FIFTH EDITION

21ST CENTURY ASTRONOMY

KAY | PALEN | BLUMENTHAL

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LAURA KAY • Barnard College

STACY PALEN • Weber State University

GEORGE BLUMENTHAL • University of California—Santa Cruz

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Laura Kay thanks her wife, M.P.M. She dedicates this book to her late uncle, Lee Jacobi, for an early introduction to physics, and to her late colleagues at Barnard College, Tally Kampen and Sally Chapman.

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George Blumenthal gratefully thanks his wife, Kelly Weisberg, and his children, Aaron and Sarah Blumenthal, for their support during this project. He also wants to thank Professor Robert Greenler for stimulating his interest in all things related to physics.

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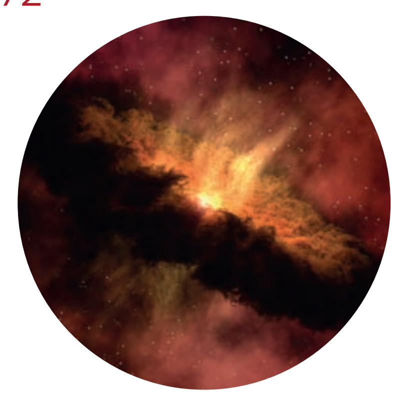
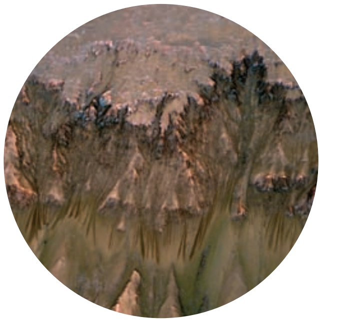
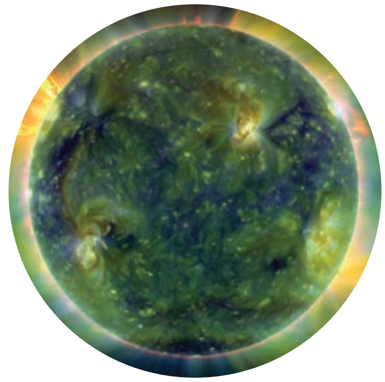
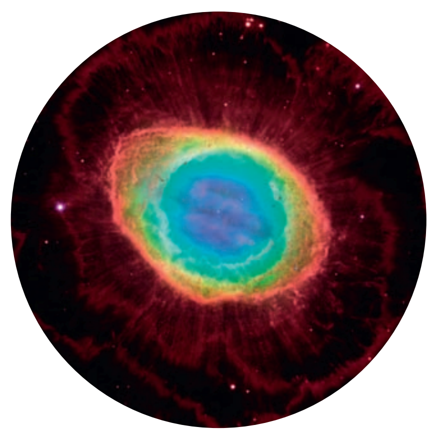
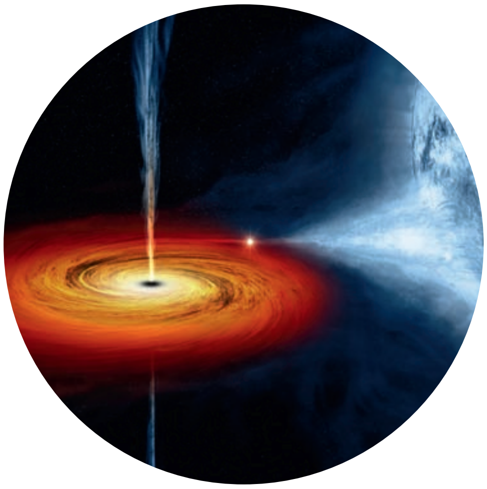










PART IV Galaxies, the Universe, and Cosmology

Working It Out

AstroTours

AstroTour animations are available from the free Student Site at the Digital Landing Page, and they are also integrated into assignable Smartwork5 exercises. Offline versions of the animations for classroom presentation are available from the Instructor's Resource USB Drive. digital.wwnorton.com/astro5.

Astronomy in Action Videos

digital.wwnorton.com/astro5

Nebraska Simulations

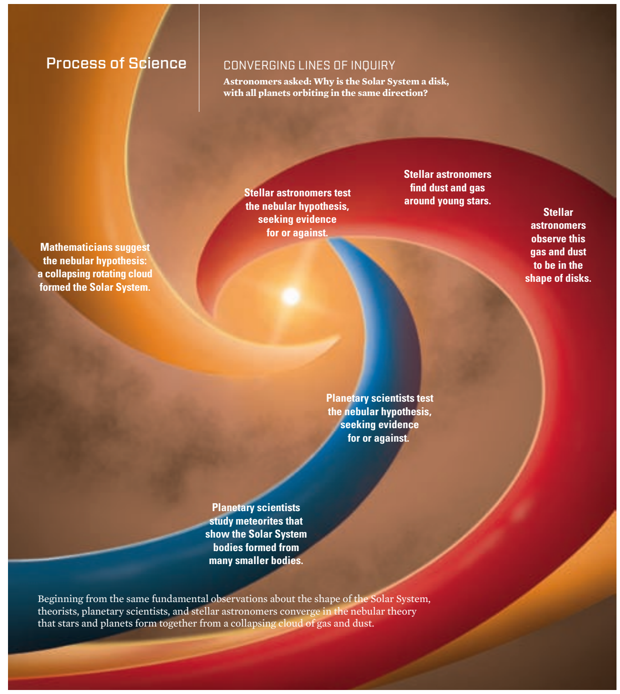
digital.wwnorton.com/astro5

Preface

Dear Student

Why is it a good idea to take a science course, and in particular, why is astronomy a course worth taking? Many people choose to learn about astronomy because they are curious about the universe. Your instructor likely has two basic goals in mind for you as you take this course. The first is to understand some basic physical concepts and how they apply to the universe around us. The second is to think like a scientist and learn to use the scientific method not only to answer questions in this course but also to make decisions in your life. We have written the fifth edition of *21st Century Astronomy* with these two goals in mind.

