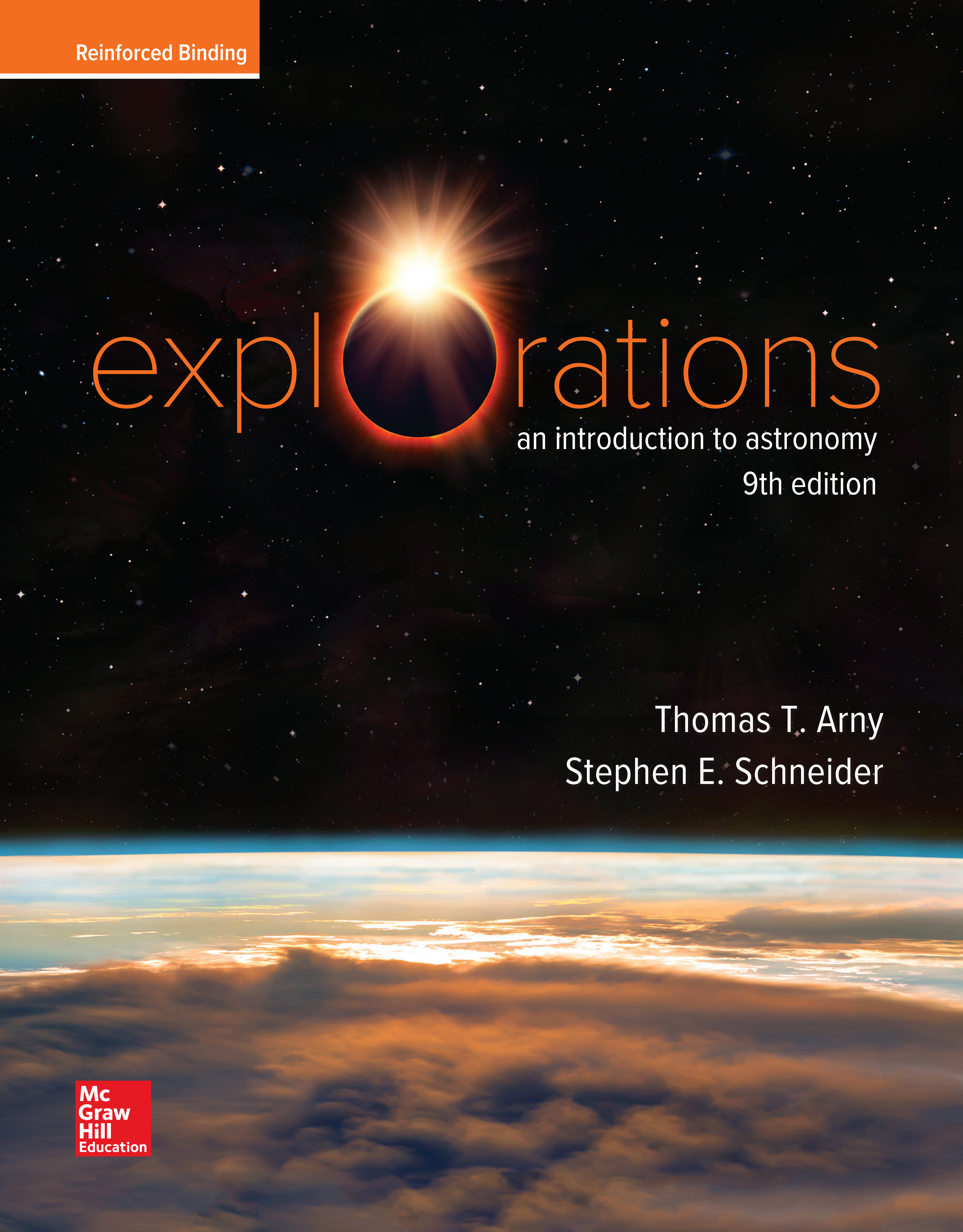

Reinforced Binding

explorations

an introduction to astronomy

9th edition

Thomas T. Arny
Stephen E. Schneider

McGraw Hill Education

Explorations

An Introduction to Astronomy

Ninth Edition

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Reinforced Binding

What does it mean?

Since high schools frequently adopt for several years, it is important that a textbook can withstand the wear and tear of usage by multiple students. To ensure durability, McGraw-Hill Education has elected to manufacture this textbook with a reinforced binding.

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.

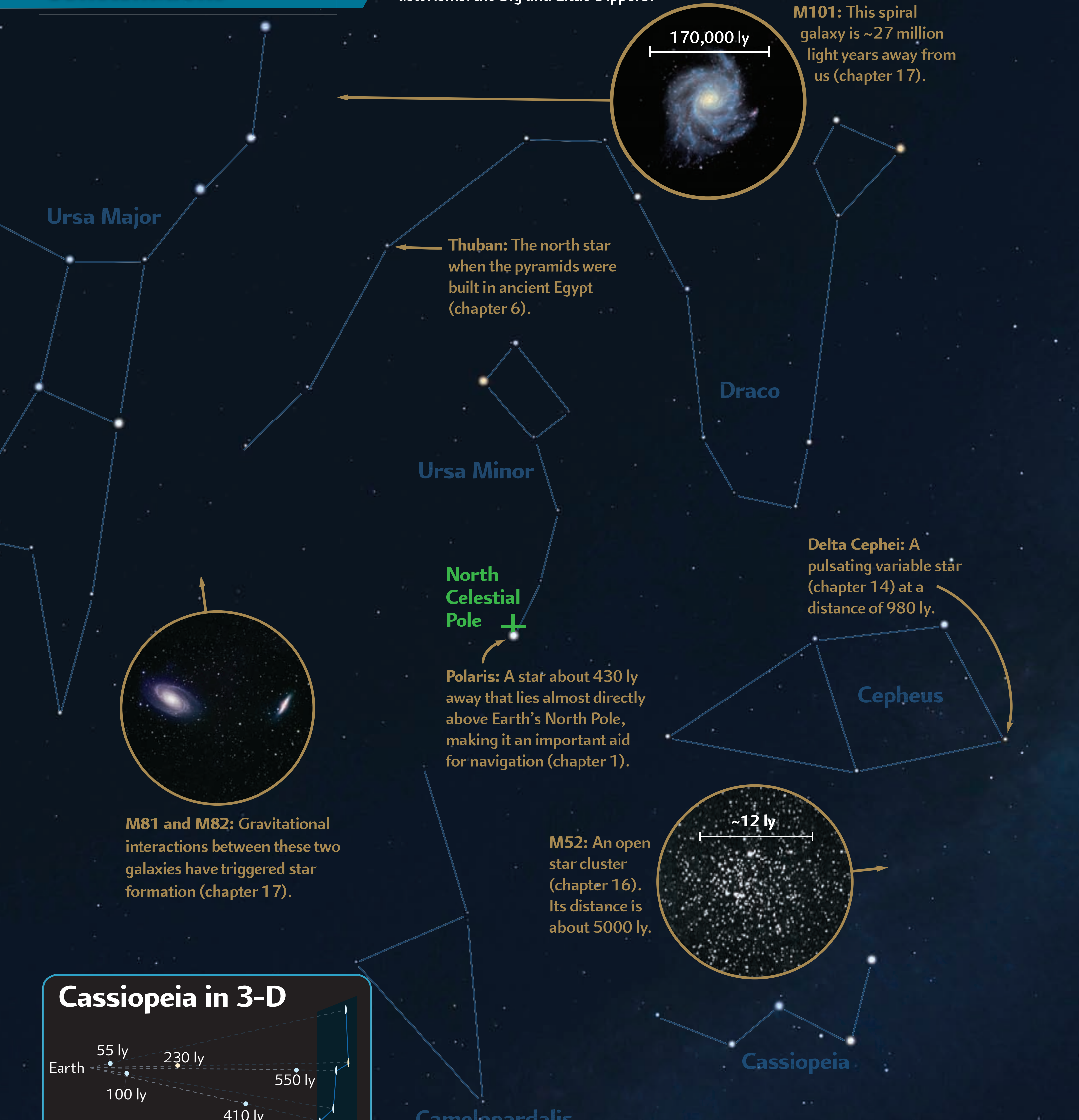


Image credits: M101: Source: Adam Block/NOAO/AURA/NSF; M81 and M82: ©Robert Gendler; M52: Source: NOAO/AURA/NSF; background image produced by S. E. Schneider using *Stellarium* software.

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

Big Dipper

Pointer stars

Ursa Major

Boötes

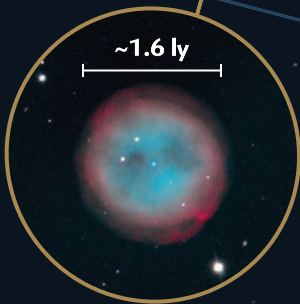
Leo Minor

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)

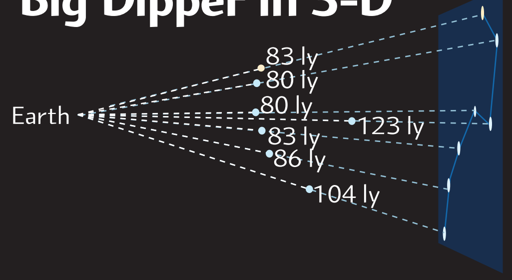
M51—The Whirlpool Galaxy: This interacting galaxy looks like a dim patch of light with a small telescope. M51 is ~37 million ly away (chapter 17).

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).



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

Big Dipper in 3-D

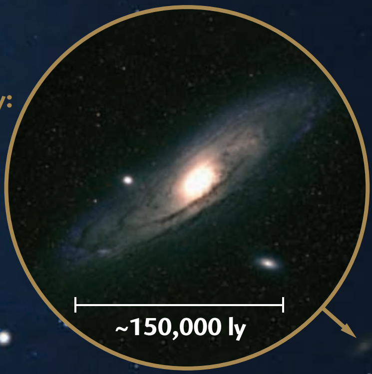


1 light year (ly) ≈ 10 trillion km ≈ 6 trillion miles

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.

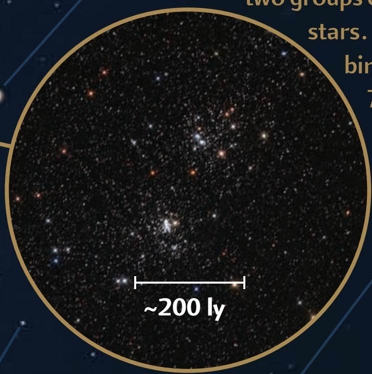
M31—The Andromeda Galaxy: The largest galaxy in the group to which the Milky Way Galaxy belongs (chapter 17).



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).

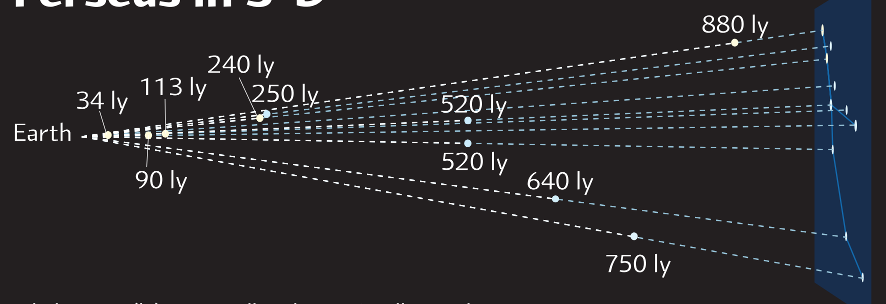
California Nebula: An emission nebula (chapter 16) with a shape like the state of California.

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

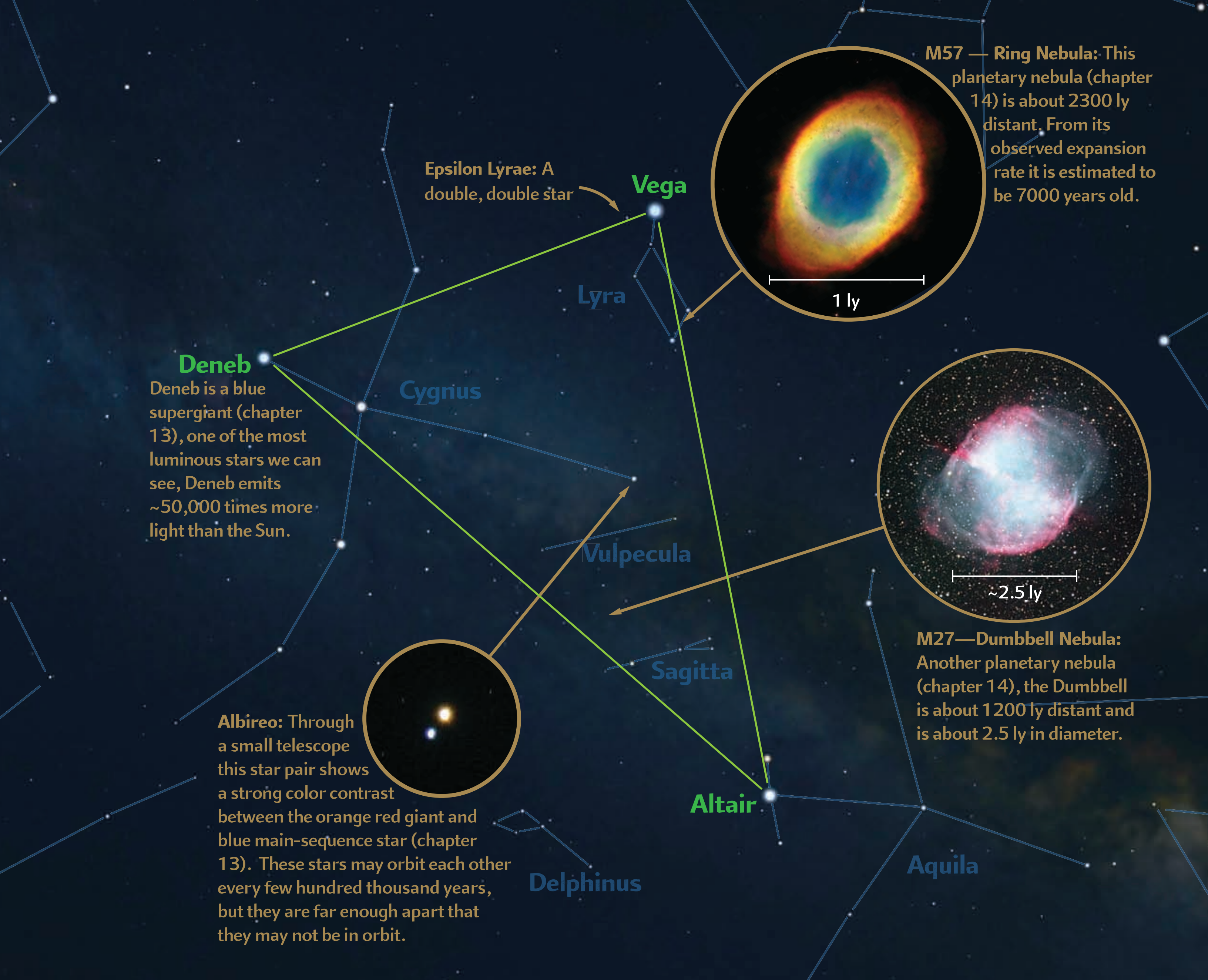


1 light year (ly) ≈ 10 trillion km ≈ 6 trillion miles

LOOKING UP #4

Summer Triangle

The Summer Triangle consists of the three bright stars Deneb, Vega, and Altair, the brightest stars in the constellations Cygnus (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.



