial poles, as illustrated in figure 1.4B. Over the course of a night, stars appear to circle the north celestial pole in a counterclockwise direction for observers in Earth's northern hemisphere.

Because it lies directly above Earth's North Pole, the north celestial pole always marks the direction of true north. Near the position of the north celestial pole, there happens to be a moderately bright star, Polaris, which is therefore known as the North Star. This is an important and widely used guide for travelers on land and sea, but it has not always been the same star throughout history. The direction of Earth's axis gradually shifts or precesses over thousands of years, so different stars have served as the North Star in ancient times. No similarly bright star has happened to lie close to the south celestial pole for many thousands of years, so there is no equivalent "South Star." We examine the precession of Earth's axis further in chapter 6.

Another important sky marker frequently used by astronomers is the **celestial equator.** The celestial equator lies directly above Earth's equator, just as the celestial poles lie above Earth's poles, as figure 1.4B shows. Only stars on the celestial equator rise due east and set due west. Stars north of the celestial equator rise in the northeast and set in the northwest, while stars south of the equator rise in the southeast and set in the southwest. For a northern observer some *circumpolar* stars near the north celestial pole never cross below the horizon, while stars close enough to the south celestial pole never rise above the horizon.

LOOKING UP

The region of the north celestial pole is shown in Looking Up #1. The region of the south celestial pole is shown in Looking Up #9.

ANIMATION

Star rise and set caused by Earth's rotation

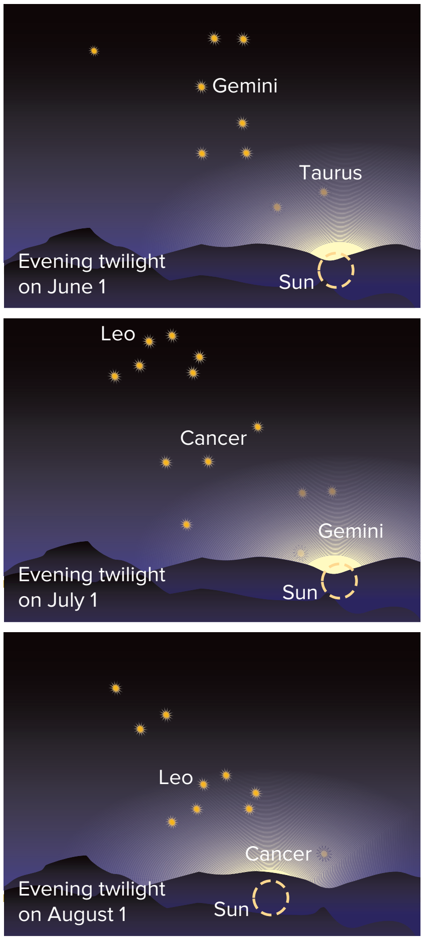

FIGURE 1.5
The Sun appears to lie in Taurus on June 1, in Gemini on July 1, in Cancer on August 1, and so forth, making the constellations we see after sunset change with the seasons.

ANIMATION

Constellations by seasons

Annual Motion of the Sun

At the same time that Earth's spin causes the apparent daily motion of the Sun and stars across the sky, Earth's orbital motion around the Sun also causes changes in the parts of the sky we see on different nights of the year. If you compare the sky at the same time each evening for a few months, you will discover that different constellations are visible.

For example, in early June the Sun appears to lie in the direction of the constellation Taurus, so this constellation's stars are lost in the Sun's glare. After sunset, however, we can see the neighboring constellation, Gemini, just above the western horizon as illustrated in figure 1.5. By July, Gemini has disappeared behind the Sun, and instead Cancer is visible just above the horizon. And by August, Cancer has disappeared to be replaced by Leo. Around the rest of the sky we see a steady change of constellations throughout the course of the year. A year later, though, the same constellations will again be visible as they were originally.

The change of the constellations with the seasons is caused by Earth's motion around the Sun. The Sun's glare blocks our view of the part of the celestial sphere that lies toward the Sun, making the stars that lie beyond the Sun invisible. If we picture Earth orbiting the Sun within the celestial sphere, as illustrated in figure 1.6, month by month the Sun covers one constellation after another. It is like sitting around a campfire and not being able to see the faces of the people on the far side. But if we get up and walk around the fire, we can see faces that were previously hidden. Similarly Earth's motion allows us to see stars previously hidden in the Sun's glare. Because these movements repeat in a yearly cycle, they are called *annual motions.*

Astronomers distinguish an object's spinning motion from its orbital motion with different terms. We say that Earth rotates on its axis (spins) daily while it revolves around the Sun (moves along its orbit) annually. Because our planet orbits in the same direction as it spins, Earth does not need to rotate quite as far each night to make a particular star visible as it does to face back toward the Sun. As a result, a star rises 3 minutes and 56 seconds earlier each night. That 3 minutes and 56 seconds, when added up each night over an entire year, amounts to 24 hours.