Throughout this book, we emphasize not only the content of astronomy (for example, the differences among the planets, the formation of chemical elements) but also *how* we know what we know. The scientific method is a valuable tool that you can carry with you and use for the rest of your life. One way we highlight the process of science is the **Process of Science Figures**. In each chapter, we have chosen one discovery and provided a visual representation illustrating the discovery or a principle of the process of science. In these figures, we try to illustrate that science is not a tidy process, and that discoveries are sometimes made by different groups, sometimes by accident, but always because people are trying to answer a question and show why or how we think something is the way it is.



The most effective way to learn something is to "do" it. Whether playing an instrument or a sport or becoming a good cook, reading "how" can only take you so far. The same is true of learning astronomy. We have written this book to help you "do" as you learn. We have created several tools in every chapter to make reading a more active process. At the beginning of each chapter, we have provided a set of Learning Goals to guide you as you read. There is a lot of information in every chapter, and the Learning Goals should help you focus on the most important points. We present a big-picture question in association with the chapter-opening figure at the beginning of each chapter. For each of these, we have tried to pose a question that is not only relevant to its chapter but also something you may have wondered about. We hope that these questions, plus the photographs that accompany them, capture your attention as well as your imagination.

In addition, there are **Check Your Understanding** questions at the end of each chapter section. These questions are designed to be answered quickly if you have understood the previous section. The answers are provided in the back of the book so you can check your answer and decide if further review is necessary.

As a citizen of the world, you make judgments about science, distinguishing between good science and pseudoscience. You use these judgments to make decisions in the grocery store, pharmacy, car dealership, and voting booth. You may base these decisions on the presentation of information you receive through the media, which is very different from the presentation in class. One important skill is the ability to recognize what is credible and to question what is not. To help you

CHECK YOUR UNDERSTANDING 7.4

Suppose that astronomers found a rocky, terrestrial planet beyond the orbit of Neptune. What is the most likely explanation for its origin? (a) It formed close to the Sun and migrated outward. (b) It formed in that location and was not disturbed by migration. (c) It formed later in the Sun's history than other planets. (d) It is a captured planet that formed around another star.


READING ASTRONOMY NEWS

ARTICLES QUESTIONS

A system with five planets was observed by NASA's Kepler space telescope.

Earth-Size Planet Found in the "Habitable Zone" of Another Star

By Science@NASA

Using NASA's Kepler space telescope, astronomers have discovered the first Earth-size planet orbiting in the "habitable zone" of another star (see Figure 7.23). The planet, named "Kepler-186f," orbits an M dwarf, or red dwarf, a class of stars that makes up 70 percent of the stars in the Milky Way Galaxy. The discovery of Kepler-186f confirms that planets the size of Earth exist in the habitable zone of stars other than our Sun.

The "habitable zone" is defined as the range of distances from a star where liquid water might pool on the surface of an orbiting planet. While planets have previously been found in the habitable zone, the previous finds are all at least 40 percent larger in size than Earth, and understanding their makeup is challenging. Kepler-186f is more reminiscent of Earth.

Kepler-186f orbits its parent M dwarf star once every 130 days and receives one-third the energy that Earth gets from the Sun, placing it nearer the outer edge of the habitable zone. On the surface of Kepler-186f, the brightness of its star at high noon is only as bright as our Sun appears to us about an hour before sunset.

"M dwarfs are the most numerous stars," said Elisa Quintana, research scientist at the SETI Institute at NASA's Ames Research Center in Moffett Field, California, and lead author of the paper published today in the journal *Science*. "The first signs of other life in the galaxy may well come from planets orbiting an M dwarf."

However, "being in the habitable zone does not mean we know this planet is habitable," cautions Thomas Barclay, a research scientist at the Bay Area Environmental Research Institute at Ames, and coauthor of the paper. "The temperature on the planet is strongly dependent on what kind of atmosphere the planet has. Kepler-186f can be thought of as an Earth-cousin rather than an Earth-twin. It has many properties that resemble Earth."

Kepler-186f resides in the Kepler-186 system, about 500 light-years from Earth in the constellation Cygnus. The system is also home to four companion planets: Kepler-186b, Kepler-186c, Kepler-186d, and Kepler-186e, whiz around their sun every four, seven, 13, and 22 days, respectively, making them too hot for life as we know it. These four inner planets all measure less than 1.5 times the size of Earth.

Although the size of Kepler-186f is known, its mass and composition are not. Previous research, however, suggests that a planet the size of Kepler-186f is likely to be rocky.

"The discovery of Kepler-186f is a significant step toward finding worlds like our planet Earth," said Paul Hertz, NASA's Astrophysics Division director at the agency's headquarters in Washington.

The next steps in the search for distant life include looking for true Earth-twins—Earth-size planets orbiting within the habitable zone of a Sun-like star—and measuring their chemical compositions. The Kepler space telescope, which simultaneously and continuously measured the brightness of more than 150,000 stars, is NASA's first mission capable of detecting Earth-size planets around stars like our Sun.

Looking ahead, Hertz said, "future NASA missions, like the Transiting Exoplanet Survey Satellite and the James Webb Space Telescope, will discover the nearest rocky exoplanets and determine their composition and atmospheric conditions, continuing humankind's quest to find truly Earth-like worlds."

ARTICLES QUESTIONS

1. This NASA press release was picked up by business and international news feeds. Why do you think coverage of this discovery was so widespread?
2. The planet is closer to its star than Earth is to the Sun yet receives much less energy. What does that imply about the temperature of the star?
3. Why is the mass of this planet not yet known? What method will be used to find its mass?
4. How will astronomers estimate the planet's composition?
5. Why is this planet called a "cousin" of Earth?

hone this skill, we have provided **Reading Astronomy News** sections at the end of every chapter. These features include a news article with questions to help you make sense of how science is presented to you. It is important that you learn to be critical of the information you receive, and these features will help you do that.

While we know a lot about the universe, science is an ongoing process, and we continue to search for new answers. To give you a glimpse of what we don't know, we provide an **Unanswered Questions** feature near the end of each chapter. Most of these questions represent topics that scientists are currently studying.