Epsilon Lyrae: A double, double star

M57 — Ring Nebula: This planetary nebula (chapter 14) is about 2300 ly distant. From its observed expansion rate it is estimated to be 7000 years old.

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

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

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.

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

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

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.

Auriga

Perseus

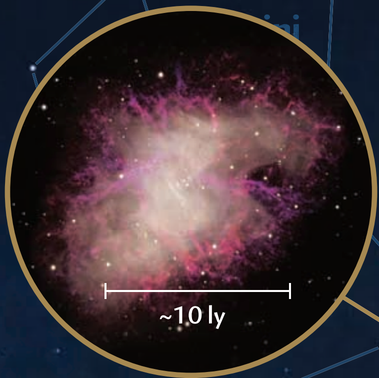
Taurus

Orion

Lepus

Aries

Cetus



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.

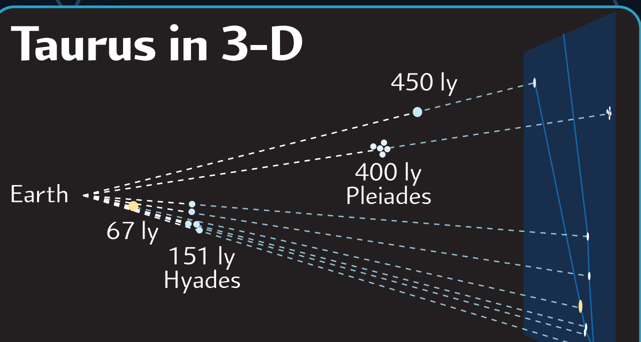
Hyades: The "V" in Taurus is another nearby star cluster, measured to be 151 ly away by the Hipparcos satellite (chapter 13). It is easy to see its many stars with binoculars.

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.

Taurus in 3-D



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

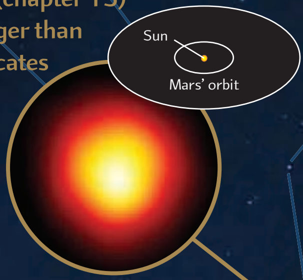
Image credits: M1: ©Courtesy of Richard Wainscoat ; M45: Courtesy of Australian Astronomical Observatory; photographs by David Malin; background image produced by S. E. Schneider using *Stellarium* software.

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.

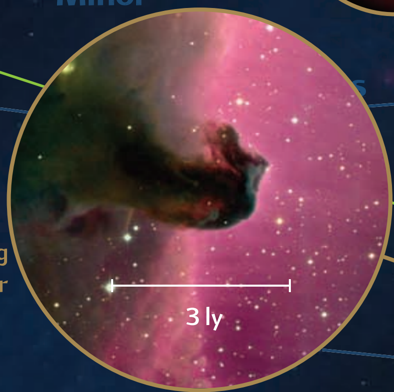
Betelgeuse: A red supergiant star (chapter 13) that has swelled to a size that is larger than the orbit of Mars. Its red color indicates that it is relatively cool for a star, about 3500 kelvin.



Taurus

Canis Minor

Orion



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

Celestial Equator

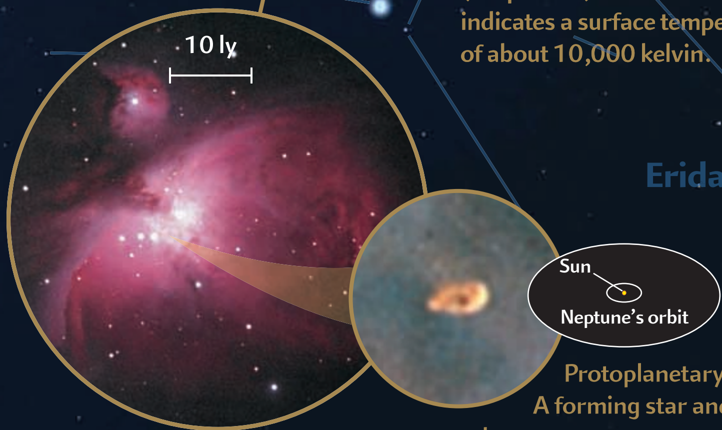
Sirius: The brightest star in the night sky, about 8.6 ly distant. It is orbited by a white dwarf (chapter 15) visible with a telescope.

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

Canis Major

Eridanus

Puppis

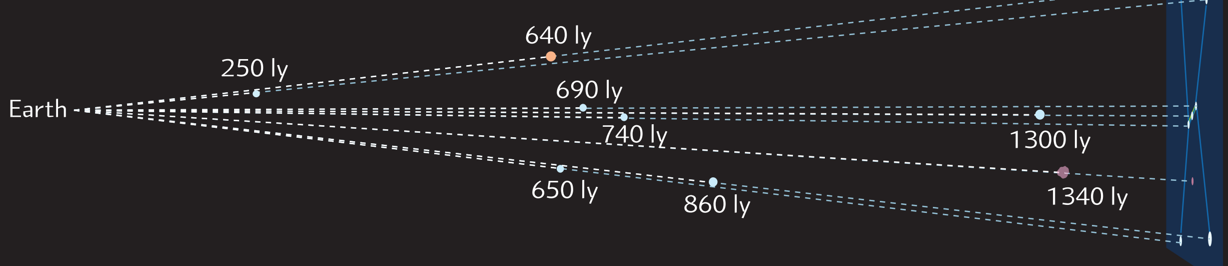


M42—Orion Nebula: An active star-forming region rich with dust and gas (chapter 14).

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

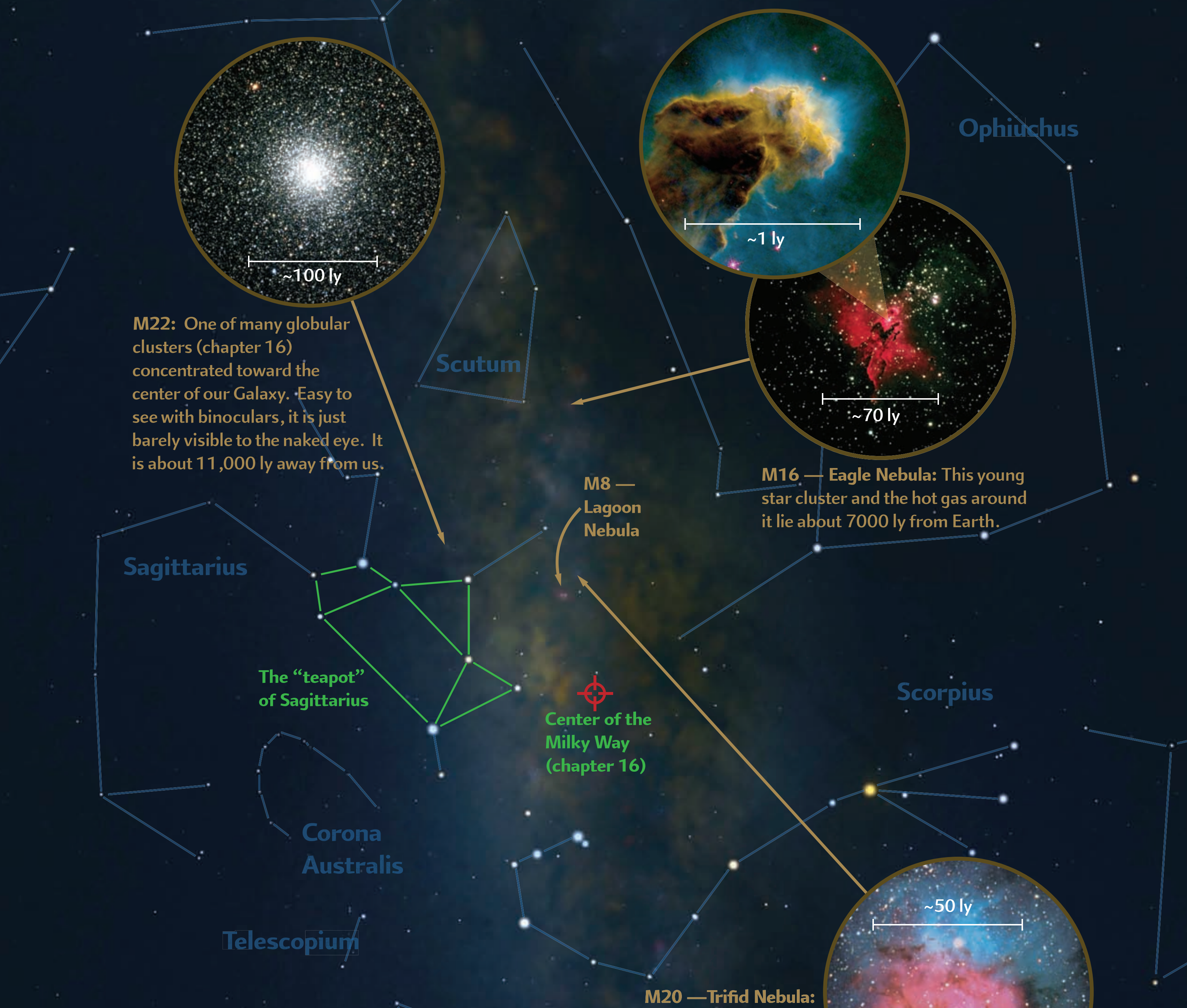


1 light year (ly) ≈ 10 trillion km ≈ 6 trillion miles

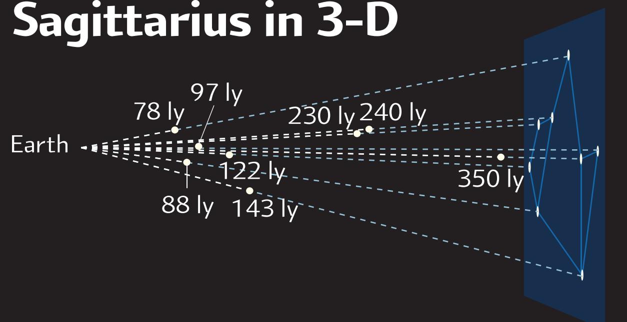
LOOKING UP #7

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).



Sagittarius in 3-D



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

LOOKING UP #8

Centaurus and Crux, The Southern Cross

These constellations 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

Centaurus

Circinus

Crux

Musca

Carina

Vela

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).

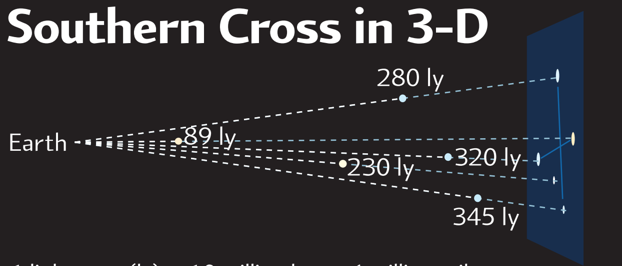
Alpha Centauri

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

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

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.

Southern Cross in 3-D



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

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.

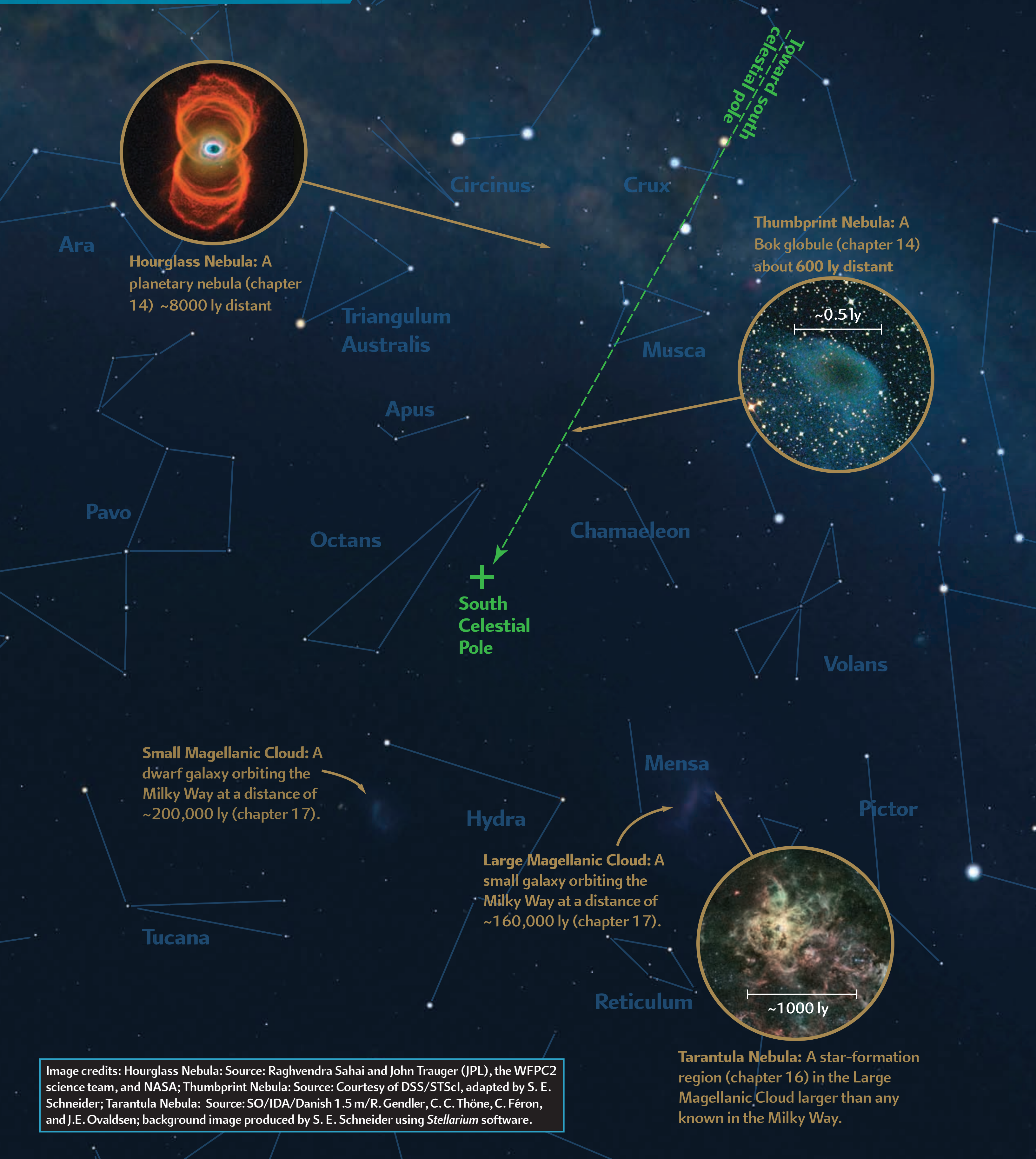


Image credits: Hourglass Nebula: Source: Raghvendra Sahai and John Trauger (JPL), the WFPC2 science team, and NASA; Thumbprint Nebula: Source: Courtesy of DSS/STScI, adapted by S. E. Schneider; Tarantula Nebula: Source: SO/IDA/Danish 1.5 m/R. Gendler, C. C. Thöne, C. Féron, and J.E. Ovaldsen; background image produced by S. E. Schneider using *Stellarium* software.