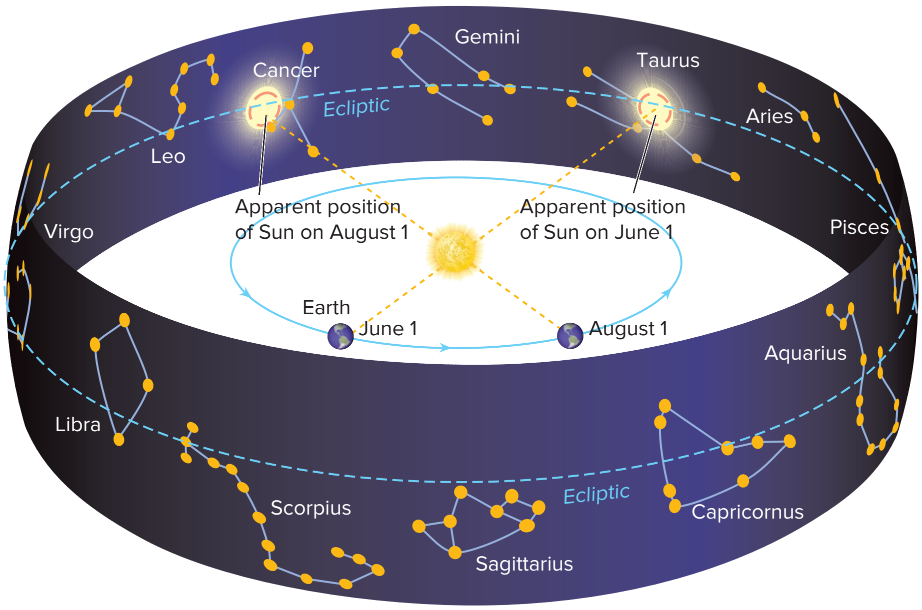

FIGURE 1.6
As Earth orbits the Sun, the Sun appears to move around the celestial sphere through the background stars. The figure illustrates the portion of the celestial sphere on either side of the Sun's path, which is called the ecliptic. As Earth orbits the Sun, the Sun appears to move through twelve constellations known as the zodiac that lie near the ecliptic. Note that the ecliptic is the extension of Earth's orbital plane out to the celestial sphere.

This motion is slow and difficult to observe, but many ancient peoples developed techniques to keep track of these motions. This was extremely important to early people because it provided a way to measure the passage of time other than by carefully counting days. Moreover, the stars demonstrated that many celestial events are predictable and that they may be used to order our lives on Earth. For example, ancient Egyptians looked for the star Sirius near the Sun just before dawn as a way of predicting when the annual rising of the Nile would occur. Knowing the exact season can be crucial for such things as planting crops. A brief warm spell might have tricked an ancient farmer into sowing seeds too early, but by studying the sky for many years, she might have discovered that when the constellation Taurus is visible just before dawn, it is time to plant.

The Sun and the Zodiac

The Ecliptic and the Zodiac

If we could mark on the celestial sphere the path traced by the Sun as it moves through the constellations, we would see a line that runs around the celestial sphere, as illustrated in figure 1.6. Astronomers call the line that the Sun traces across the celestial sphere the **ecliptic.** The name *ecliptic* was given because only when the new or full moon is on this line can an eclipse occur, as discussed in section 1.4. Examining figure 1.6, you can see that the ecliptic is the extension of Earth's orbit onto the celestial sphere, just as the celestial equator is the extension of Earth's equator onto the celestial sphere.

The belt-shaped region of the sky surrounding the ecliptic passes primarily through twelve constellations and is called the **zodiac.** The word *zodiac* is from the Greek *zoidion,* "little animal," and *kyklos,* "circle." That is, zodiac refers to a circle of animals, which the majority of its constellations represent. The names of these constellations are Aries (ram), Taurus (bull), Gemini (twins), Cancer (crab), Leo (lion), Virgo (maiden), Libra (scales), Scorpius (scorpion), Sagittarius (archer), Capricornus (sea-goat), Aquarius (water-bearer), and Pisces (fish).

The names of the constellations of the zodiac may look familiar from horoscope "signs," part of an ancient belief system of *astrology* that stars determined human destinies, much as they predicted the rising of the Nile. Astrology is today regarded as a pseudoscience, although horoscopes remain a popular entertainment (see Extending Our Reach: "Are You an Ophiuchan?").

EXTENDING *our reach*

ARE YOU AN OPHIUCHAN?

The origin of horoscope signs dates back several thousand years. It is based on the notion that the location of the Sun along the zodiac at the time of people's birth (their "Sun sign") determines their basic personal traits. Astrologers often say things such as that a person born under the sign of Taurus is "strong and silent like a bull."

If you check where the Sun was actually located on the date of your birth, chances are that it was not in the constellation you would think based on your newspaper horoscope sign. This is because the dates of Sun signs were established thousands of years ago, but the precession of Earth's axis (see chapter 6) has caused a shift in the dates of our calendar relative to the location of the Sun among the stars.

In fact, the Sun has shifted almost one full constellation, so if you think your sign is Aquarius, for example, the Sun was probably in Capricornus when you were born. In fact, the boundaries of the constellations are a little arbitrary, but the Sun actually moves through the constellation Ophiuchus, a snake charmer, during the first half of December. So many people who think they are Sagittarians are in fact "Ophiuchans"! Astronomers are not concerned about this, however, since there is no scientific evidence that astrology has any predictive power.