? UNANSWERED QUESTIONS

- How typical is the Solar System? Only within the past few years have astronomers found other systems containing four or more planets, and so far the observed distributions of large and small planets in these multiplanet systems have looked different from those of the Solar System. Computer simulations of planetary system formation suggest that a system with an orbital stability and a planetary distribution like those of the Solar System may develop only rarely. Improved supercomputers can run more complex simulations, which can be compared with the observations to understand better how solar systems are configured.
- How Earth-like must a planet be before scientists declare it to be "another Earth"? An editorial in the science journal *Nature* cautioned that scientists should define "Earth-like" in advance—before multiple discoveries of planets "similar" to Earth are announced and a media frenzy ensues. Must a planet be of similar size and mass, be located in the habitable zone, and have spectroscopic evidence of liquid water before we call it "Earth 2.0"?

The language of science is mathematics, and it can be as challenging to learn as any other language. The choice to use mathematics as the language of science is not arbitrary; nature "speaks" math. To learn about nature, you will need to speak its language. We don't want the language of math to obscure the concepts, so we have placed this book's mathematics in **Working It Out** boxes to make it clear when we are beginning and ending a mathematical argument, so that you can spend time with the concepts in the chapter text and then revisit the mathematics of the concept to study the formal language of the argument. You will learn to work with data and identify when data aren't quite right. We want you to be comfortable reading, hearing, and speaking the language of science, and we will provide you with tools to make it easier.

7.3 Working It Out Estimating the Radius of an Extrasolar Planet

The masses of extrasolar planets can often be estimated using Kepler's laws and the conservation of angular momentum. When planets are detected by the transit method, astronomers can estimate the radius of an extrasolar planet. In this method, astronomers look for planets that eclipse their stars and observe how much the star's light decreases during this eclipse (see Figure 7.19). In the Solar System when Venus or Mercury transits the Sun, a black circular disk is visible on the face of the circular Sun. During the transit, the amount of light from the transited star is reduced by the area of the circular disk of the planet divided by the area of the circular disk of the star:

$$\text{Percentage reduction in light} = \frac{\text{Area of disk of planet}}{\text{Area of disk of star}}$$

$$= \frac{\pi R^2_{\text{planet}}}{\pi R^2_{\text{star}}} = \frac{R^2_{\text{planet}}}{R^2_{\text{star}}}$$

Then, to solve for the radius of the planet, astronomers need an estimate of the radius of the star and a measurement of the percentage reduction in light during the transit. The radius of a star is estimated from the surface temperature and the luminosity of the star.

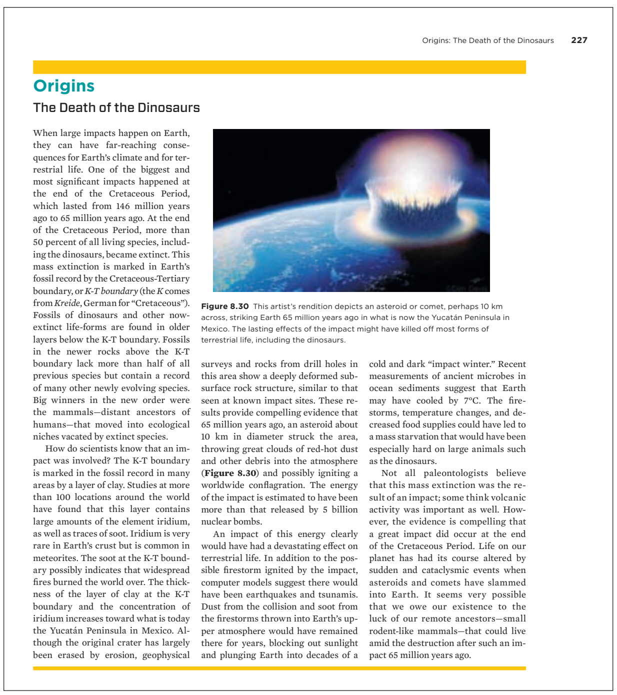
Let's consider an example. Kepler-11 is a system of at least six planets that transit a star. The radius of the star, R_{star}, is estimated to be 1.1 times the radius of the Sun, or $1.1 \times (7.0 \times 10^5\ \text{km}) = 7.7 \times 10^5\ \text{km}$. The light from planet Kepler-11c is observed to decrease by 0.077 percent, or 0.00077 (see Figure 7.19). What is Kepler-11c's size?

$$0.00077 = \frac{R^2_{\text{Kepler-11c}}}{R^2_{\text{star}}} = \frac{R^2_{\text{Kepler-11c}}}{(7.7 \times 10^5\ \text{km})^2}$$

$$R^2_{\text{Kepler-11c}} = 4.5 \times 10^8\ \text{km}^2$$

$$R_{\text{Kepler-11c}} = 2.1 \times 10^4\ \text{km}$$

Dividing Kepler-11c's radius by the radius of Earth (6,400 km) shows that the planet Kepler-11c has a radius of 3.3 R_{Earth}.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Origins

The Death of the Dinosaurs

When large impacts happen on Earth, they can have far-reaching consequences for Earth's climate and for terrestrial life. One of the biggest and most significant impacts happened at the end of the Cretaceous Period, which lasted from 146 million years ago to 65 million years ago. At the end of the Cretaceous Period, more than 50 percent of all living species, including the dinosaurs, became extinct. This mass extinction is marked in Earth's fossil record by the Cretaceous-Tertiary boundary, or *K-T boundary* (the *K* comes from *Kreide*, German for "Cretaceous"). Fossils of dinosaurs and other now-extinct life-forms are found in older layers below the K-T boundary. Fossils in the newer rocks above the K-T boundary lack more than half of all previous species but contain a record of many other newly evolving species. Big winners in the new order were the mammals—distant ancestors of humans—that moved into ecological niches vacated by extinct species.

How do scientists know that an impact was involved? The K-T boundary is marked in the fossil record in many areas by a layer of clay. Studies at more than 100 locations around the world have found that this layer contains large amounts of the element iridium, as well as traces of soot. Iridium is very rare in Earth's crust but is common in meteorites. The soot at the K-T boundary possibly indicates that widespread fires burned the world over. The thickness of the layer of clay at the K-T boundary and the concentration of iridium increases toward what is today the Yucatán Peninsula in Mexico. Although the original crater has largely been erased by erosion, geophysical surveys and rocks from drill holes in this area show a deeply deformed subsurface rock structure, similar to that seen at known impact sites. These results provide compelling evidence that 65 million years ago, an asteroid about 10 km in diameter struck the area, throwing great clouds of red-hot dust and other debris into the atmosphere (**Figure 8.30**) and possibly igniting a worldwide conflagration. The energy of the impact is estimated to have been more than that released by 5 billion nuclear bombs.