Explorations

An Introduction to Astronomy

Ninth Edition

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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.

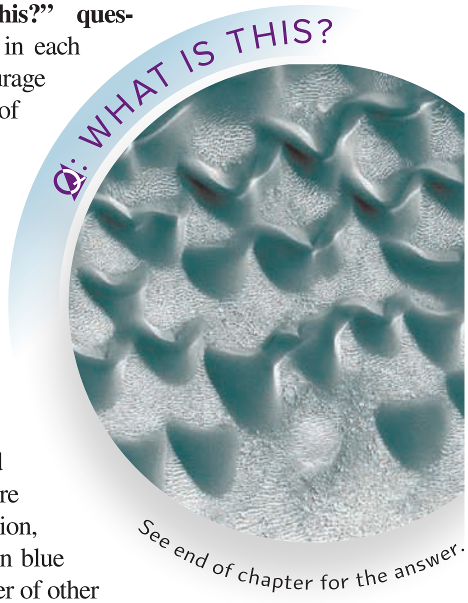
Knowing the facts about astronomical objects is important, but it is equally important to understand how astronomers deduce those facts. Thus, an additional aim throughout this text is to explain *how* astronomers have come to their understanding of our Universe. New observations can force astronomers 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."

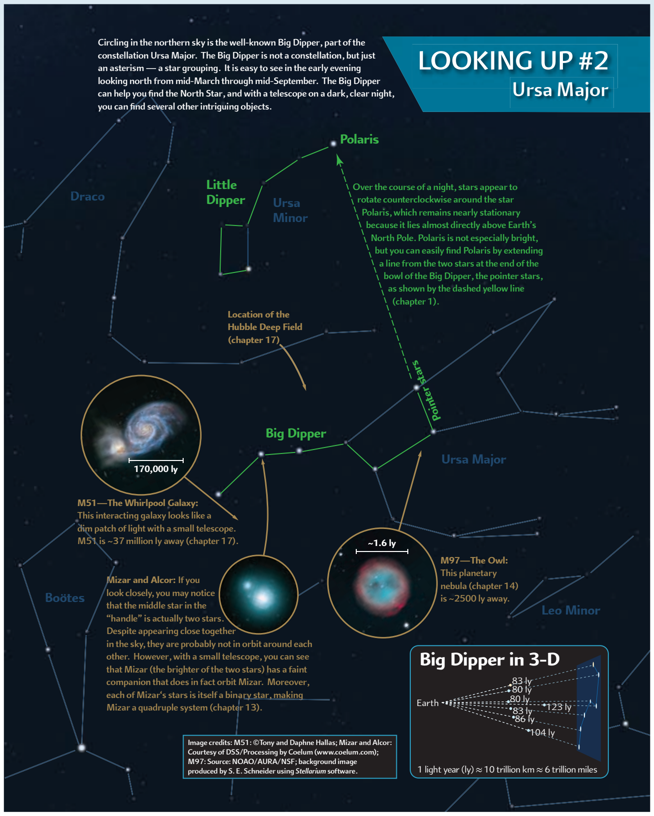
Concepts and Skills to Review are listed at the start of each chapter to provide quick pointers to earlier material that is critical for understanding the content of the chapter. If any look unfamiliar, you should review them before reading the chapter.

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.

Animations and Interactives are available with the online resources at My.MHEducation.com to help you gain a better grasp of key concepts. Icons have been placed in the eBook 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 in the eBook by a their own icon, and are 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 correlated 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 teacher. 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 TEACHER

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 digital 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 teacher 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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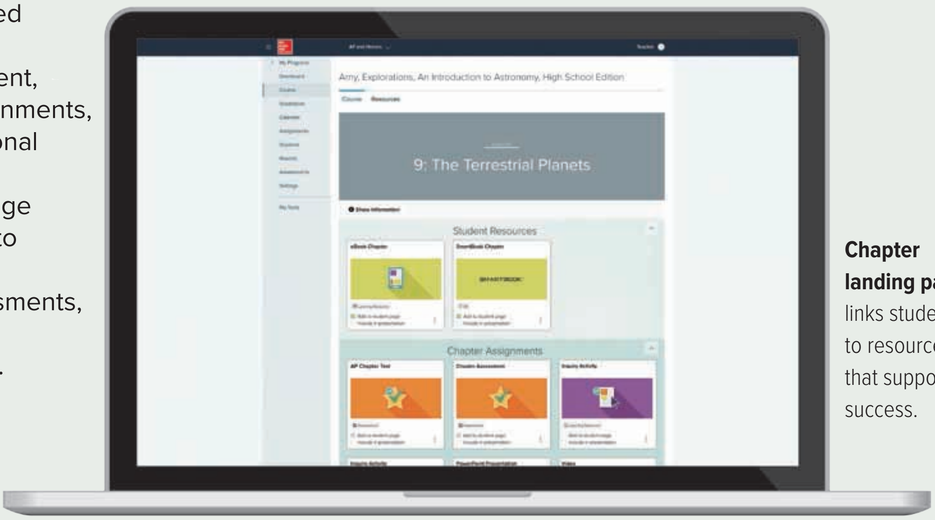

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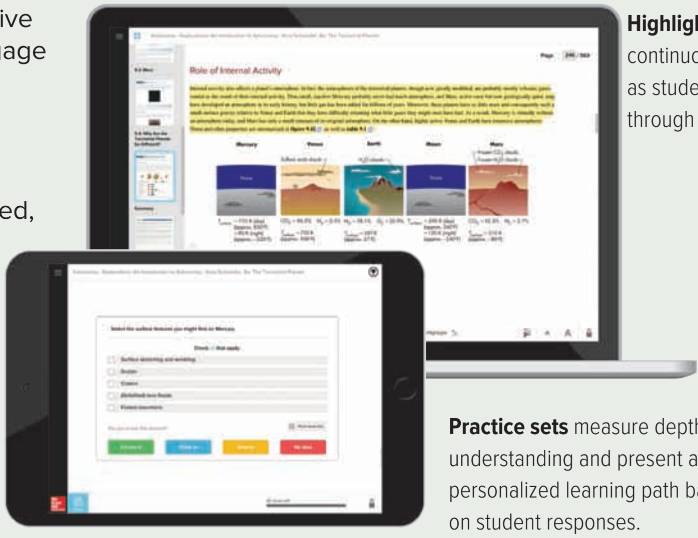

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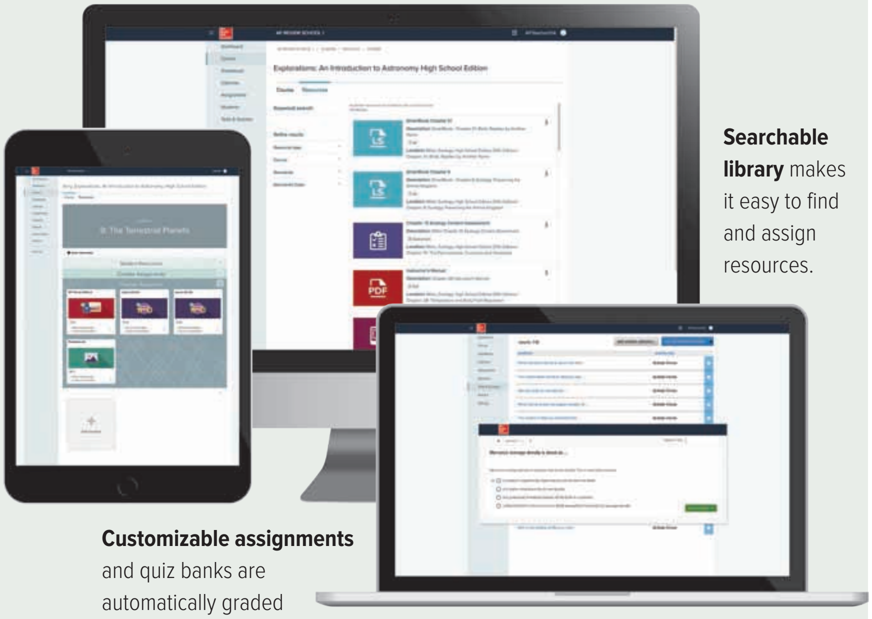

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- chapter 7: Revised discussion of tides.
- chapter 8: Haumea and Makemake included in figures and text when discussing dwarf planets. Mentions of Bode's rule are now further de-emphasized since findings that it does not appear to apply to other planetary 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.

The authors and McGraw-Hill would also like to extend a special thank-you to Padraig Houlahan at Embry-Riddle Aeronautical University, Alan Hulsebus at Iowa State University, Christopher Shope at Cintoet, Inc., Michael Stage at Amherst College, and Christopher Taylor at California State University-Sacramento, who were instrumental in the development of this edition's interactives and teacher resources as well as online and SmartBook content.

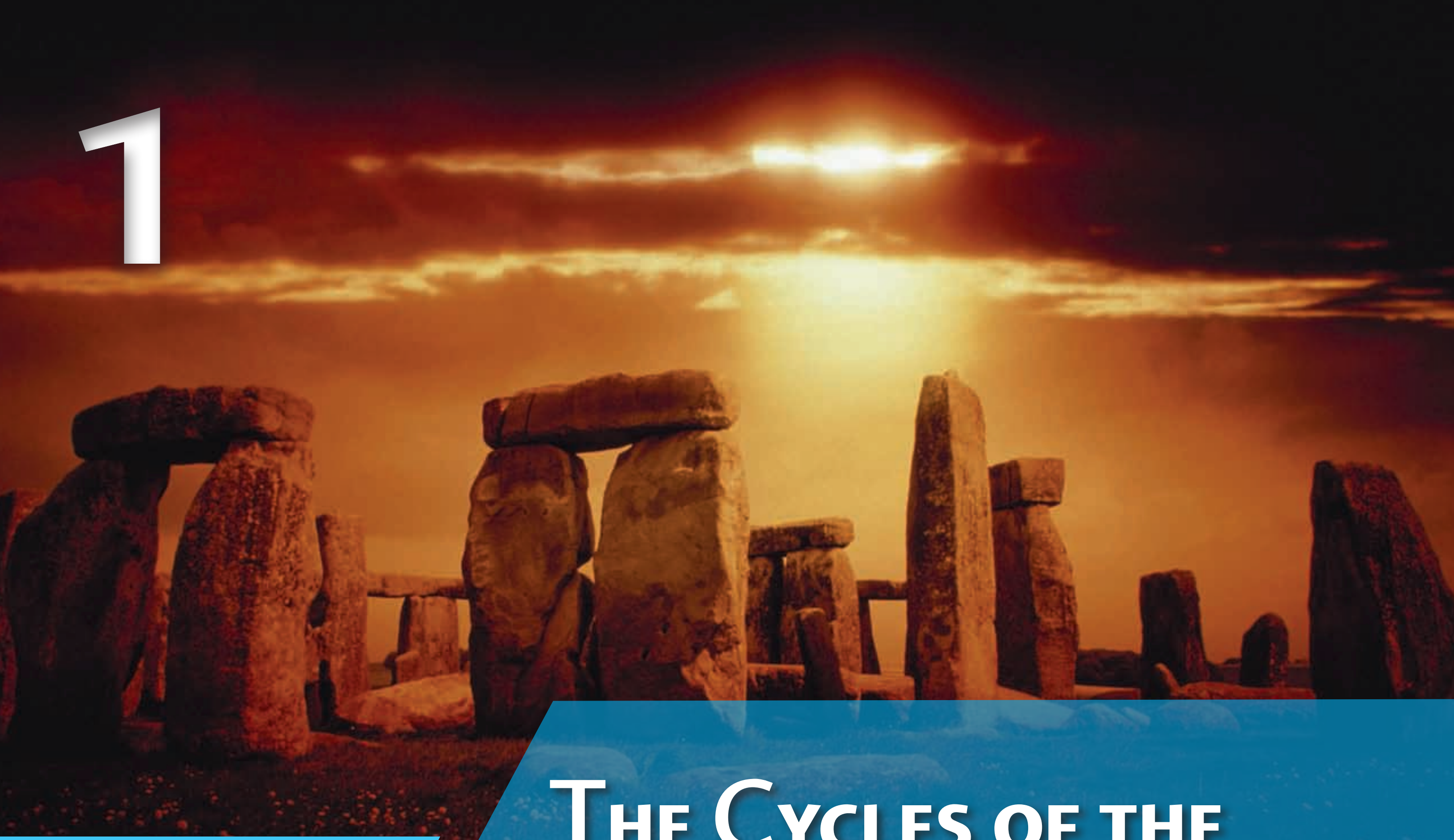
REVIEWERS OF THIS AND PREVIOUS EDITIONS

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*.

Ninth Edition Reviewers

Pam Bryant, Howard Payne University
Jeffrey Butikofer, Upper Iowa University
Christine Russell, Missouri Valley College
Michael Scanlon, Louisiana State University at Eunice
Lisa Shier, University of Maryland University College
Chad Thibodeaux, Northwestern State University
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.



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.

1 The Cycles of the Sky

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.

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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.**

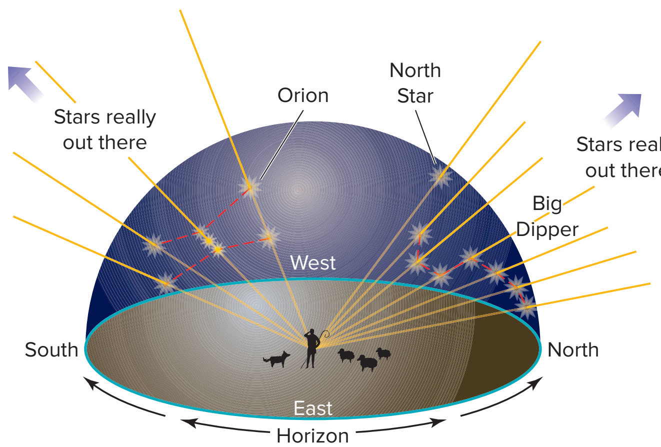


FIGURE 1.1
The stars appear to lie on a hemisphere over us that meets the ground at the horizon.

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

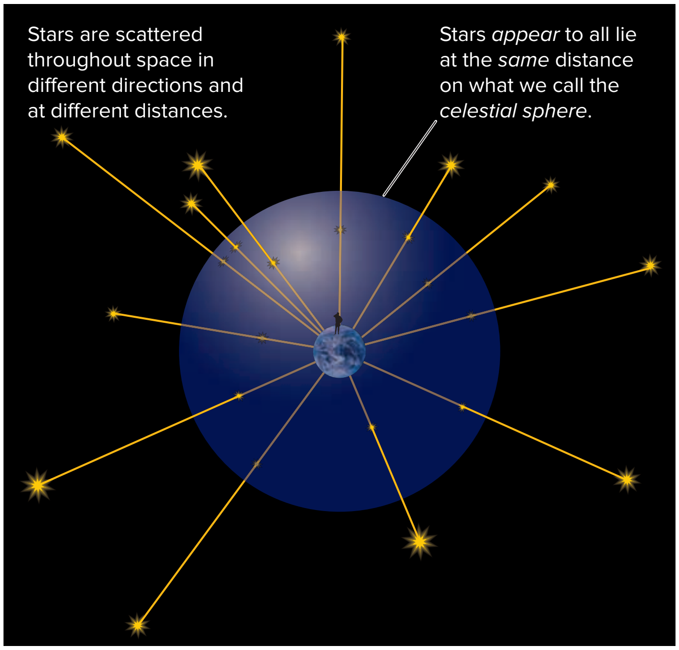


FIGURE 1.2
The stars are scattered through space at very different distances, but they *appear* to lie at the same distance from us on what we call the celestial sphere.