1.2 The Seasons

Many people mistakenly believe that we have seasons because Earth's orbit is elliptical. They suppose that summer occurs when we are closest to the Sun and winter when we are farthest away. It turns out, however, that Earth is nearest the Sun in early January, when the Northern Hemisphere is coldest. Clearly, then, seasons must have some other cause.

To see what *does* cause seasons, we need to look at how our planet is oriented in space. As Earth orbits the Sun, our planet also spins. That spin is around an imaginary line—the **rotation axis**—that runs through Earth from its North Pole to its South Pole. Earth's rotation axis is *not* perpendicular to its orbit around the Sun. Rather, it is tipped by 23.5° from the vertical, as shown in figure 1.7A. As our planet moves along its orbit, its rotation axis maintains nearly exactly the same tilt and direction, as figure 1.7B shows. That is, Earth behaves much like a giant gyroscope. The tendency of Earth to preserve its tilt is shared by all spinning objects. For example, it is what

ANIMATION

Earth's rotation axis

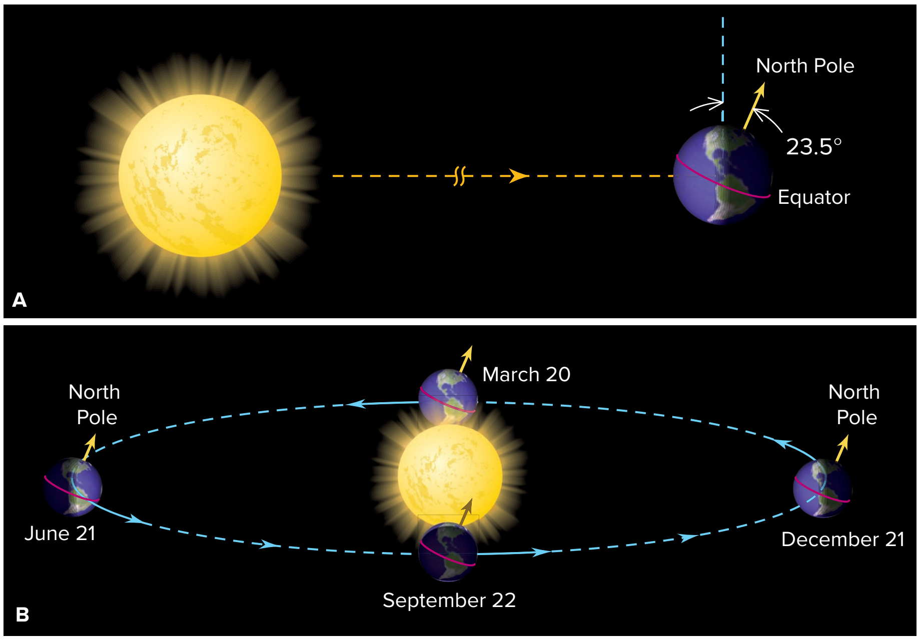

FIGURE 1.7
(A) Earth's rotation axis is tilted 23.5° to Earth's orbit around the Sun. (B) Earth's rotation axis keeps the same tilt and direction as it moves around the Sun. (Sizes and distances are not to scale.)

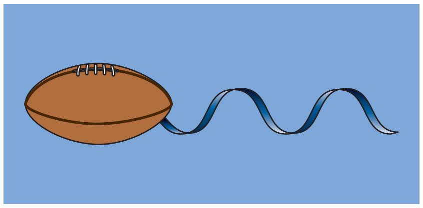

FIGURE 1.8
The tendency of a spinning object to keep its orientation is called “conservation of angular momentum,” and it is the principle on which gyroscopes operate and the reason a quarterback puts “spin” on a football.

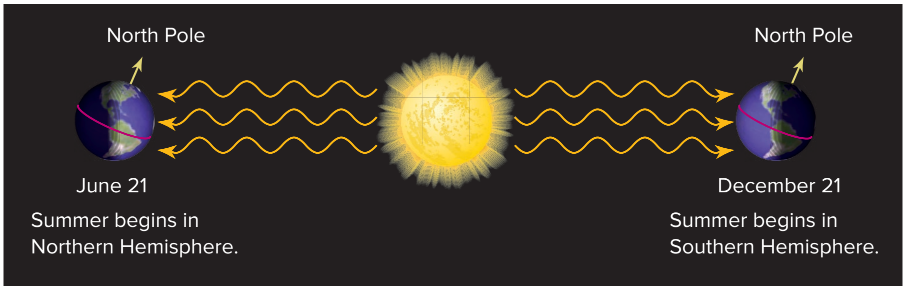

FIGURE 1.9
Because Earth’s rotation axis keeps the same tilt as we orbit the Sun, sunlight falls more directly on the Northern Hemisphere during part of the year and on the Southern Hemisphere during the other part of the year. (Sizes and distances are not to scale.)

keeps a rolling coin upright, a Frisbee horizontal, and a thrown football pointed properly (fig. 1.8). You can feel this tendency of a spinning object to resist changes in its orientation by lifting a bicycle by the handlebars with the wheel spinning, then trying to twist it from side to side.

Because Earth’s tilt remains nearly constant as we move around the Sun, sunlight falls more directly on the Northern Hemisphere in June and surrounding months and more directly on the Southern Hemisphere around the month of December, as illustrated in figure 1.9. This causes a variation in the amount of heat each hemisphere receives from the Sun over the course of a year.