An impact of this energy clearly would have had a devastating effect on terrestrial life. In addition to the possible firestorm ignited by the impact, computer models suggest there would have been earthquakes and tsunamis. Dust from the collision and soot from the firestorms thrown into Earth's upper atmosphere would have remained there for years, blocking out sunlight and plunging Earth into decades of a cold and dark "impact winter." Recent measurements of ancient microbes in ocean sediments suggest that Earth may have cooled by 7°C. The firestorms, temperature changes, and decreased food supplies could have led to a mass starvation that would have been especially hard on large animals such as the dinosaurs.

Not all paleontologists believe that this mass extinction was the result of an impact; some think volcanic activity was important as well. However, the evidence is compelling that a great impact did occur at the end of the Cretaceous Period. Life on our planet has had its course altered by sudden and cataclysmic events when asteroids and comets have slammed into Earth. It seems very possible that we owe our existence to the luck of our remote ancestors—small rodent-like mammals—that could live amid the destruction after such an impact 65 million years ago.

Figure 8.30 This artist's rendition depicts an asteroid or comet, perhaps 10 km across, striking Earth 65 million years ago in what is now the Yucatán Peninsula in Mexico. The lasting effects of the impact might have killed off most forms of terrestrial life, including the dinosaurs.

Each chapter concludes with an **Origins** section, which relates material or subjects found in the chapter to questions about the origin of the universe and the origin of life in the universe and on Earth. Astrobiologists have made much progress in recent years on understanding how conditions in the universe may have helped or hindered the origin of life, and in each Origins we explore an example from its chapter that relates to how the universe and life formed and evolved.

At the end of each chapter, we have provided several types of questions, problems, and activities for you to practice your skills. The Test Your Understanding questions focus on more detailed facts and concepts from the chapter. Thinking about the Concepts questions ask you to synthesize information and explain the "how" or "why" of a situation. Applying the Concepts problems give you a chance to practice the quantitative skills you learned in the chapter and to work through a situation mathematically. The **Using the Web** questions and **Explorations** represent other opportunities to "learn by doing." Using the Web sends you to websites of space missions, observatories, experiments, or archives to access recent observations, results, or press releases. Other sites are for "citizen science" projects in which you can contribute to the analysis of new data.

Explorations show you how to use the concepts and skills you learned in an interactive way. Most of the book's Explorations ask you to use animations and simulations on the Student Site, while the others are hands-on, paper-and-pencil activities that use everyday objects such as ice cubes or balloons.

The resources outside of the book (at the Student Site) can help you understand and visualize many of the physical concepts described in the book. **AstroTours** and **Nebraska Simulations** are represented by icons in the margins of the book. There is also a series of short **Astronomy in Action** videos that are represented by icons in the margins and available at the Student Site. These videos feature one of the authors (and several students) demonstrating physical concepts at work. Your instructor might assign these videos to you or you might choose to watch them on your own to create a better picture of each concept in your mind.

Astronomy gives you a sense of perspective that no other field of study offers. The universe is vast, fascinating, and beautiful, filled with a wealth of objects that, surprisingly, can be understood using only a handful of principles. By the end of this book, you will have gained a sense of your place in the universe.

USING THE WEB

46. Go to the "Extrasolar Planets Global Searches" Web page (http://exoplanet.eu/searches.php) of the Extrasolar Planets Encyclopedia. Click on one ongoing project under "Ground" and one ongoing project under "Space." What method is used to detect planets in each case? Has the selected project found any planets, and if so, what type are they? Now click on one of the future projects. When will the one you chose be ready to begin? What will be the method of detection?
47. Using the exoplanet catalogs:
    a. Go to the "Catalog" Web page (http://exoplanet.eu/catalog) of the Extrasolar Planets Encyclopedia and set to "All Planets detected." Look for a star that has multiple planets. Make a graph showing the distances of the planets from that star, and note the masses and sizes of the planets. Put the Solar System planets on the same axis. How does this extrasolar planet system compare with the Solar System?
    b. Go to the "Exoplanets Data Explorer" website (http://exoplanets.org) and click on "Table." This website lists planets that have detailed orbital data published in scientific journals, and it may have a smaller total count than the website in part (a). Pick a planet that was discovered this year or last, as specified in the "First Reference" column. What is the planet's minimum mass? What is its semimajor axis and the period of its orbit? What is the eccentricity of its orbit?

EXPLORATION **Exploring Extrasolar Planets**

digital.wwnorton.com/astro5

Visit the Student Site at the Digital Landing Page, and open the Exoplanet Radial Velocity Simulator in Chapter 7. This applet has a number of different panels that allow you to experiment with the variables that are important for measurement of radial velocities. First, in the window labeled "Visualization Controls," check the box to show multiple views. Compare the views shown in panels 1–3 with the colored arrows in the last panel to see where an observer would stand to see the view shown. Start the animation (in the "Animation Controls" panel), and allow it to run while you watch the planet orbit its star from each of the views shown. Stop the animation, and in the "Presets" panel, select "Option A" and then click "set."

1 Is Earth's view of this system most nearly like the "side view" or most nearly like the "orbit view"?

2 Is the orbit of this planet circular or elongated?

3 Study the radial velocity graph in the upper right panel. The blue curve shows the radial velocity of the star over a full period. What is the maximum radial velocity of the star?

4 The horizontal axis of the graph shows the "phase," or fraction of the period. A phase of 0.5 is halfway through a period. The vertical red line indicates the phase shown in views in the upper left panel. Start the animation to see how the red line sweeps across the graph as the planet orbits the star. The period of this planet is 365 days. How many days pass between the minimum radial velocity and the maximum radial velocity?

5 When the planet moves away from Earth, the star moves toward Earth. The sign of the radial velocity tells the direction of the motion (toward or away). Is the radial velocity of the star positive or negative at this time in the orbit? If you could graph the radial velocity of the planet at this point in the orbit, would it be positive or negative?