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!

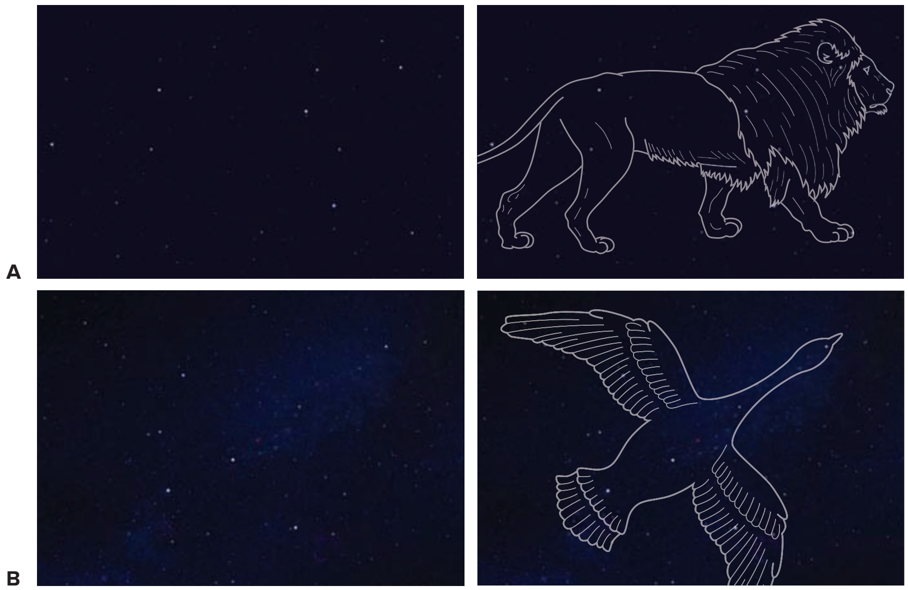
Depicting the stars as though they lie on a celestial sphere is not physically accurate, but it serves as a useful **model** of the heavens—a way of simplifying the arrangement and motions of celestial bodies so they are easier to visualize. We use the term *model* to mean a representation of some aspect 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.

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

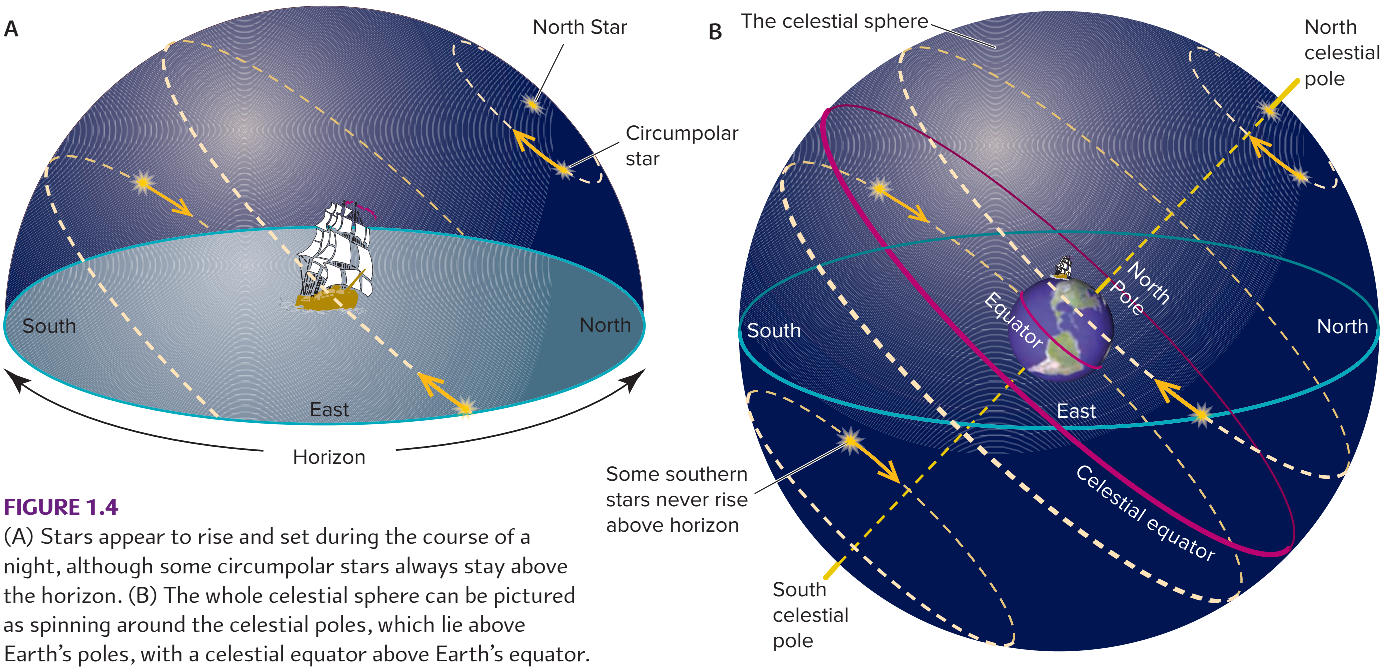


FIGURE 1.4
(A) Stars appear to rise and set during the course of a night, although some circumpolar stars always stay above the horizon. (B) The whole celestial sphere can be pictured as spinning around the celestial poles, which lie above Earth's poles, with a celestial equator above Earth's equator.

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.

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.

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

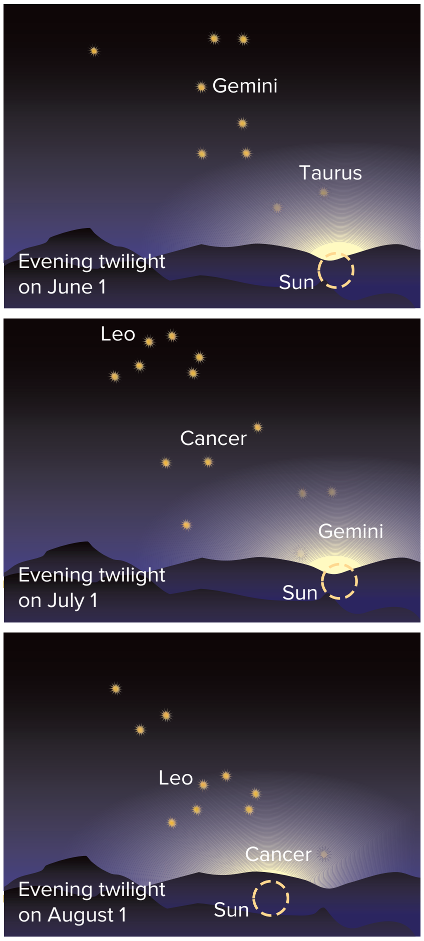


FIGURE 1.5
The Sun appears to lie in Taurus on June 1, in Gemini on July 1, in Cancer on August 1, and so forth, making the constellations we see after sunset change with the seasons.

ANIMATION

Constellations by seasons

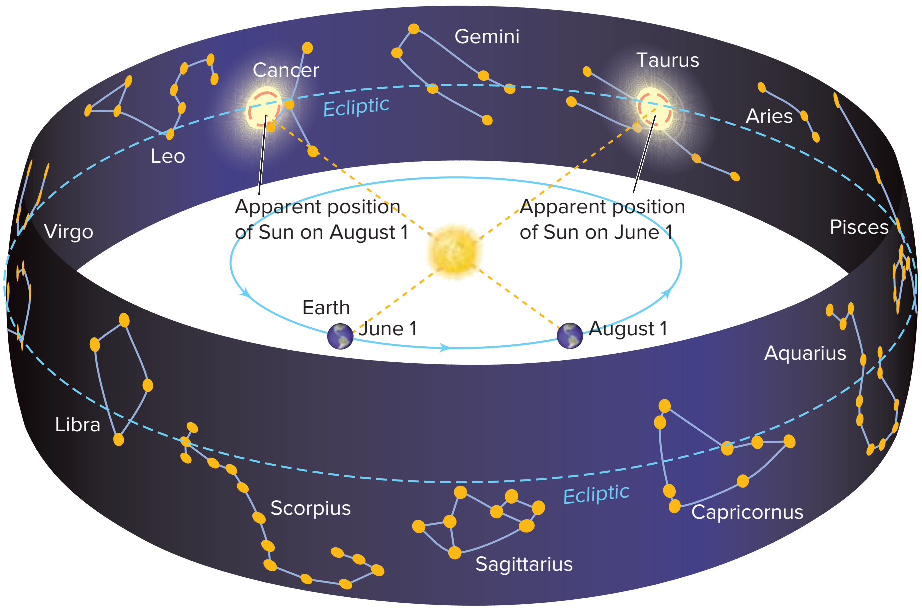


FIGURE 1.6
As Earth orbits the Sun, the Sun appears to move around the celestial sphere through the background stars. The figure illustrates the portion of the celestial sphere on either side of the Sun's path, which is called the ecliptic. As Earth orbits the Sun, the Sun appears to move through twelve 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.

PROJECT

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

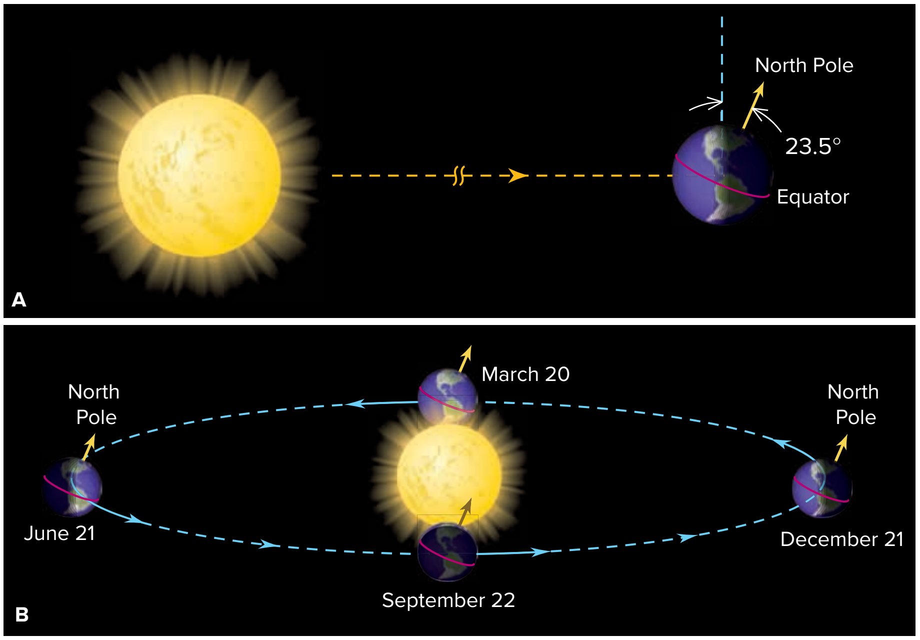


FIGURE 1.7
(A) Earth's rotation axis is tilted 23.5° to Earth's orbit around the Sun. (B) Earth's rotation axis keeps the same tilt and direction as it moves around the Sun. (Sizes and distances are not to scale.)

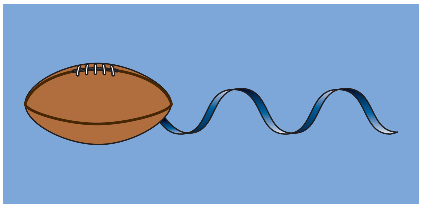


FIGURE 1.8
The tendency of a spinning object to keep its orientation is called "conservation of angular momentum," and it is the principle on which gyroscopes operate and the reason a quarterback puts "spin" on a football.

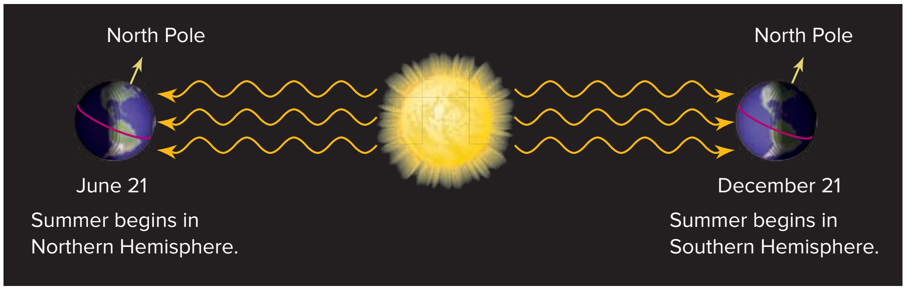


FIGURE 1.9
Because Earth's rotation axis keeps the same tilt as we orbit the Sun, sunlight falls more directly on the Northern Hemisphere during part of the year and on the Southern Hemisphere during the other part of the year. (Sizes and distances are not to scale.)

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

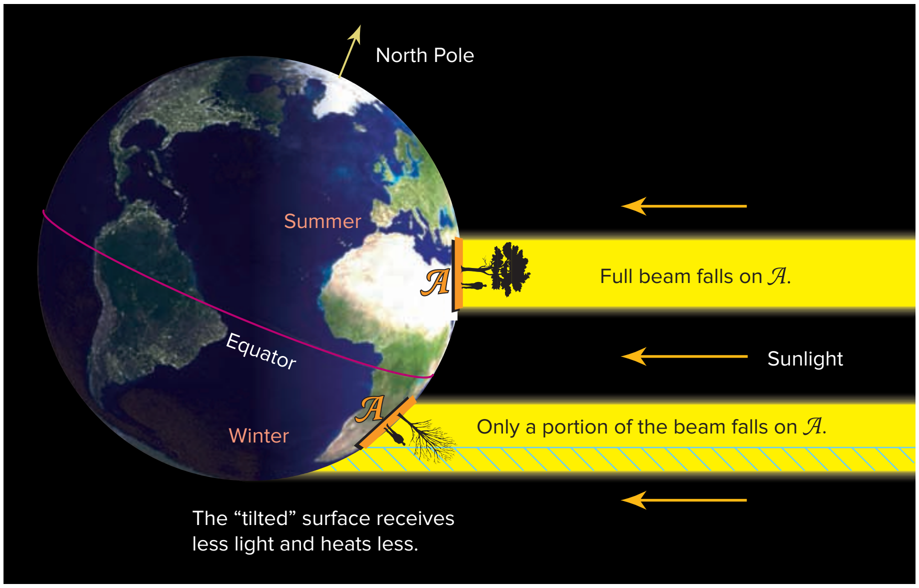


FIGURE 1.10
A portion of Earth's surface directly facing the Sun receives more concentrated light (and thus more heat) than other parts of Earth's surface of equal area. The same size "beam" of sunlight (carrying the same amount of energy) gets spread out over a larger area where the surface is "tilted."