A surface facing directly toward a source of radiation is heated more than when the same surface is tilted. You take advantage of this effect instinctively when you warm your hands at a fire by holding your palms flat toward the fire, not edgewise. Figure 1.10 illustrates how this affects regions north and south of the equator. Equal areas of land do not receive the same amount of sunlight. When the North Pole is tilted toward the Sun in June, an area south of the equator receives an amount of radiation that is only a portion of the radiation intercepted by an equal area north of the equator. Therefore, over the course of a June day, the Northern Hemisphere is heated more than the Southern Hemisphere.

This extra heating causes the Northern Hemisphere to warm up and move into summer. Six months later, the Northern Hemisphere receives its sunlight least directly,

INTERACTIVE

Seasons

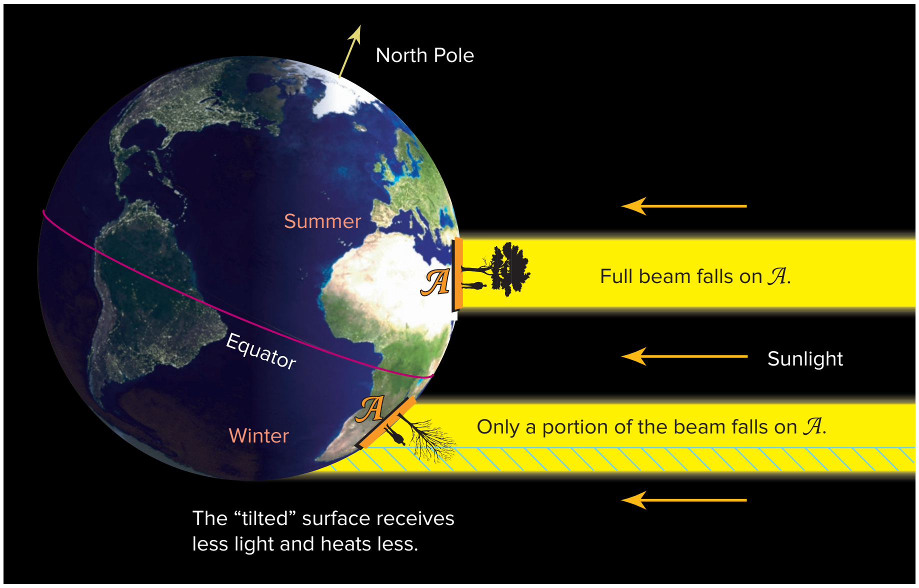

FIGURE 1.10
A portion of Earth’s surface directly facing the Sun receives more concentrated light (and thus more heat) than other parts of Earth’s surface of equal area. The same size “beam” of sunlight (carrying the same amount of energy) gets spread out over a larger area where the surface is “tilted.”

ANIMATION

Seasonal changes in daylight

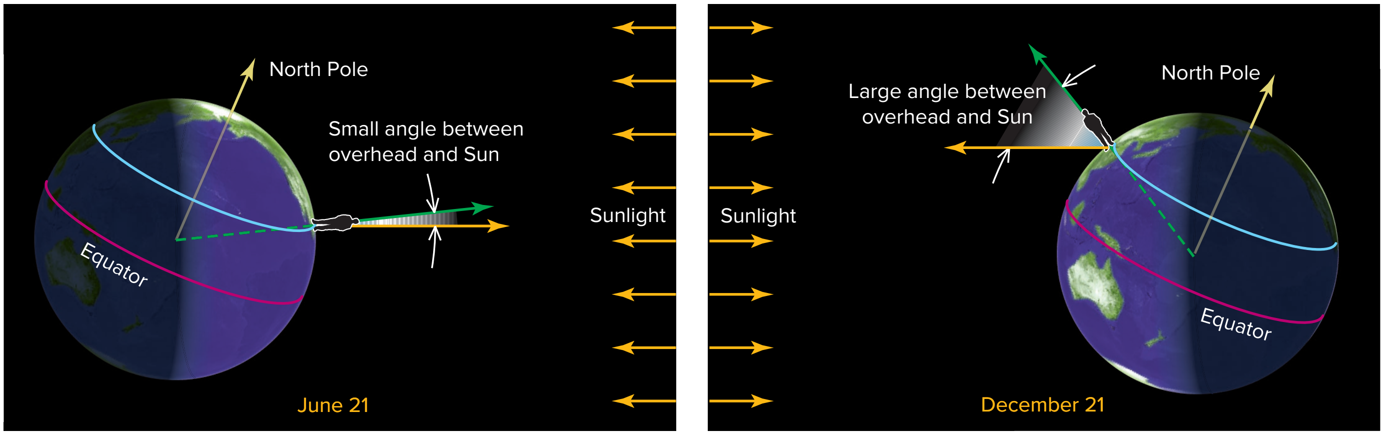

FIGURE 1.11
Between the extremes of the year six months apart, the angle at which sunshine strikes the ground at the same latitude can vary greatly.

and so the hemisphere cools and winter ensues (fig. 1.11). This heating difference is enhanced because Earth's tilt leads to many more hours of daylight in the summer than in the winter. As a result, not only do we receive the Sun's light more directly, we receive it for a longer time. Thus,

the seasons are caused by the tilt of Earth's rotation axis.