In the "Presets" window, select "Option B" and then click "set."

6 What has changed about the orbit of the planet as shown in the views in the upper left panel?

7 When is the planet moving fastest: when it is close to the star or when it is far from the star?

8 When is the star moving fastest: when the planet is close to it or when the planet is far away?

9 Explain how an astronomer would determine, from a radial velocity graph of the star's motion, whether the orbit of the planet was in a circular or elongated orbit.

10 Study the "Earth view" panel at the top of the window. Would this planet be a good candidate for a transit observation? Why or why not?

In the "System Orientation" panel, change the inclination to 0.0.

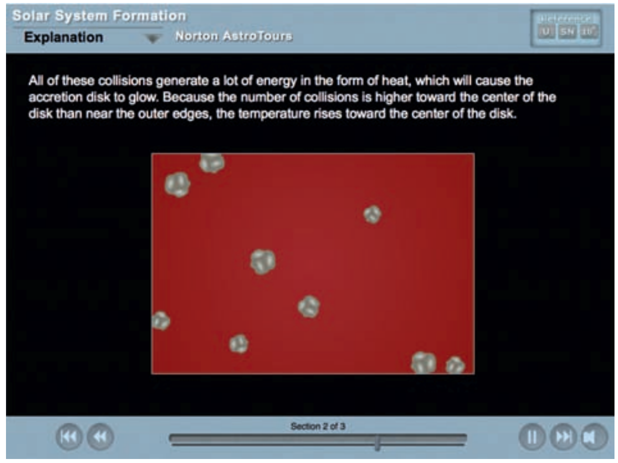
11 Now is Earth's view of this system most nearly like the "side view" or most nearly like the "orbit view"?

12 How does the radial velocity of the star change as the planet orbits?

13 Click the box that says "show simulated measurements," and change the "noise" to 1.0 m/s. The gray dots are simulated data, and the blue line is the theoretical curve. Use the slider bar to change the inclination. What happens to the radial velocity as the inclination increases? (Hint: Pay attention to the vertical axis as you move the slider, not just the blue line.)

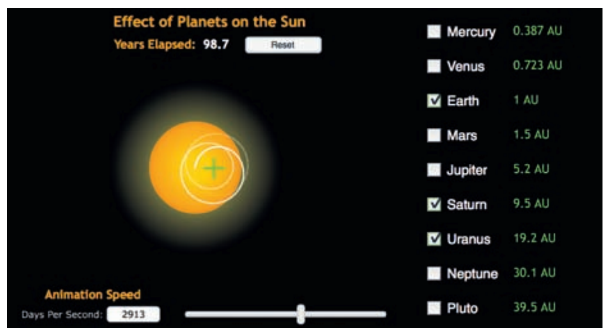
14 What is the smallest inclination for which you would find the data convincing? That is, what is the smallest inclination for which the theoretical curve is in good agreement with the data?

Student Site : digital.wwnorton.com/astro5 199



AstroTour

Astronomy in Action



Nebraska Simulation

Dear Instructor

We wrote this book with a few overarching goals: to inspire students, to make the material interactive, and to create a useful and flexible tool that can support multiple learning styles.

As scientists and as teachers, we are passionate about the work we do. We hope to share that passion with students and inspire them to engage in science on their own. Through our own experience, familiarity with education research, and surveys of instructors, we have come to know a great deal about how students learn and what goals teachers have for their students. We have explicitly addressed many of these goals and learning styles in this book, sometimes in large, immediately visible ways such as the inclusion of features but also through less obvious efforts such as questions and problems that relate astronomical concepts to everyday situations or a fresh approach to organizing material.

For example, many teachers state that they would like their students to become "educated scientific consumers" and "critical thinkers" or that their students should "be able to read a news story about science and understand its significance." We have specifically addressed these goals in our Reading Astronomy News feature, which presents a news article and a series of questions that guide a student's critical thinking about the article, the data presented, and the sources.

In nearly every chapter, we have Visual Analogy figures that compare astronomy concepts to everyday events or objects. Through these analogies, we strive to make the material more interesting, relevant, and memorable.

Education research shows that the most effective way to learn is by doing. Exploration activities at the end of each chapter are hands-on, asking students to take the concepts they've learned in the chapter and apply them as they interact with animations and simulations on the Student Site or work through pencil-and-paper activities. Many of these Explorations incorporate everyday objects and can be used either in your classroom or as activities at home. The Using the Web problems direct students to "citizen science" projects, where they can contribute to the analysis of new astronomical data. Other problems send students to websites of space missions, observatories, collaborative projects, and catalogs to access the most current observations, results, and news releases. These Web problems can be used for homework, lab exercises, recitations, or "writing across the curriculum" projects.

We also believe students should be exposed to the more formal language of science—mathematics. We have placed the math in Working It Out boxes, so it does not interrupt the flow of the text or get in the way of students' understanding of conceptual material. But we've gone further by beginning with fundamental ideas in early Working It Out boxes and slowly building in complexity through the book. We've also worked to remove some of the stumbling blocks that affect student confidence by providing calculator hints, references to earlier Working It Out boxes, and detailed, fully worked examples. Many chapters include problems on reading and interpreting graphs. Appendix 1, "Mathematical Tools," has also been reorganized and expanded.

Discussion of basic physics is contained in Part I to accommodate courses that use the *Solar System* or *Stars and Galaxies* volumes. A "just-in-time" approach to introducing the physics is still possible by bringing in material from Chapters 2–6 as needed. For example, the sections on tidal forces in Chapter 4 can be taught along with the moons of the Solar System in Part II, or with mass transfer in binary stars in Part III, or with galaxy interactions in Part IV. Spectral lines in Chapter 5 can be taught with planetary atmospheres in Part II or with stellar spectral types in Part III, and so on.

In our overall organization, we have made several efforts to encourage students to engage with the material and build confidence in their scientific skills as they proceed through the book. For planets, stars and galaxies, we have organized the material to cover the general case first and then delve into more details with specific examples. Thus, you will find "planetary systems" before our own Solar System, "stars" before the Sun, and "galaxies" before the Milky Way. This allows us to avoid frustrating students by making assumptions about what they know about stars or galaxies or forward-referencing to basic definitions and overarching concepts. This organization also implicitly helps students understand their place in the universe: our galaxy and our star are each one of many. They are specific examples of a physical universe in which the same laws apply everywhere. Planets have been organized comparatively to emphasize that science is a process of studying individual examples that lead to collective conclusions. All of these organizational choices were made with the student perspective in mind and a clear sense of the logical hierarchy of the material.