ANIMATION
Seasonal changes in daylight

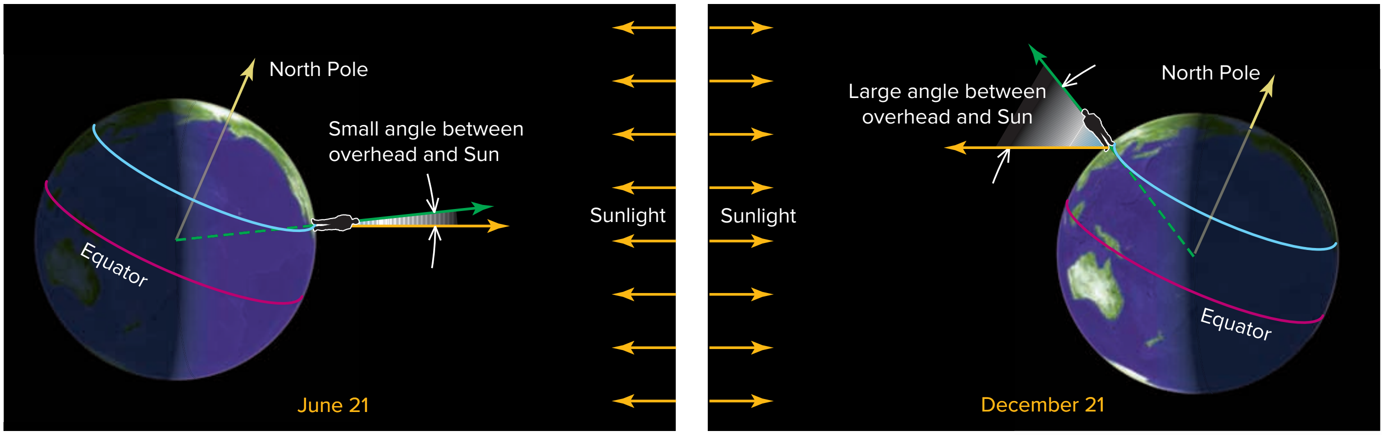


FIGURE 1.11
Between the extremes of the year six months apart, the angle at which sunshine strikes the ground at the same latitude can vary greatly.

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.

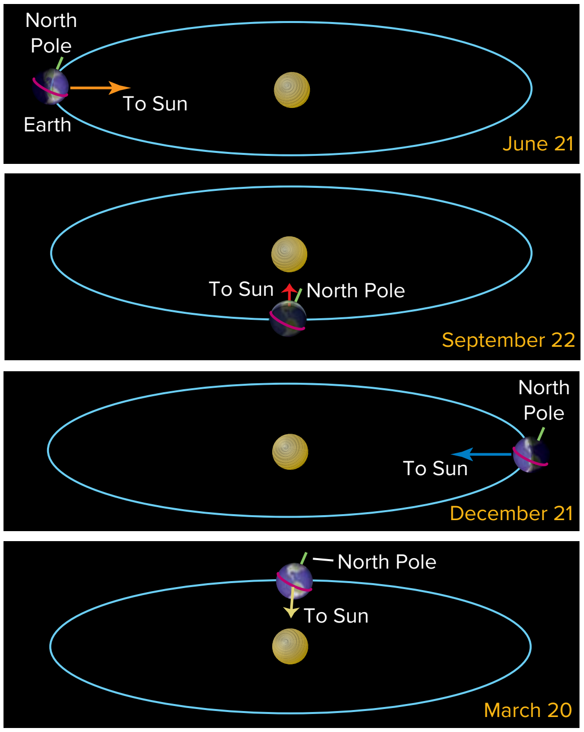
As a result of this north–south motion, the Sun's path crosses the celestial equator twice during the year as illustrated in figure 1.12. The dates when the Sun reaches its extreme north and south positions are used to mark the beginning of summer and of winter, while the dates when the Sun crosses the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



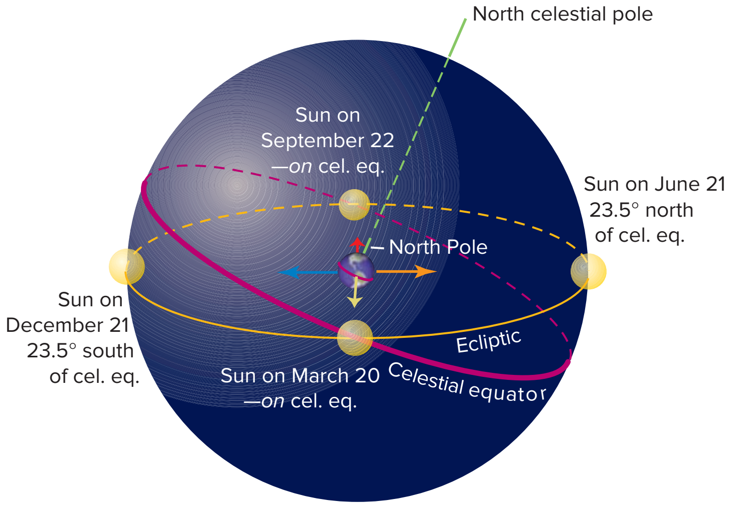
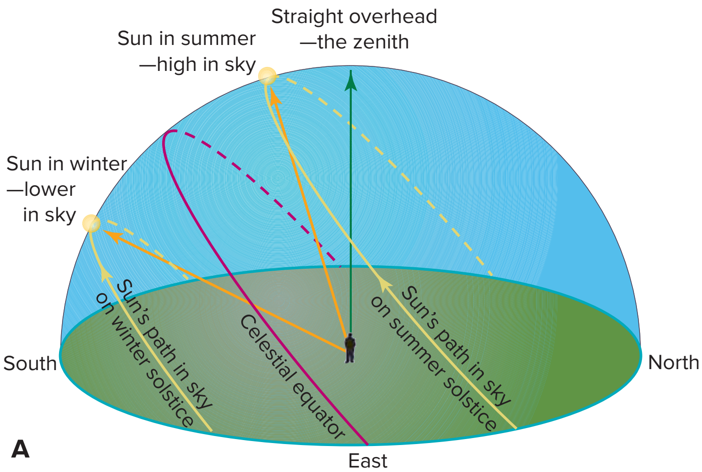


FIGURE 1.12
As Earth orbits the Sun, the Sun's position with respect to the celestial equator changes. The Sun reaches 23.5° north of the celestial equator on June 21 but 23.5° south of the celestial equator on December 21. The Sun crosses the celestial equator on about March 20 and September 22 each 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



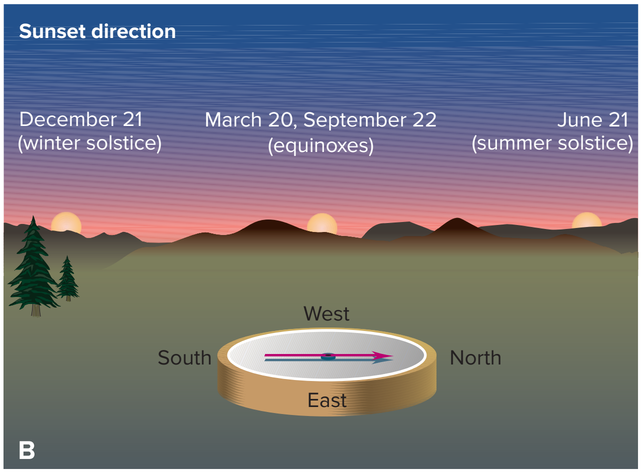


FIGURE 1.13
(A) The shifting location of the Sun north and south of the celestial equator causes it to reach different heights in the sky each day throughout the year. This diagram illustrates the Sun's path in the sky for an observer at about 40° northern latitude. (B) The motion of the Sun throughout 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

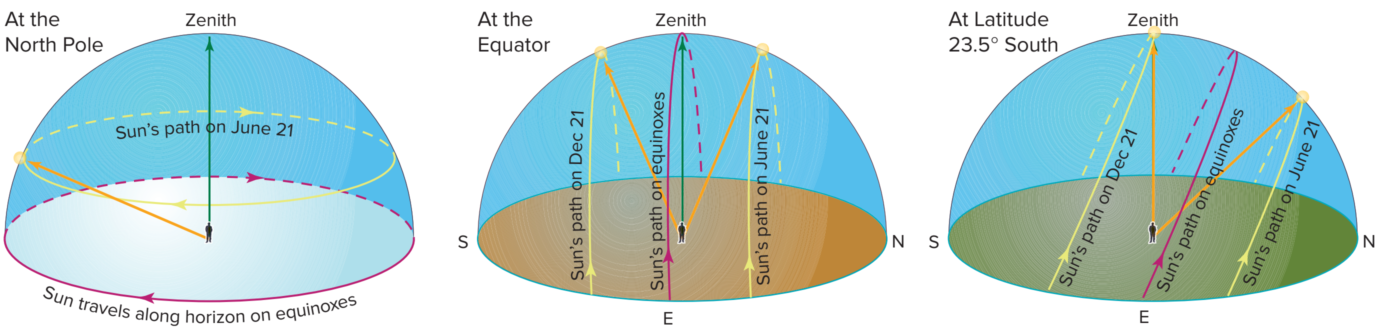


FIGURE 1.15
The path of the Sun in the sky differs depending on your latitude. At the North Pole, the Sun never sets for six months but gradually spirals up from the horizon from the vernal equinox to the summer solstice, then spirals back down to the horizon at the autumnal equinox before it disappears 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.

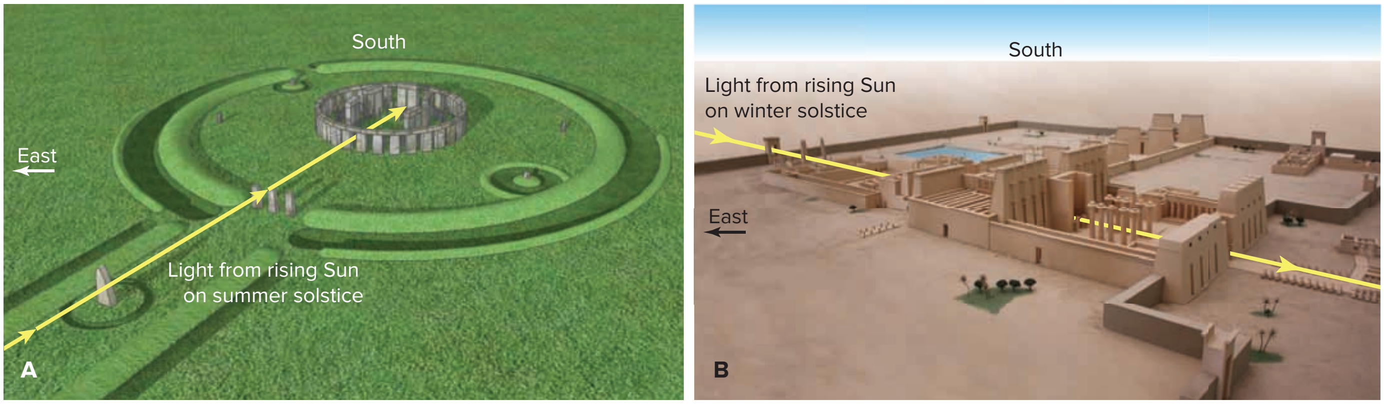


FIGURE 1.16
(A) Stonehenge, built more than 4000 years ago on the Salisbury plain in Britain. The enormous stones are arranged to frame various positions of the Sun on the horizon, helping to mark dates such as when the Sun reaches its point farthest north on the summer solstice. (B) The huge Karnak 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

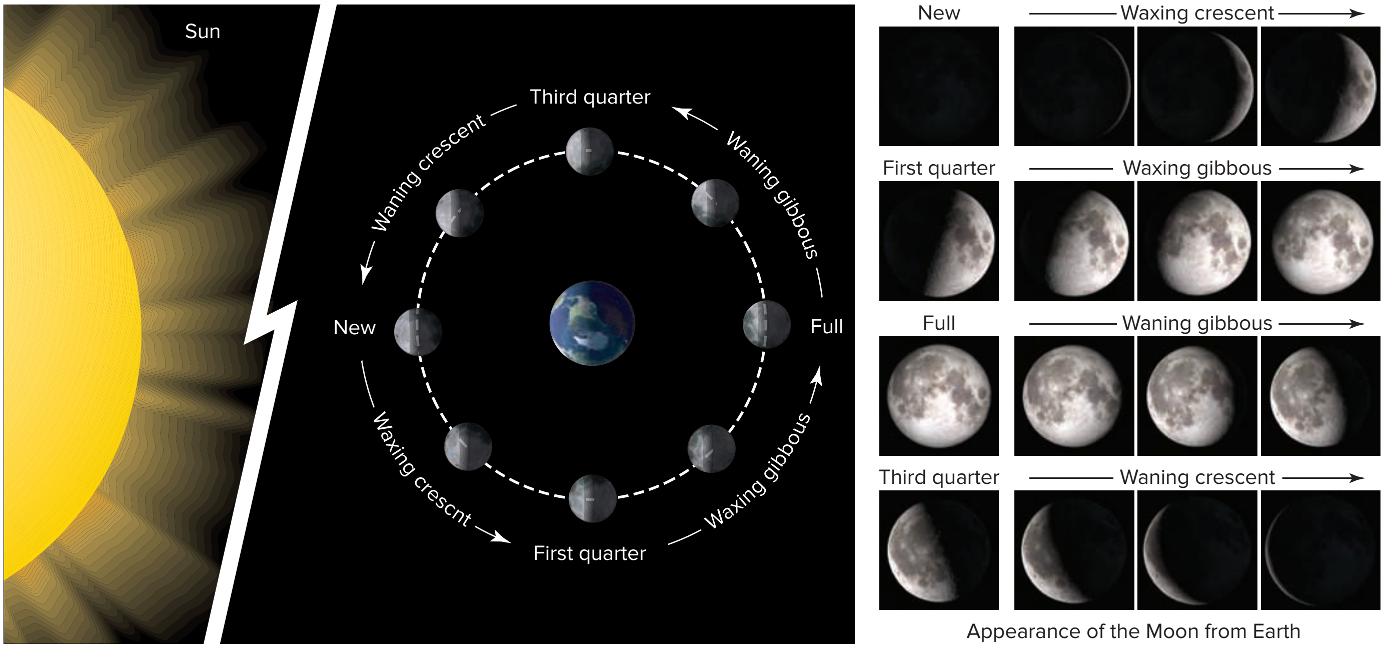


FIGURE 1.18
The cycle of the phases of the Moon, from new to full and back again. The phases are caused by our seeing different amounts of the half of the Moon's surface that is illuminated by the Sun. The panel of images of the Moon on the right show its appearance in different phases. Sizes and distances 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

ASTRONOMY *by the numbers* — ESTIMATING WHEN THE MOON WILL RISE

If you know the Moon's phase, you can estimate the times when the Moon rises, sets, and is highest in the sky.

For example, when the Moon is at first quarter, it is one-quarter of the way around the sky, eastward of the Sun by about 90° (fig. 1.18). Therefore, Earth must turn about an additional 90° to bring the Moon to approximately the same position as the Sun. How long does it take Earth to rotate those extra 90°? Since it takes Earth 24 hours to rotate once (360°), to rotate 90°(= 360°/4) takes 6 hours (= 24 hours/4). Thus, the first-quarter moon is highest in the sky at 6 hours after noon, or 6 P.M., rises about 6 hours earlier at about noon, and sets at about midnight. With similar reasoning, you can find when the Moon rises and sets in other phases.