From figure 1.11 it can be seen why the seasons are reversed between the Northern and Southern Hemispheres; when it is summer in one, it is winter in the other.

Solstices, Equinoxes, and the Ecliptic's Tilt

ANIMATION

The Sun's motion north and south in the sky as the seasons change

PROJECT

Earth as seen from the Sun

The tilt of Earth's rotation axis causes the Sun's apparent path on the celestial sphere—the ecliptic—to be tilted with respect to the celestial equator. Earth's axis remains oriented in the same direction as Earth orbits the Sun, so there is a point in the orbit when the North Pole is tipped most closely toward the Sun. This occurs on about June 21, as illustrated in figure 1.12. On this date the North Pole is tilted 23.5° toward the Sun, so the Sun is 23.5° north of the celestial equator. (The date can vary from year to year, mostly because a year is about a quarter of a day longer than 365 days—which is also what causes us to insert leap years.) Half a year later, on about December 21, Earth is on the other side of the Sun, and the Sun is 23.5° south of the celestial equator.

As a result of this north–south motion, the Sun's path crosses the celestial equator twice during the year as illustrated in figure 1.12. The dates when the Sun reaches its extreme north and south positions are used to mark the beginning of summer and of winter, while the dates when the Sun crosses the celestial equator mark the beginning of spring and of autumn.

Although the seasons begin on the solstices and equinoxes, the hottest and coldest times of year occur roughly 6 weeks after the solstices. The delay, known as the lag of the seasons, results from the oceans and land being slow to warm up in summer and slow to cool down in winter.

Astronomers give these dates special names. When the Sun is on the celestial equator, the days and nights are of equal length (approximately), so these dates are called the **equinoxes,** from the Latin for "equal nights." The spring (or vernal) equinox occurs near March 20; the fall or autumnal equinox occurs near September 22. The beginning of summer and of winter mark the times of year when the Sun pauses in its north–south motion and seems to stand still before reversing direction. Accordingly, these times are called the **solstices,** from the Latin for the Sun (sol) being stationary. The dates of the solstices (summer and winter) also change slightly from one year to the next, but they are always close to June 21 and December 21.

Tracking the Sun's Changing Position

The motion of the Sun north and south in the sky over the course of the year causes the Sun to follow different paths through the sky each day as Earth rotates. For a northern observer the Sun is high in the sky at noon on a summer day but low in the sky at