Even our layout has been designed to maximize student engagement—one wide text column is interrupted as seldom as possible. Material from the earlier edition's Connections boxes has been streamlined and incorporated into the text.

We have continued to respond to commentary from you, our colleagues. We have reorganized the material in the first half of Part IV to reflect user feedback. We begin in Chapter 19 by introducing galaxies as a whole and our measurements of them, including recession velocities. Then we address the Milky Way in Chapter 20—a specific example of a galaxy that we can discuss in detail. This follows the repeating motif of moving from the general to the specific that exists throughout the text and gives students a basic grounding in the concepts of spiral galaxies, supermassive black holes, and dark matter before they need to apply those concepts to the specific example of our own galaxy. Chapter 21, "The Expanding Universe," covers the cosmological principle, the Hubble expansion, and the observational evidence for the Big Bang.

We revised each chapter, streamlining some topics, and updating the science to reflect the progress in the field. When appropriate, we have updated the Origins sections, which often illustrate how astrobiologists and other scientists approach the study of a scientific question from the chapter related to the origin of the universe and of life. We have enhanced the material on exoplanets and incorporated material about exoplanets into other chapters when appropriate. We include new images of Mars, Ceres, Comet 67P/Churyumov-Gerasimenko, and Pluto. We note the discovery of our new home supercluster, Laniakea. We've updated the cosmology sections on the highest-redshift objects and the first stars and galaxies.

Many professors find themselves under pressure from accrediting bodies or internal assessment offices to assess their courses in terms of learning goals. To help you with this, we've revised each chapter's Learning Goals and organized the end-of-chapter Summary to correspond to the chapter's Learning Goals. In Smartwork5, questions and problems are tagged and can be sorted by Learning Goal. Smartwork5 contains more than 2,000 questions and problems that are tied directly to this text, including the Check Your Understanding questions and versions of the Reading Astronomy News and Exploration questions. Any of these could be used as a reading quiz to be completed before class or as homework. Every question in Smartwork5 has hints and answer-specific feedback so that students are coached to work toward the correct answer. An instructor can easily modify any of the provided questions, answers, and feedback or can create his or her own questions.

We've also created a series of 23 videos explaining and demonstrating concepts from the text, accompanied by questions integrated into Smartwork5. You might assign these videos prior to lecture—either as part of a flipped modality or as a "reading quiz." In either case, you can use the diagnostic feedback from the questions in Smartwork5 to tailor your in-class discussions. Or you might show them in class, to stimulate discussion. Or you might simply use them as a jumping-off point—to get ideas for activities to do with your own students.

We continue to look for better ways to engage students, so please let us know how these features work for your students.

Ancillaries for Students digital.wwnorton.com/astro5

Smartwork5

Steven Desch, Guilford Technical Community College
Violet Mager, Penn State Wilkes-Barre
Todd Young, Wayne State College

More than 2,000 questions support *21st Century Astronomy, Fifth Edition*—all with answer-specific feedback, hints, and ebook links. Questions include Check Your Understanding, Test Your Understanding, Reading Astronomy News, and versions of the Explorations (based on AstroTours and the University of Nebraska simulations). New ranking, sorting, and labeling tasks are designed to get students thinking visually. Also new to this edition, Astronomy in Action video questions focus on getting students to come to class prepared and on overcoming common misconceptions. Rounding out the Smartwork5 course, Process of Science Guided Inquiry Assignments help students apply the scientific method to important questions in astronomy, challenging them to think like scientists.

Student Site

W. W. Norton's free and open student website features the following:

- Thirty AstroTour animations. These animations, some of which are interactive, use art from the text to help students visualize important physical and astronomical concepts. All are now tablet-compatible.
- Nebraska Simulations (sometimes called applets or NAAPs, for Nebraska Astronomy Applet Programs). These simulations allow students to manipulate variables and see how physical systems work.
- Twenty-three Astronomy in Action videos that feature author Stacy Palen demonstrating the most important concepts in a visual, easy to understand, and memorable way.

Learning Astronomy by Doing Astronomy: Collaborative Lecture Activities

Stacy Palen, Weber State University
Ana Larson, University of Washington

Students learn best by doing. Devising, writing, testing, and revising suitable in-class activities that use real astronomical data, illuminate astronomical concepts, and pose probing questions that ask students to confront misconceptions can be challenging and time consuming. In this workbook, the authors draw on their experience teaching thousands of students in many different types of courses (large in-class, small in-class, hybrid, online, flipped, and so forth) to bring 30 field-tested activities that can be used in any classroom today. The activities have been designed to require no special software, materials, or equipment and to take no more than 50 minutes to do.

Starry Night Planetarium Software (College Version) and Workbook

Steven Desch, Guilford Technical Community College
Michael Marks, Bristol Community College

Starry Night is a realistic, user-friendly planetarium simulation program designed to allow students in urban areas to perform observational activities on a computer screen. Norton's unique accompanying workbook offers observation assignments that guide students' virtual explorations and help them apply what they've learned from the text reading assignments.

For Instructors

Instructor's Manual

Ben Sugerman, Goucher College

This resource includes brief chapter overviews; suggested discussion points; notes on the AstroTour animations, Nebraska Simulations, and Astronomy in Action videos contained on the Instructor Resource USB Drive (described later); and worked solutions to all end-of-chapter questions and problems, including answers to all Reading Astronomy News and Check Your Understanding questions found in the textbook.

PowerPoint Lecture Slides

Jack Hughes, Rutgers University
Jack Brockway, Radford University

These ready-made lecture slides integrate selected textbook art, all Check Your Understanding and Working It Out questions from the text, and links to the AstroTour animations. Designed with accompanying lecture outlines, these lecture slides are fully editable and are available in Microsoft PowerPoint format.