As the Moon moves eastward from the Sun and its phase changes, it rises about 49 minutes later each night. This shift is simply the result of the Moon's orbital motion around Earth, resulting in a complete cycle of phases over 29.5 days: 24 hours/29.5 days = 49 minutes/day.

Because the Moon orbits close to the plane of the ecliptic, it shifts north and south of the celestial equator during the month, just as the Sun does during the year. A consequence of this is that the full moon's behavior is the opposite of the Sun's—the full moon is relatively low in the sky in the summer and high in the sky in the winter. The Moon's position north or south of the celestial equator also affects the time between moonrise and moonset, just as the length of days depends on the Sun's position.

completely away from us, and therefore the side facing us is dark, as illustrated in figure 1.18. At the *first quarter* and *third quarter* points, the Moon is 90° from the Sun and appears half lit. When the Moon lies approximately opposite the Sun in the sky, the side of the Moon facing Earth is fully lit. The alignment is rarely exact, so Earth's shadow is usually "above" or "below" the Moon.

The Moon's motion around Earth causes it to shift eastward through the stars. As a result, Earth itself must rotate eastward a little extra each day to bring the Moon back above the horizon. This extra rotation takes about 50 minutes each day, on average. So if the Moon rises at 8 P.M. one evening, the next evening it will rise at about 8:50 P.M., the following night at about 9:40 P.M., and so forth. See Astronomy by the Numbers: "Estimating When the Moon Will Rise."

The changing time of moonrise means that the Moon is visible at different times and places during the night or day depending on its phase. For example, shortly after the new phase you can see the Moon low in the western sky after sunset. A few hours later that same evening it will have set and become invisible. On the other hand, when the Moon is full, it rises at about sunset and doesn't set until dawn. Thus, the full moon is visible throughout the night. In most of its phases, you can see the Moon during some part of the day if you know where to look. The different times when the Moon is visible are explored further in Extending Our Reach: "Observing the Moon."

Because the Moon's orbit is close to the orbital plane of Earth around the Sun, the Moon, like the Sun, moves through the constellations of the zodiac. While the Moon takes about 29.5 days to go through its cycle of phases, the combination of the Moon's and Earth's orbits have the effect that the Moon requires only 27.3 days to complete its motion through the constellations of the zodiac. The reason for this is illustrated in figure 1.19, where you can see that after a month has passed Earth has shifted its position in its orbit, so the Sun is in a different direction. After the Moon comes back into alignment with distant stars in 27.3 days, it must still travel farther around in its orbit two more days to come back into alignment with the Sun.

PROJECT

Tracking the Moon among the Stars

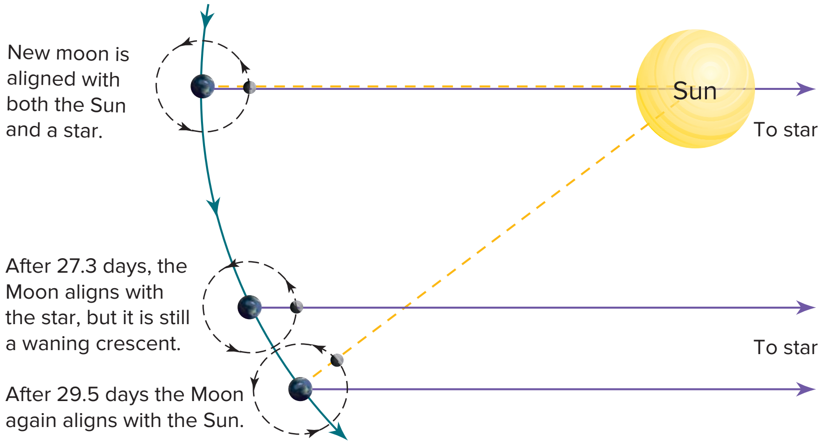


FIGURE 1.19
The sidereal month is the time the Moon takes to complete an orbit relative to the distant stars. This is about 27.3 days, 2.2 days less than the lunar month because as the Moon is orbiting Earth, Earth is orbiting the Sun. It takes a little more than two additional days for the Moon to come back in alignment with the Sun.

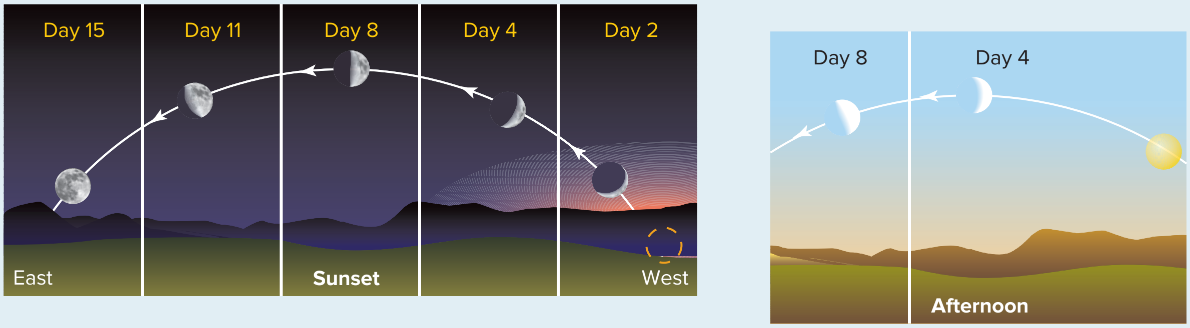
EXTENDING *our reach*

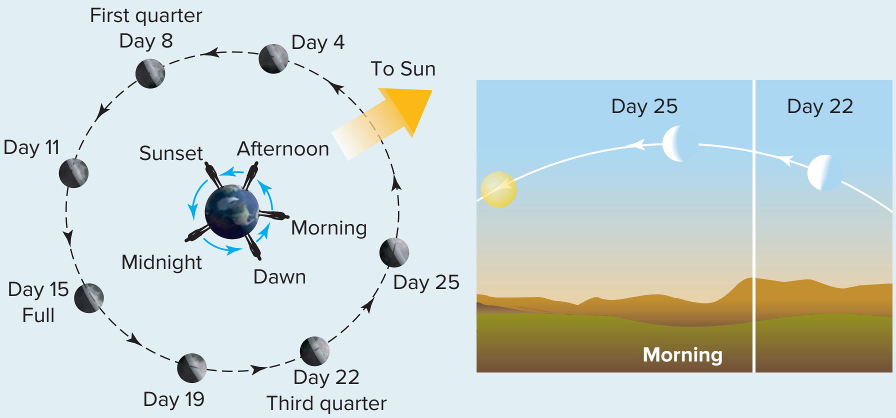
OBSERVING THE MOON

When the Moon is full, it lies approximately opposite to where the Sun lies, but when the Moon is a thin crescent, it lies in nearly the same direction as the Sun (see the middle of fig. 1.20). These connections between the Moon's phase and its position with respect to the Sun are the key to understanding when the Moon is visible from Earth.

Because the full moon is approximately opposite the Sun, it *rises* above the eastern horizon at about the same time that the Sun *sets* below the western horizon. Likewise, the full moon *sets* at about the time the Sun *rises*. Therefore, the full moon is visible all night and highest in the sky near midnight.

On the other hand, the crescent moon is not visible during most of the night. Because it lies in nearly the same direction as the Sun, once the Sun is well below the horizon, the crescent moon must be below the horizon too. Moreover, the crescent moon is hard to see during the day because it is only a sliver of light, so it is lost in the brightness of the daytime sky. Therefore, when the Moon is a few days past its new phase and is a thin crescent, you can see it low in the western sky at sunset. This crescent moon will set shortly after the Sun and not be visible again until after sunrise the next day.





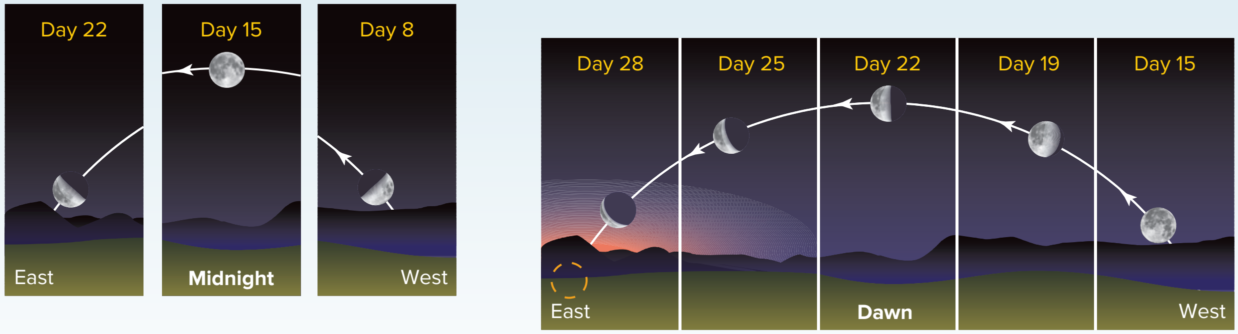


FIGURE 1.20
Where do you look for the Moon and how does it appear at different times of day as it goes through its monthly cycle of phases? The central diagram shows a person standing on Earth at five times of day: dawn, morning, afternoon, sunset, and midnight. The Moon's position in its orbit is shown on 7 days of the lunar cycle (days 4, 8, 11, 15, 19, 22, and 25).The five surrounding panels show what a person would see at each of those times of day as the Moon moves through its orbit.

1.4 Eclipses

An eclipse occurs when Earth lies directly between the Sun and the Moon, or when the Moon passes exactly between Earth and the Sun so that all three bodies are on a straight line. Thus, there are two types of eclipse: lunar and solar.

A **lunar eclipse** occurs when Earth passes between the Sun and the Moon and casts its shadow on the Moon, as shown in figure 1.21. A **solar eclipse** occurs whenever the Moon passes directly between the Sun and Earth and blocks our view of the Sun, as depicted in figure 1.22.

INTERACTIVE

Eclipses

Appearance of Eclipses

Eclipses generally take a few hours from start to finish. It is more common for an eclipse to be *partial,* with only a portion of the Moon or the Sun ever being covered over. These partial eclipses often pass unnoticed unless you know to look for them. However, *total* eclipses are beautiful and marvelous events.

PROJECT

Appearance of Eclipses

As the Moon reaches the point along its orbit when it is full, it usually misses Earth's shadow. If it happens to be less than about 0.5° from the ecliptic when it is full, however, the Moon will pass through Earth's shadow, and a total lunar eclipse will occur. Total lunar eclipses are visible if you are anywhere on the night side of Earth when the eclipse is occurring. A total lunar eclipse begins as one edge of the Moon enters Earth's shadow and becomes dark. The Moon takes about an hour to reach *totality,* when it is completely within the Earth's shadow. During totality, the Moon generally appears a deep ruddy color, almost as if dipped in blood. After totality, the Moon again becomes lit, bit by bit, reverting over the next hour to its unsullied, silvery light.

A little light falls on the Moon even at totality because Earth's atmosphere bends some sunlight into the shadow. The light reaching the Moon is red because interactions with particles in the air remove the blue light as it passes through our atmosphere, exactly as happens when we see the setting Sun, and the path of the light is bent by the atmosphere much as a prism bends the direction of light, as shown in figure 1.23. (The bending of light by the atmosphere is discussed further in chapter 5.)

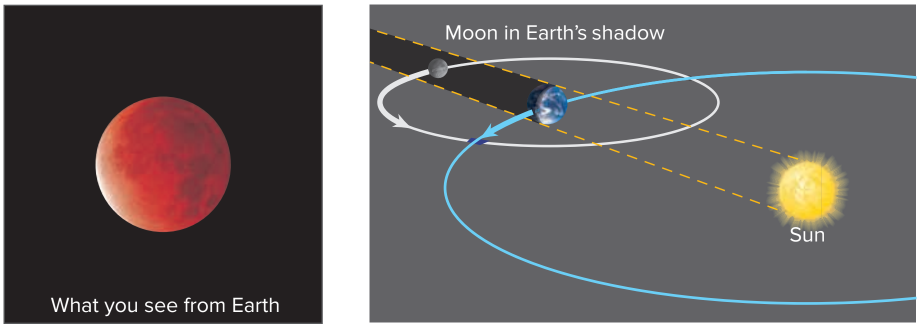


FIGURE 1.21
A lunar eclipse occurs when Earth passes between the Sun and Moon, causing Earth's shadow to fall on the Moon. Some sunlight leaks through Earth's atmosphere, casting a deep reddish light on the Moon. The photo shows what the eclipse looks like from Earth. left: Source: John Walker

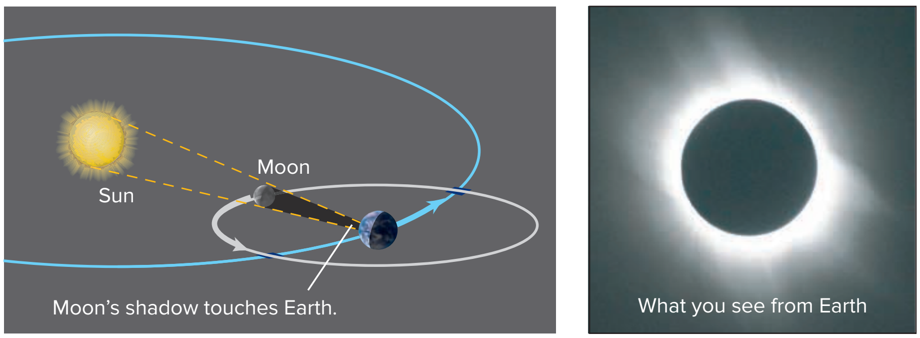


FIGURE 1.22
A solar eclipse occurs when the Moon passes between the Sun and Earth so that the Moon's shadow touches Earth. The photo shows what the eclipse looks like from Earth. right: Source: S. E. Schneider

Q: Sometimes you see clouds after sunset that are lit red. How is this like the red color you see on the totally eclipsed Moon?

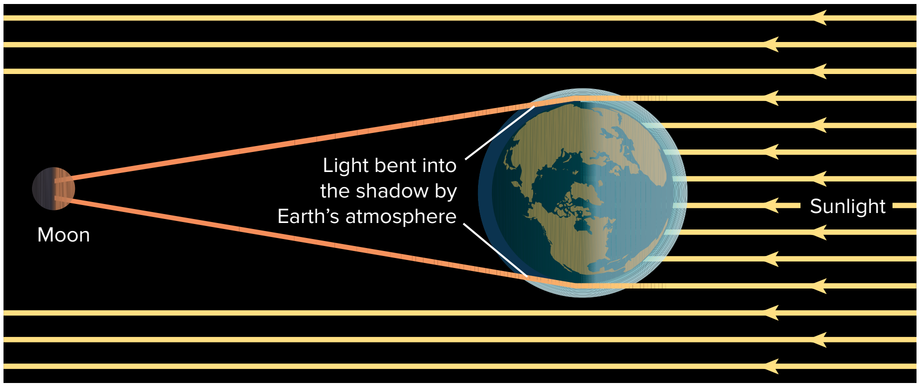


FIGURE 1.23
As sunlight falls on Earth, some passes through Earth's atmosphere and is slightly bent so that it ends up in Earth's shadow. In its passage through our atmosphere, most of the blue light is removed, leaving only the red. That red light then falls on the Moon, giving it its ruddy color at totality.