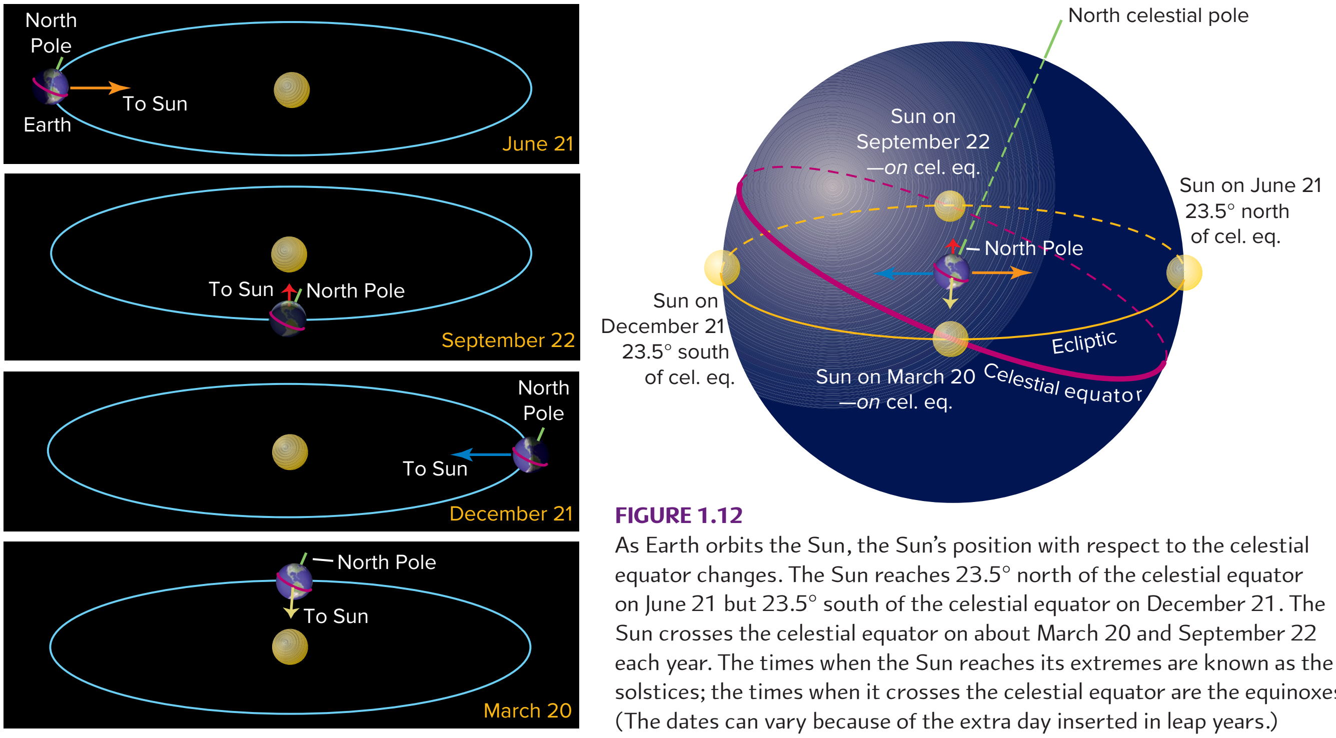

FIGURE 1.12

As Earth orbits the Sun, the Sun's position with respect to the celestial equator changes. The Sun reaches 23.5° north of the celestial equator on June 21 but 23.5° south of the celestial equator on December 21. The Sun crosses the celestial equator on about March 20 and September 22 each year. The times when the Sun reaches its extremes are known as the solstices; the times when it crosses the celestial equator are the equinoxes. (The dates can vary because of the extra day inserted in leap years.)

noon on a winter day (fig. 1.13A). For example, on June 21 at a midnorthern latitude of 40°, the noon Sun is about 73.5° above the horizon, or about 16.5° away from the **zenith**—the point in the sky straight overhead. On December 21 at this latitude, on the other hand, the highest point the Sun reaches is only about 26.5° above the horizon. See Astronomy by the Numbers: "The Angle of the Sun at Noon."

Like any other celestial object, the Sun only rises due east and sets due west when it is on the celestial equator (fig. 1.13A). Throughout the rest of the year, the Sun moves north or south of the celestial equator, so the direction to the rising and setting position of the Sun constantly changes (fig. 1.13B). On the vernal equinox the Sun is on the celestial equator, so it rises and sets due east and due west. From this date up to the summer solstice, the Sun's rising and setting points shift northward each day. After

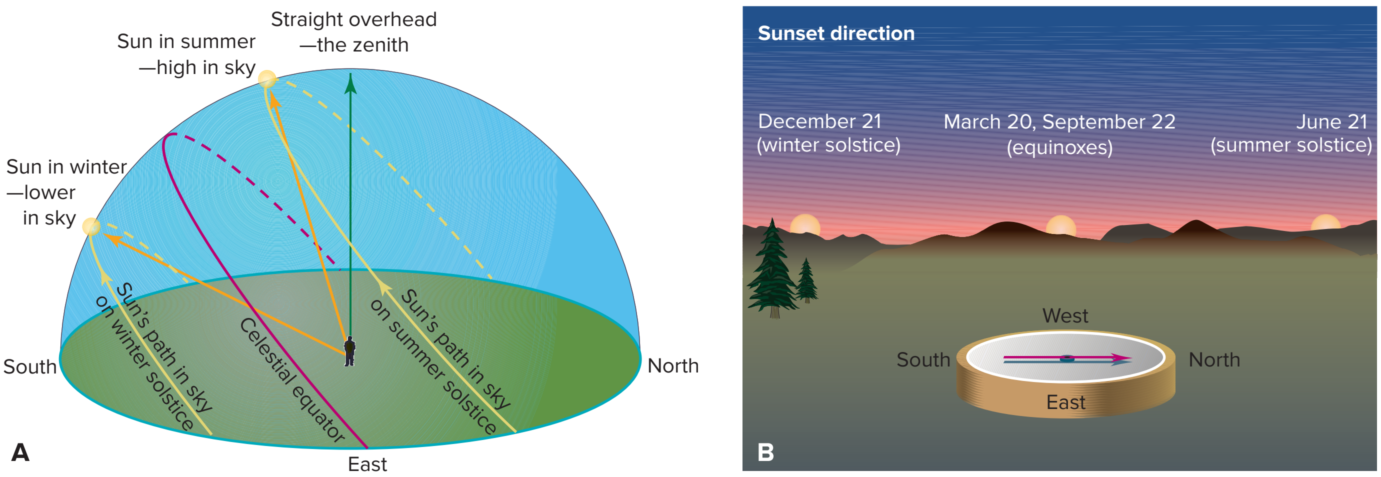

FIGURE 1.13

(A) The shifting location of the Sun north and south of the celestial equator causes it to reach different heights in the sky each day throughout the year. This diagram illustrates the Sun's path in the sky for an observer at about 40° northern latitude. (B) The motion of the Sun throughout the year results in the sunset (and sunrise) position shifting relative to features on the horizon each day.

ASTRONOMY *by the numbers*

THE ANGLE OF THE SUN AT NOON

The angle of the Sun above the horizon at noon is almost never straight overhead, contrary to common belief. The only place the Sun ever passes straight overhead is in the tropics (between latitudes 23.5° South and 23.5° North), and this happens on only one or two days each year.

Because the celestial sphere's equator and poles lie directly above Earth's equator and poles, an observer's zenith is as far north or south of the celestial equator as the observer's latitude is north or south of Earth's equator. This tells you where the noon Sun will be on the equinoxes, when the Sun is on the celestial equator.

For example, consider Phoenix, Arizona, at latitude 33.5° North. At noon on the equinoxes, the Sun is 33.5° south of the zenith. Because the zenith is by definition 90° above the horizon, this means the Sun is 56.5° above the horizon. And the Sun is never straight overhead.