Test Bank

Joshua Thomas, Clarkson University
Parviz Ghavamian, Towson University
Adriana Durbala, University of Wisconsin–Stevens Point

The Test Bank has been revised using Bloom's Taxonomy and provides a quality bank of more than 2,400 multiple-choice and short-answer questions. Each chapter of the Test Bank consists of six question levels classified according to Bloom's Taxonomy:

Remembering
Understanding
Applying
Analyzing
Evaluating
Creating

Questions are further classified by section and difficulty, making it easy to construct tests and quizzes that are meaningful and diagnostic. The Test Bank assesses a common set of Learning Objectives consistent with the textbook and Smartwork5 online homework.

Norton Instructor's Resource Site

This Web resource contains the following resources to download:

- Test Bank, available in ExamView, Word RTF, and PDF formats
- Instructor's Manual in PDF format
- Lecture PowerPoint slides with lecture notes
- All art and tables in JPEG and PPT formats
- Starry Night College, W. W. Norton Edition, Instructor's Manual
- AstroTour animations
- Selected Nebraska Simulations
- Coursepacks, available in BlackBoard, Angel, Desire2Learn, and Moodle formats

Coursepacks

Norton's Coursepacks, available for use in various Learning Management Systems (LMSs), feature all Test Bank questions, links to the AstroTours and Nebraska Simulations, worksheets based on the Explorations and Astronomy in Action videos, and automatically graded versions of the end-of-chapter Test Your Understanding multiple-choice questions. Coursepacks are available in BlackBoard, Canvas, Desire2Learn, and Moodle formats.

Instructor Resource USB Drive

This USB drive contains all instructor resources found on the Instructor's Resource Site, including offline versions of the Astronomy in Action videos, AstroTour animations, and Nebraska Simulations.

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Laura Kay
Stacy Palen
George Blumenthal

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Ezekiel Walker, University of North Texas
James Webb, Florida International University
Paul Wiita, Georgia State University
Richard Williamon, Emory University
David Wittman, University of California–Davis

About the Authors

Laura Kay is a professor of Physics and Astronomy at Barnard College, where she has taught since 1991. She received a BS degree in physics and an AB degree in feminist studies from Stanford University, and MS and PhD degrees in astronomy and astrophysics from the University of California–Santa Cruz. As a graduate student she spent 13 months at the Amundsen Scott station at the South Pole in Antarctica. She studies active galactic nuclei, using ground-based and space telescopes. She teaches courses in astronomy, astrobiology, women and science, and polar exploration. At Barnard she has served as chair of the Physics & Astronomy Department, chair of the Women's Studies Department, chair of Faculty Governance, and interim associate dean for Curriculum and Governance.

Stacy Palen is an award-winning professor in the physics department and the director of the Ott Planetarium at Weber State University. She received her BS in physics from Rutgers University and her PhD in physics from the University of Iowa. As a lecturer and postdoc at the University of Washington, she taught Introductory Astronomy more than 20 times over 4 years. Since joining Weber State, she has been very active in science outreach activities ranging from star parties to running the state Science Olympiad. Stacy does research in formal and informal astronomy education and the death of Sun-like stars. She spends much of her time thinking, teaching, and writing about the applications of science in everyday life. She then puts that science to use on her small farm in Ogden, Utah.

George Blumenthal is chancellor at the University of California–Santa Cruz, where he has been a professor of astronomy and astrophysics since 1972. He received his BS degree from the University of Wisconsin–Milwaukee and his PhD in physics from the University of California–San Diego. As a theoretical astrophysicist, George's research encompasses several broad areas, including the nature of the dark matter that constitutes most of the mass in the universe, the origin of galaxies and other large structures in the universe, the earliest moments in the universe, astrophysical radiation processes, and the structure of active galactic nuclei such as quasars. Besides teaching and conducting research, he has served as Chair of the UC–Santa Cruz Astronomy and Astrophysics Department, has chaired the Academic Senate for both the UC–Santa Cruz campus and the entire University of California system, and has served as the faculty representative to the UC Board of Regents.

FIFTH EDITION

21ST CENTURY ASTRONOMY

1 Thinking Like an Astronomer

This is a fascinating time to be studying this most ancient of the sciences. Loosely translated, the word **astronomy** means "patterns among the stars." But modern astronomy—the astronomy we will talk about in this book—is about far more than looking at the sky and cataloging the visible stars. The contents of the universe, the origin and fate of the universe, and the nature of space and time have become the subjects of rigorous scientific investigation. Humans have long speculated about our *origins*. How and when did the Sun, Earth, and Moon form? Are other galaxies, stars, planets, and moons similar to our own? The answers that scientists are finding to these questions are changing not only our view of the cosmos but also our view of ourselves.

LEARNING GOALS

In this chapter, we will begin the study of astronomy by exploring our place in the universe and the methods of science. By the conclusion of this chapter, you should be able to:

LG 1 Describe the size and age of the universe and Earth's place in it.

LG 2 Use the scientific method to study the universe.

LG 3 Demonstrate how scientists use mathematics, including graphs, to find patterns in nature.

The first view of Earth seen from deep space. In December 1968, *Apollo 8* astronauts photographed Earth above the Moon's limb. ▶▶▶

What is your cosmic address?