Be extremely careful when watching a partial solar eclipse. Looking at the Sun through improper filters will blind you. A safer way is to *not* look directly at the Sun but to use eyepiece projection to view the Sun. Hold a piece of paper about a foot from the eyepiece of a small telescope (or even binoculars), and a large image of the Sun will be visible on it. This method also allows many people to watch the eclipse simultaneously.

It is far rarer to see a total solar eclipse because the Moon's shadow on Earth is quite small. In fact, you are unlikely to ever see a total solar eclipse in your lifetime unless you travel to see it, because on average they occur in any location only once every several centuries. A total solar eclipse begins with a small black "bite" taken out of the Sun's edge as the Moon begins to move in front of it (fig. 1.24A). Over the next hour or so, the Moon gradually covers over more and more of the Sun. While the Sun is only partially covered, you must be careful when viewing it, so you don't hurt your eyes. If you are fortunate enough to be at a location where the eclipse is total, you will see one of the most amazing sights in nature.

As totality approaches, when the Moon's disk completely covers the Sun, the landscape takes on an eerie light. Shadows become incredibly sharp and black: even individual hairs on your head cast crisp shadows. Sunlight filtering through leaves creates tiny bright crescents on the ground. Seconds before totality, pale ripples of light sweep across the ground, and to the west the deep purple shadow of the Moon hurtles toward you at more than 1000 miles per hour. In one heartbeat you are plunged into darkness. Overhead, the sky is black, and stars become visible. Perhaps a solar prominence—a tiny, glowing, red flamelike cloud in the Sun's atmosphere—may protrude beyond the Moon's black disk (fig. 1.24C). The corona of the Sun—its outer atmosphere—gleams with a steely light around the Moon's black disk (fig. 1.24D). Birds call as if it were evening. A deep chill descends, because for a few minutes the Sun's warmth is blocked by the Moon. The horizon takes on sunset colors: the deep blue of twilight with perhaps a distant cloud in our atmosphere glowing orange. As the Moon continues in its

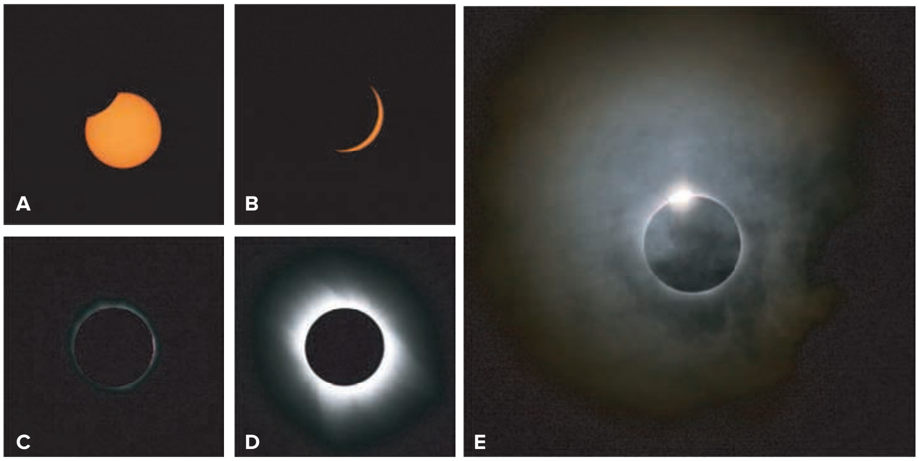
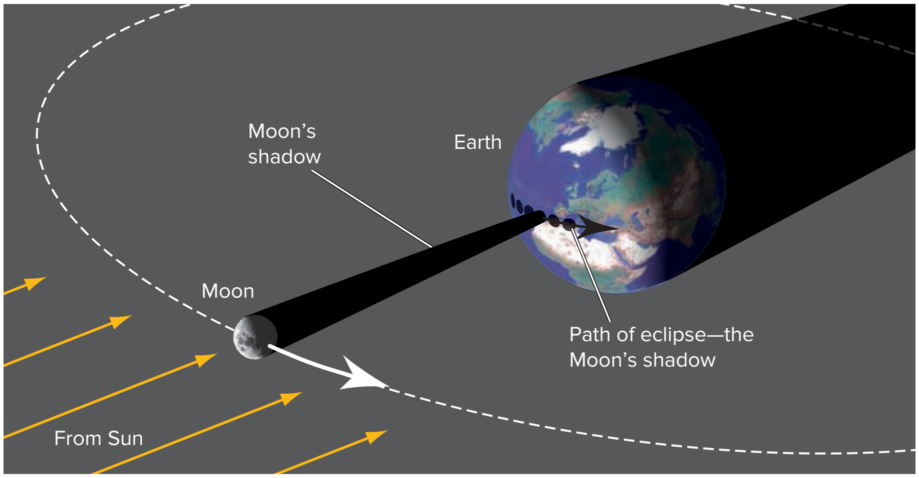
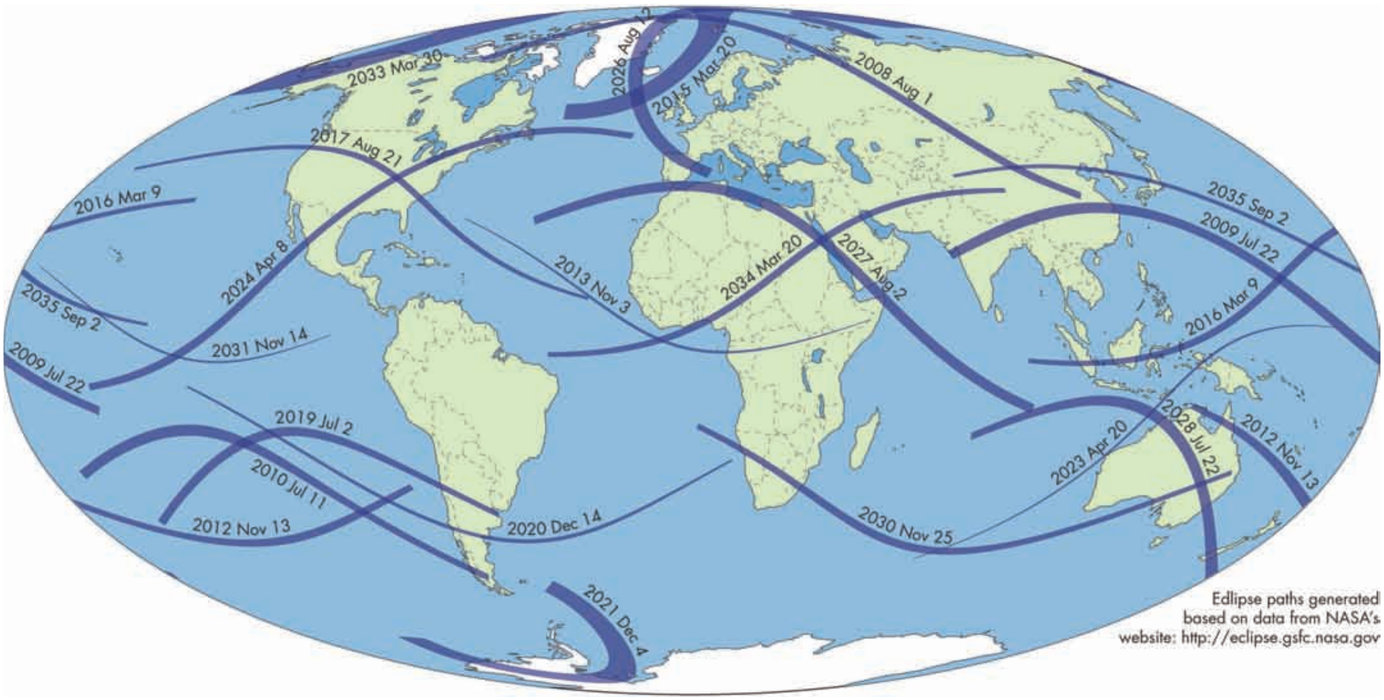


FIGURE 1.24
Pictures of a total solar eclipse in 2010. (A) One hour before totality, the Moon only partially eclipses the Sun. (B) About 5 minutes before totality. (C) With the bright part of the Sun covered, the Sun's glowing pink atmosphere becomes visible. (D) Faint hot gases form a corona around the Sun. (E) As the Moon slides off the Sun, the first glimpse of the bright portion of the Sun makes a "diamond ring," while thin clouds in Earth's atmosphere are colored by optical phenomena.
a-e: Source: S. E. Schneider



A



B

FIGURE 1.25
(A) When the Moon casts a shadow on Earth, the Moon's orbit shifts it from west to east along a narrow line. (B) The locations of recent and upcoming total solar eclipses are shown through 2035. The paths show where totality can be observed. In regions outside of these paths, a partial eclipse may be visible. b: Map by S. E. Schneider based on data from NASA's website. http//eclipse.gsfc.nasa.gov

Q: According to the map, when will the next total solar eclipse occur after 2017 in North America? In South America?

orbit, it begins to uncover the Sun, and in the first moments after totality, the partially eclipsed Sun looks a little like a diamond ring (fig. 1.24E). Now the cycle continues in reverse. The sky rapidly brightens, and the shadow of the Moon, racing away to the east, may be glimpsed on distant clouds or mountains.

Total solar eclipses can be seen only within a narrow path on Earth where the Moon's shadow crosses Earth. Because the Moon is physically smaller than the Sun, the Moon's shadow grows narrower farther from the Moon (fig. 1.25A), and is at most a few hundred kilometers wide at the distance of Earth. The locations of the paths of totality are shown for total eclipses from 2008 to 2035 in figure 1.25B. The first total solar eclipse visible in the continental United States since 1979 occurred in 2017, and the next two in 2024 and 2045. If you ever have the chance to travel to the path of totality, do it!

Sometimes the Moon is so far away that its shadow does not reach Earth. What we see when this happens is that the Moon does not completely cover the Sun, even though it is precisely in line with the Sun. An example is shown in figure 1.26, where a ring of sunlight is seen as the Sun is setting. This is called an **annular eclipse** because it leaves an *annulus* of the Sun's surface still visible.

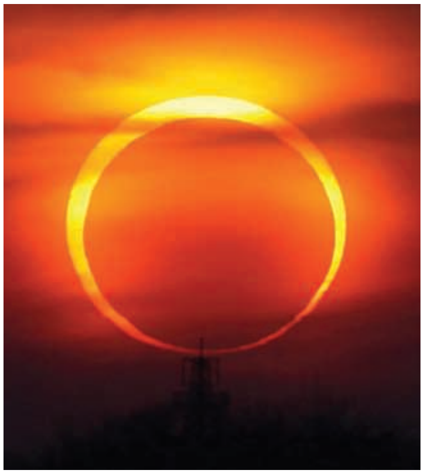


FIGURE 1.26
An annular eclipse of the Sun on January 15, 2010 occurring near sunset in Qingdao, China. The Moon is at a distant point in its orbit, so it appears smaller and cannot block the Sun entirely. ©VCG/Getty Images

Rarity of Eclipses

Total lunar and solar eclipses occur only once every year or two on average, while partial eclipse occur about twice as often. Eclipses do not occur every lunar month because the Moon's orbit is tilted with respect to Earth's orbit. Because of this tilt, even if the Moon is new, the Moon's shadow may pass above or below Earth, as you can see in figure 1.27A, which shows the Moon and Earth and their shadows drawn to scale. Similarly, when the Moon is full, Earth's shadow may pass above or below the Moon so that again no eclipse occurs. Only a nearly exact alignment of the Moon, Sun, and Earth leads to eclipses.

The tilt of the Moon's orbit remains nearly fixed—like that of the spinning Earth—by a gyroscopic effect or, more technically, by the conservation of angular momentum. The result is that as Earth orbits the Sun, twice each year, the Moon's orbital plane (if extended) passes through the Sun, as shown in figure 1.27B. For a little more than a month at those times there are **eclipse seasons** when the new and full moons will be close enough to the ecliptic for an eclipse to occur. In 2017 the eclipse seasons were during February and August. Only at those times could eclipses happen: in other months, the shadows of Earth and the Moon fell on empty space. You can also see from figure 1.27B that when a solar eclipse occurs at new moon, conditions are right for a lunar eclipse to happen at either the previous or the following full moon. Thus, eclipses often occur in pairs (and sometimes even triplets) with a solar eclipse

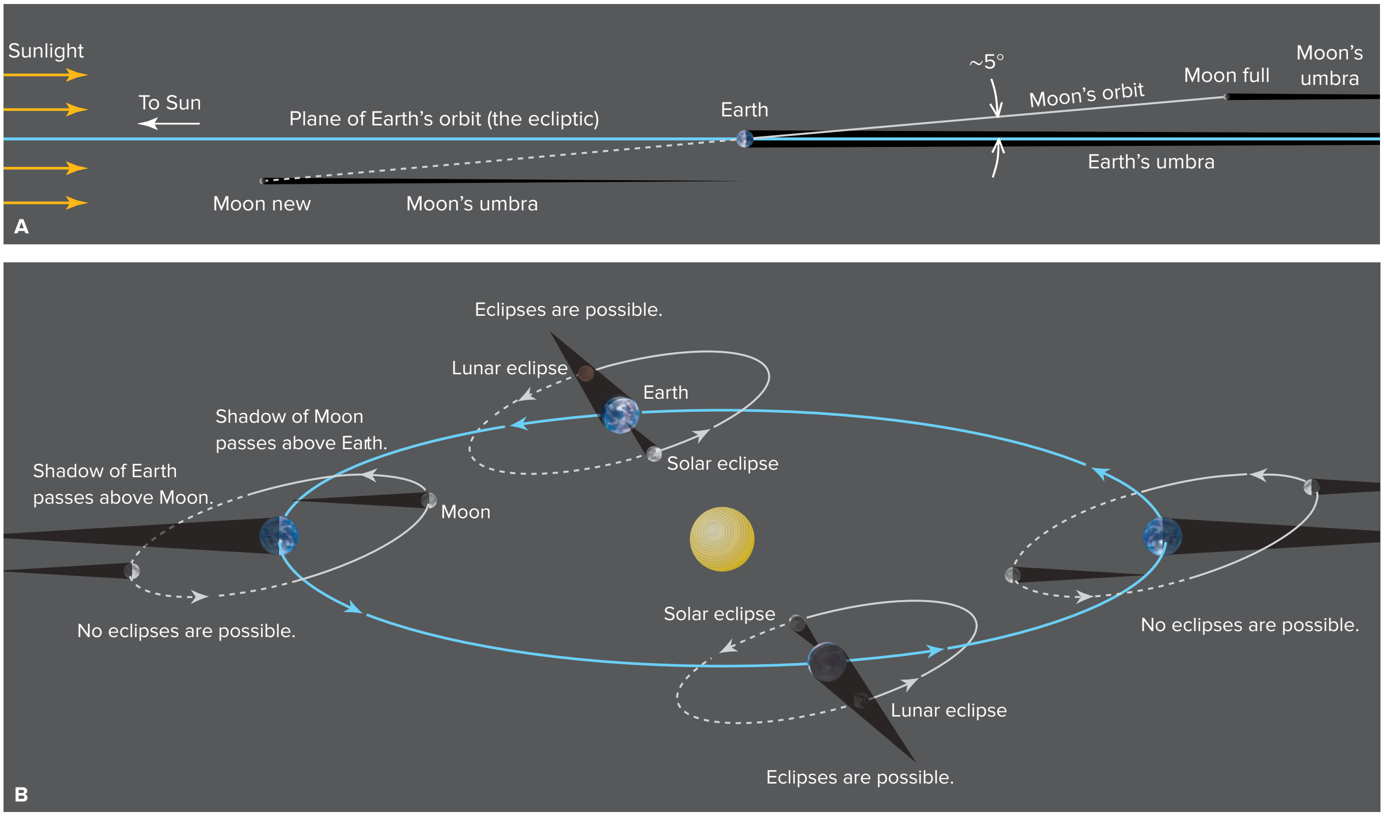


FIGURE 1.27
(A) The Moon and Earth are drawn to correct relative size and separation, with their orbits seen here edge-on. The Moon's orbit around Earth is tilted by about 5° with respect to Earth's orbit around the Sun (the ecliptic) so their shadows are usually cast above or below each other. (B) The Moon's orbit keeps approximately the same orientation as Earth orbits the Sun. Because of its orbital tilt, the Moon generally is either above or below Earth's orbit. Thus, the Moon's shadow can only hit Earth, and Earth's shadow can hit the Moon during "eclipse seasons," when Earth is in either of two places in its orbit, about 6 months apart. These occur where the Moon's orbital plane crosses the ecliptic during a new or full moon.