On the summer solstice in Phoenix, the Sun is 23.5° north of the celestial equator, so it is only 10° from the zenith, or 80°(= 90° − 10°) above the horizon. On the other hand, at the winter solstice, the Sun is 23.5° south of the celestial equator, so it is now 57° south of the zenith (33.5° + 23.5°), or only 33° above the horizon.

FIGURE 1.14
The sunset position shifted about 4° to the south between these two photos taken 8 days apart in September. The outstretched thumb in the lower picture has a width of about 2°. Source: S. E. Schneider

the summer solstice the position shifts southward each day, rising and setting due east and due west again on the autumnal equinox, and continuing southward until the winter solstice. After the winter solstice, the Sun begins to move north again. The shift of the Sun's position is particularly obvious near the equinoxes, when the Sun's position on the horizon shifts by almost its own diameter each day (fig. 1.14).

The path the Sun follows each day can be quite different at different latitudes, as illustrated in figure 1.15. At the North Pole the Sun remains above the horizon for half the year, circling the sky above the horizon in each 24-hour period while gradually changing its height above the horizon. It skims along the horizon on the March equinox, and gradually spirals to its highest altitude at the June solstice, then spirals back down to the horizon by the September equinox.

At the equator the Sun is up for 12 hours every day of the year, but it reaches its highest point in the sky on the equinoxes rather than one of the solstices. The Sun's path in equatorial regions is almost perpendicular to the horizon, so the Sun seems to set quickly and the period of twilight is short. At the edge of the tropics, 23.5° North or South, the Sun reaches the zenith just on the day of one of the solstices.

Because the Sun shifts northward or southward on the celestial sphere, its rising and setting positions on the horizon also shift. And just as the changing position of the Sun against the constellations can be used as an indicator of the seasons, so too can the position on the horizon of the rising or setting Sun. One well-known example

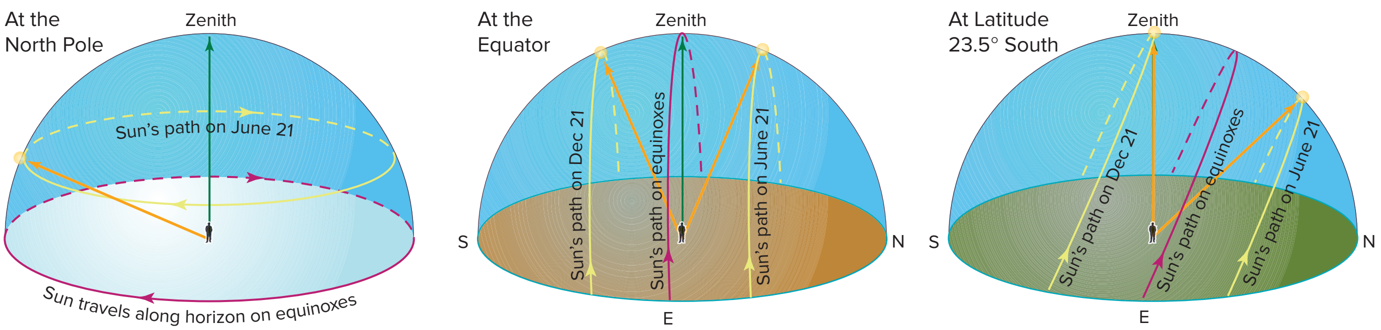

FIGURE 1.15
The path of the Sun in the sky differs depending on your latitude. At the North Pole, the Sun never sets for six months but gradually spirals up from the horizon from the vernal equinox to the summer solstice, then spirals back down to the horizon at the autumnal equinox before it disappears for six months. At the equator, the Sun rises straight upward from the horizon, but reaches the zenith only on the equinoxes. At 23.5° South, the Sun reaches the zenith at noon only on December 21, the start of summer in the Southern Hemisphere.