Table 1.1 Some Upcoming Solar and Lunar Eclipses

Solar Eclipses			Lunar Eclipses		
2019 July 2	Total	S. Pacific, Chile, Argentina	**2018 July 27**	Total	S. America, Europe, Africa, Asia, Australia
2019 December 26	Annular	Saudi Arabia, India, Sumatra, Borneo	**2019 January 21**	Total	Asia, Australia, Pacific, N. America
2020 June 21	Annular	Central Africa, South Asia, China	**2019 July 16**	Partial	S. America, Europe, Africa, Asia, Australia
2020 December 14	Total	S. Pacific, Chile, Argentina, S. Atlantic	**2021 May 26**	Total	Asia, Australia, Pacific, Americas
2021 June 10	Annular	Canada, Greenland, Russia	**2021 November 19**	Partial	Americas, Europe, Asia, Aus., Pacific
2021 December 4	Total	Antarctica	**2022 May 16**	Total	Americas, Europe, Africa
2023 April 20	Annular/Total	Australia, Indonesia	**2022 November 8**	Total	Asia, Australia, Pacific, Americas
2023 October 14	Annular	U.S.A., Central America, Colombia, Brazil	**2023 October 28**	Partial	Americas, Europe, Africa, Asia, Australia

Source: NASA's eclipse website. http//eclipse.gsfc.nasa.gov

followed approximately 14 days later by a lunar eclipse, or vice versa. This can be seen in table 1.1 where several upcoming solar and lunar eclipses are listed.

ANIMATION

Eclipses and the Moon's orbital inclination

Precession of the Moon's Orbit

Eclipse seasons do not always remain in the same months, because the orientation of the Moon's orbit does not remain exactly the same over time. The plane of the orbit slowly changes direction, as illustrated in figure 1.28. That is, the Moon's orbit *precesses,* swinging once around about every 18.6 years. This orbital **precession** makes the dates of the eclipse seasons shift by 1/18.6 of a year (about 20 days) each year. Thus, eclipses occurred about 3 weeks earlier in 2015, on average, than in 2014.

If one of the eclipse seasons begins in early January with the next in June, a third eclipse season will begin in late December. As a result, as many as seven eclipses, solar and lunar combined, can occur each year. No matter when the eclipse season falls, at least two solar and two lunar eclipses must happen each year. However, on average only about half of the lunar eclipses will be visible at any particular location, and a far smaller fraction of the solar eclipses. Most of these eclipses are partial and go unnoticed even where they are visible, so when you get an opportunity to see a total eclipse, don't miss it!

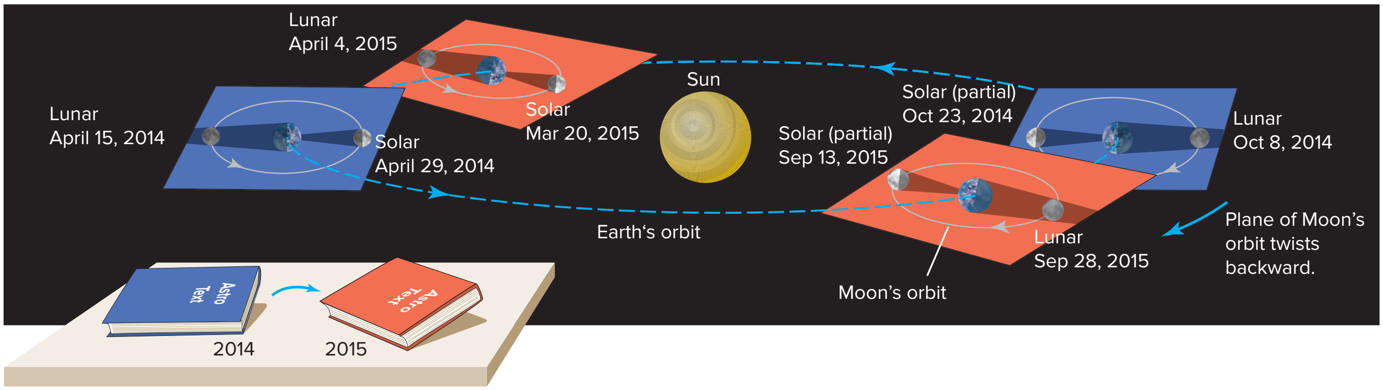


FIGURE 1.28
Precession of the Moon's orbit causes eclipses to come a few weeks earlier (on average) each year. The shift of the orbital plane is similar to twisting a tilted book that has one edge resting on a table, as illustrated in the inset diagram. (Sizes and separations are not to scale.)

SUMMARY

The night sky looks like a giant dome, which we model as part of a *celestial sphere*. Star patterns on the celestial sphere are called constellations. According to this model, stars rise in the east and set in the west as the celestial sphere rotates around Earth. This apparent motion is actually caused by Earth's spin.

The Sun's glare hides the stars behind it. However, as Earth orbits the Sun, the Sun changes its position with respect to the stars, making different constellations visible at different times of year. The path that the Sun follows around the celestial sphere is called the ecliptic, and the 12 constellations close to the ecliptic are called the zodiac.

The ecliptic is tipped at an angle of 23.5° to the celestial equator because Earth's rotation axis is tipped by that amount with respect to its orbit. The solstices and equinoxes mark when the Sun reaches its maximum angle from the celestial equator and when it crosses the equator, respectively. These dates define the onsets of the seasons.

Earth's spin keeps its rotation axis pointing in nearly a fixed direction as we orbit the Sun. Because the axis is tipped, the Sun shines more directly on the Northern Hemisphere for half the year and on the Southern Hemisphere for the other half of the year. This difference in exposure to the Sun's light and warmth creates the seasons.

Ancient peoples built monuments to trace the motions of the Sun through the seasons. They also tracked the position of the Moon, which moves through a cycle of phases every 29.5 days. The plane of the Moon's orbit around Earth is at a small angle to Earth's orbital plane around the Sun (the ecliptic). When a new or full Moon is close to the ecliptic, there can be a solar or lunar eclipse, respectively.

Because of the small size of the Moon relative to Earth, the full moon can be completely in Earth's shadow during a lunar eclipse, but during a solar eclipse the Moon's shadow covers only a narrow path across Earth. The dates close to when the orbital planes of the Moon and Earth cross are called eclipse seasons, which gradually shift as the orientation of the Moon's orbit changes over time.

QUESTIONS FOR REVIEW

1. (1.1) What is the celestial sphere? What are the celestial equator and the ecliptic?
2. (1.1) What is the difference between rotation and revolution?
3. (1.1/1.2) What is a constellation, and what is special about the zodiac constellations?
4. (1.2) What causes the seasons?
5. (1.3) What causes the Moon's phases?
6. (1.3) How long does it take the Moon to go through a cycle of phases?
7. (1.4) What is the difference between lunar and solar eclipses?
8. (1.4) Why aren't there eclipses each month?

THOUGHT QUESTIONS

1. (1.1) If you were standing on Earth's equator, where would you look to see the north celestial pole? Could you see this pole from Australia?
2. (1.1) Draw a sketch of Earth and a distant North Star, and show that your latitude is the angle of the north celestial pole above the northern horizon.
3. (1.1) Can you think of an astronomical reason why the zodiac may have been divided into 12 signs rather than 8 or 16?
4. (1.1) Draw sketches to show the angles setting stars would make relative to the horizon for someone watching at the equator, the north pole, and a midlatitude.
5. (1.1/1.2) When it is winter in New York, what season is it in Australia, and in Paris? If you see Orion in the evening in New York, would you see it in the evening in Australia or Paris?
6. (1.2) If the shape of Earth's orbit were unaltered but its rotation axis were shifted so that it had no tilt with respect to the orbit, how would the seasons be affected?
7. (1.2) Why does the position of sunrise along the eastern horizon change during the year?
8. (1.2) Why do we have time zones? Sketch and label a diagram to justify your answer.
9. (1.3) Provide two or three pieces of evidence you could use to explain to someone that the Moon's phases are not caused by Earth's shadow.
10. (1.3) If the Moon orbited Earth in the opposite direction, but everything else remained the same, how would the sidereal and solar months change (if at all)? Create a drawing like figure 1.19 representing this situation.

PROBLEMS

1. (1.1) If Earth turns one full rotation in approximately 24 hours, how many degrees per hour does the sky turn?
2. (1.2) From a latitude of 55°, what is the highest and lowest angle above the horizon of the noon Sun? What will the angle be on September 22?
3. (1.3) Make a sketch to calculate what times the waxing crescent moon will rise and set. Indicate the observer's location and lines of sight to the Moon for these times.
4. (1.3) Calculate how many degrees the Moon moves in its orbit in one day based on its 27.3 day period relative to the stars. Use this result and the answer to problem 1 to determine how much later the Moon rises each day.
5. (1.3/1.4) The Moon crosses down through the ecliptic every 27.21222 days ("draconic period"). Its synodic period, the period of the phases, is 29.5306 days. Show that 242 draconic periods very nearly equals 223 synodic periods. How long is this in years? What does this suggest about eclipses and why? (This match of cycles is called the saros and was used by ancient astronomers to predict eclipses.)
6. (1.4) Find how many hours it takes the Moon to move in its orbit a distance equal to Earth's diameter. (You will need to determine the speed of the Moon in its orbit. You can find values for the diameter of Earth and the radius and period

of the Moon's orbit in the appendix.) How does this relate to the time it takes for a lunar eclipse to occur?

7. (1.4) List some of the details left out of problem 6 that you would need to consider to exactly calculate the length of an eclipse. What effect would each have on the final answer?
8. (1.4) The Moon's shadow at Earth is much smaller than the Moon's diameter because the Moon is smaller than the Sun. Draw a diagram of a large circle representing the Sun and a smaller circle representing the Moon at a distance d (center to center) from the Sun. Use a straight edge to draw the conical shadow cast by the Moon where sunlight is fully blocked. Use your diagram to come up with a formula for how long the shadow is based on d and the radii of the two circles? Using their actual distances and radii, what is the length of our Moon's shadow? Discuss how this affects the duration and frequency of solar eclipses given that the Moon ranges from about 360,000 km to about 405,000 km distant from Earth.

TEST YOURSELF

1. (1.1) If you are standing at Earth's North Pole, which of the following will be directly overhead?
   (a) The celestial equator
   (b) The ecliptic
   (c) The zodiac
   (d) The north celestial pole
   (e) The Sun
2. (1.1) If you observe Polaris to be 30° above the horizon, you are at a latitude of approximately
   (a) 6.5°.
   (b) 30°.
   (c) 53.5°.
   (d) 60°.
   (e) 83.5°.
3. (1.1/1.2) For this question, choose as many answers as are correct. If Earth reversed its direction of spin,
   (a) the Sun would rise in the west and set in the east.
   (b) the seasons would be reversed.
   (c) the stars would circle Polaris clockwise.
   (d) the Moon would rise in the west and set in the east.
   (e) the Moon would rise in the east and set in the west.
4. (1.2) In the Northern Hemisphere, summertime is warmer than wintertime because
   (a) Earth's orbit is an ellipse.
   (b) the Sun is visible for more hours.
   (c) sunlight is more concentrated on the ground.
   (d) both b and c.
   (e) all the answers are true.
5. (1.2) In which of the following locations can the length of daylight range from zero to 24 hours?
   (a) Only on the equator
   (b) At latitudes closer than 23.5° to the equator
   (c) At latitudes between 23.5° and 66.5° north or south
   (d) At latitudes greater than 66.5° north or south
   (e) Nowhere on Earth
6. (1.3) If the Moon is waning gibbous in Chicago, then that night in Australia the Moon will be
   (a) waxing crescent.
   (b) waning gibbous
   (c) waxing gibbous.
   (d) waning crescent.
7. (1.3) You observe the Moon rising at 6 P.M., around sunset. Its phase is
   (a) first quarter.
   (b) new.
   (c) full.
   (d) third quarter.
8. (1.3) You observe the Moon rising at 3 P.M., a few hours before sunset. Its phase is
   (a) between new and first quarter.
   (b) between first quarter and full.
   (c) between full and third quarter.
   (d) between third quarter and new.
9. (1.3) If you see a full moon at midnight, about how long will it be until there is a new moon?
   (a) 12 hours
   (b) 3 days
   (c) 2 weeks
   (d) 6 months
10. (1.4) Figure 1.22 (right) shows an eclipse of the Sun. The black circle in the middle of the photo is
    (a) Earth's shadow on the Sun.
    (b) the Sun's shadow on the Moon.
    (c) the Moon covering the Sun.
    (d) Earth's shadow on the Moon.
    (e) a dark cloud in our atmosphere.
11. (1.4) If the Moon were to expand to twice its current diameter, we would have total solar eclipses
    (a) every month.
    (b) more often than now but less often than every month.
    (c) never.
    (d) occasionally, but less often than now.

KEY TERMS

annular eclipse, 31
celestial equator, 18
celestial poles, 17
celestial sphere, 16
constellation, 16
eclipse season, 32
ecliptic, 19
equinox, 22
horizon, 15
lunar eclipse, 29
model, 16
phase, 26
precession, 33
rotation axis, 20
solar eclipse, 29
solstice, 22
zenith, 23
zodiac, 19

FIGURE QUESTION ANSWERS

WHAT IS THIS? (chapter opening): The figure at the start of the chapter shows the Moon's shadow on Earth's surface. The shadow is usually a few hundred kilometers across. People within the region of the shadow would be able to see a total solar eclipse.

FIGURE 1.4: Counterclockwise.

FIGURE 1.23: In both cases they are lit by sunlight that has passed through our atmosphere, which has removed most of its blue light.

FIGURE 1.25: 2024 for North America; 2019 for South America.