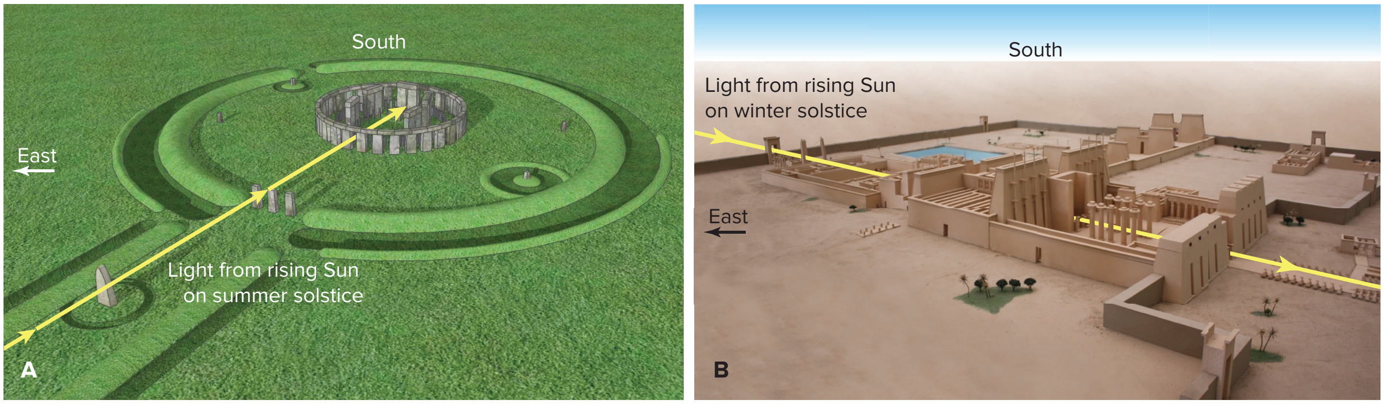

FIGURE 1.16
(A) Stonehenge, built more than 4000 years ago on the Salisbury plain in Britain. The enormous stones are arranged to frame various positions of the Sun on the horizon, helping to mark dates such as when the Sun reaches its point farthest north on the summer solstice. (B) The huge Karnak Temple complex in Luxor was built with its main axis aligned in the direction of the rising Sun on the winter solstice. It was begun almost 4000 years ago, and was expanded repeatedly. a: www.stone-circles.org.uk; b: Source: S. E. Schneider

is Stonehenge, the ancient stone circle in England (a photograph of which opens this chapter). Although we do not know for certain how this ancient monument was used, it was laid out so that such seasonal changes in the Sun's position could be observed by noting through which of the stone arches the Sun was visible when it rose or set. For example, on the summer solstice at sunrise, an observer standing at the center of this circle of immense standing stones would see the rising Sun framed by an arch, as illustrated in figure 1.16A. Similarly, some ancient Egyptian temples and pyramids have astronomical alignments, such as the Temple of Amun-Ra at Karnak, whose main axis points toward the position of sunrise at the winter solstice (fig. 1.16B).

Structures designed with astronomical alignments were built in many other places as well. For example, in Chankillo, Peru, a series of towers was built on a ridge about 2300 years ago. As viewed from an ancient observatory at the base of the ridge, the towers span the shift on the horizon of the rising Sun (fig. 1.17A). The Maya, native peoples of Central America, and their neighbors built pyramids from the summits of which they could get a clear view of the sky over the surrounding rain forest. The

PROJECT

Nature's Calendar

FIGURE 1.17
(A) The oldest known astronomical observatory in the Americas is found in Chankillo, Peru. This ancient observatory marked the shifting position of sunrise with a series of 13 towers built along a ridge about 2300 years ago. (B) At sunrise on the equinoxes, sunlight raking across the edge of the Mayan pyramid at Chichén Itzá creates a shape that resembles a serpent slithering down the steps. The head of the serpent is depicted in a sculpture at the base of the stairs. a: ©Courtesy Ivan Ghezzi, PhD; b: ©Photoimagerie/Alamy Stock Photo

pyramid at Chichén Itzá was specially designed so that on the equinoxes, sunlight would create the image of a snake slithering down the steps (fig. 1.17B).

Many cultures also built monuments that appear to have been used to track another important celestial body: the Moon. Like the Sun, the Moon shifts relative to the stars, and its cyclic changes formed the basis for calendar systems around the world. Some archaeo-astronomers claim that sites such as Stonehenge were used to track the moonrises and moonsets and perhaps even used to predict eclipses.

1.3 The Moon

INTERACTIVE

Lunar phases

PROJECT

Modeling Moon Phases

Like all celestial objects, the Moon rises in the east and sets in the west because of Earth's rotation. Also, like the Sun, the Moon shifts its position across the background stars from west to east. You can verify this motion by observing the Moon at the same time each evening and checking its position with respect to nearby stars. In fact, if the Moon happens to lie close to a bright star, its motion is visible in a few minutes, because in 1 hour the Moon moves against the sky by more than its own apparent diameter.

One of the most striking features of the Moon is that, unlike the Sun, its shape seems to change throughout the month in what is called the cycle of lunar **phases.** During a period of approximately 29.5 days, the Moon grows or *waxes* from invisibility (*new* phase), to a *crescent* shape, then *gibbous* (bulging) when it is more than half lit, until it is a fully illuminated disk (*full*). Next it shrinks or *wanes* backward through this sequence until it is new again (fig. 1.18). This is the origin of the month as a time period and also the source of the name "month," which was derived from the word moon.

The cycle of the phases and the Moon's changing position against the stars are caused by the Moon's orbital motion around Earth. Many people mistakenly believe that these changes in shape are caused by Earth's shadow falling on the Moon. However, this cannot be the explanation—the crescent phases occur when the Moon and Sun lie approximately in the same direction in the sky, so Earth's shadow must be pointing *away* from the Moon. In fact, half of the Moon is always lit by the Sun, but as the Moon orbits around us, we see different amounts of its illuminated half. When the Moon lies approximately between us and the Sun, its fully lit side is turned nearly

FIGURE 1.18
The cycle of the phases of the Moon, from new to full and back again. The phases are caused by our seeing different amounts of the half of the Moon's surface that is illuminated by the Sun. The panel of images of the Moon on the right show its appearance in different phases. Sizes and distances of objects are not to scale. In particular, the Moon is so small and far away that Earth's shadow rarely falls upon it. (moon images) Source: NASA/Goddard Space Flight Center Scientific Visualization Studio