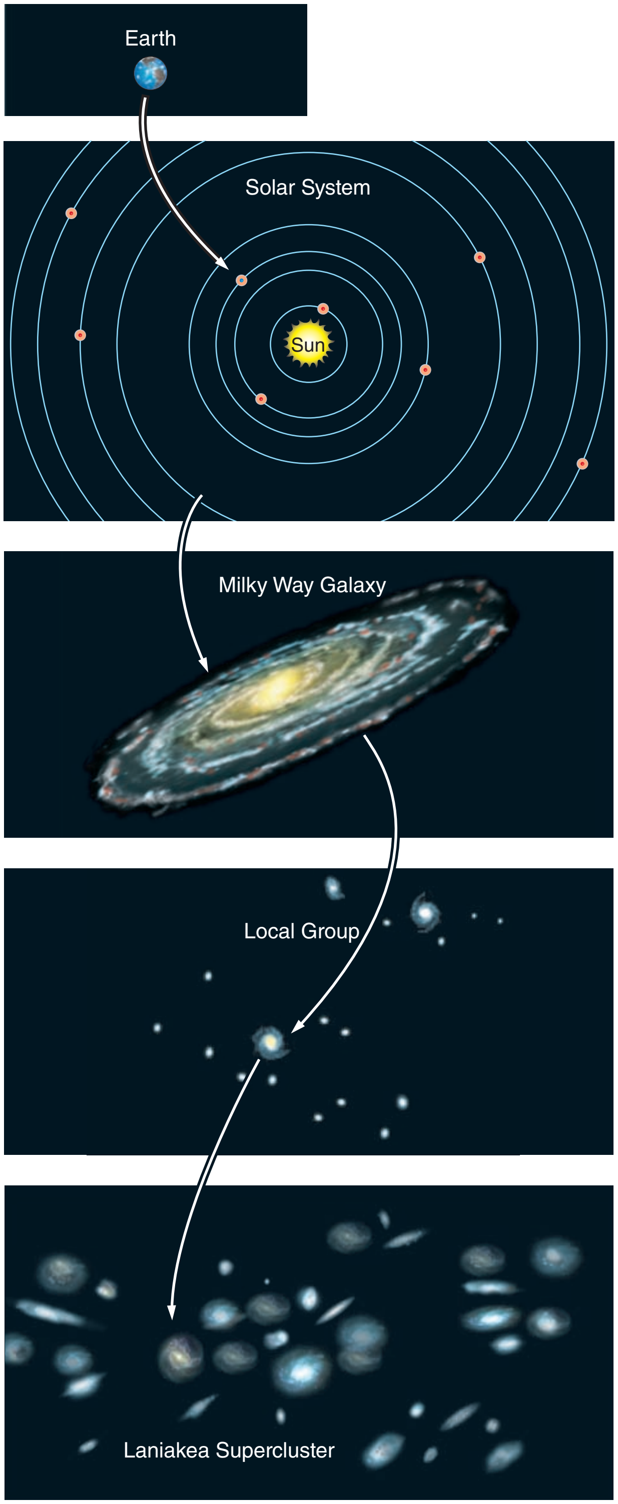


Figure 1.1 Our cosmic address is Earth, Solar System, Milky Way Galaxy, Local Group, Laniakea Supercluster. We live on Earth, a planet orbiting the Sun in our Solar System, which is a star in the Milky Way Galaxy. The Milky Way is a large galaxy within the Local Group of galaxies, which in turn is located in the Laniakea Supercluster.

1.1 Earth Occupies a Small Place in the Universe

Astronomers contemplate our place in the universe by studying Earth's position in space and time. Locating Earth in the larger universe is the first step in learning the science of astronomy. In this section, you will get a feel for the neighborhood in which Earth is located. You will also begin to explore the scale of the universe in space and time.

Our Place in the Universe

Most people receive their postal mail at an address—building number, street, city, state, and country. We can expand our view to include the enormously vast universe we live in. What is our "cosmic address"? We reside on a planet called Earth, which is orbiting under the influence of gravity around a star called the Sun. The **Sun** is a typical, middle-aged star and seems extraordinary only because of its importance to us within our own **Solar System**. Our Solar System consists of eight planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. It also contains many smaller bodies, such as dwarf planets, asteroids, and comets. All of these objects are bound to the Sun by gravity.

The Sun is located about halfway out from the center of the **Milky Way Galaxy**, a flattened collection of stars, gas, and dust. Our Sun is just one among several hundred billion stars scattered throughout our galaxy, and many of these stars are themselves surrounded by planets.

The Milky Way is a member of a collection of a few dozen galaxies called the **Local Group**. Most galaxies in this group are much smaller than the Milky Way. Looking farther outward, the Local Group is part of a vastly larger collection of thousands of galaxies—a **supercluster**—called the Laniakea Supercluster. There are millions of superclusters in the observable universe.

We can now define our cosmic address—Earth, Solar System, Milky Way Galaxy, Local Group, Laniakea Supercluster—as illustrated in **Figure 1.1**. Yet even this address is not complete, as the Laniakea Supercluster encompasses only the *local universe*. The part of the universe that we can see—the *observable universe*—extends to 50 times the size of Laniakea in every direction. Within this volume, there are about as many galaxies as there are stars in the Milky Way—several hundred billion. The universe is not only much larger than the local universe but also contains much more than the observed planets, stars, and galaxies. Up to 95 percent of the mass of the universe is made up of matter that does not interact with light, known as *dark matter*, and a form of energy that permeates all of space, known as *dark energy*. Neither of these is well understood, and they are among the many exciting areas of research in astronomy.

The Scale of the Universe

As you saw in Figure 1.1, the size of the universe completely dwarfs our human experience. We can start by comparing astronomical sizes and distances to something more familiar. For example, the diameter of our Moon is about equal to the distance between the offices of the first two authors of this book, in New York, New York, and Ogden, Utah (**Figure 1.2a**). The distance from Earth to the Moon is about 100 times the Moon's diameter, and the planet Saturn with its majestic rings would fill much of that distance (Figure 1.2b). The distance from Earth to the Sun is about 400 times the Earth–Moon distance, and the distance to the planet Neptune is about 30 times the Earth–Sun distance.

But as we move out from the Solar System to the stars, the distances become so enormous that they are difficult to comprehend. The nearest star is about 9,000 times farther away from the Sun than the Sun's distance to the planet Neptune. The diameter of our Milky Way Galaxy is 30,000 times the distance to that nearest star. The Andromeda Galaxy, the nearest similar large galaxy to the Milky Way, is about 600,000 times farther away than that nearest star. The diameter of the Local Group of galaxies is about 4 times the distance to Andromeda, and the diameter of the recently identified Laniakea Supercluster, which includes the Local Group and many other galaxy groups, is 50 times larger than the Local Group. As noted earlier, this is just one of millions of superclusters in the observable universe.

To get a better sense of these distances, imagine a model in which the objects and distances in the universe are 1 billion times smaller than they really are. In this model, Earth is about the size of a marble or a peanut M&M (about 1.3 centimeters, or half an inch), the Moon is 38 centimeters (cm) away, and the Sun is 150 meters away. Neptune is 4.5 kilometers (km) from the Sun, and the nearest star to the Sun is about 40,000 km away (or about the length of the circumference of the real Earth). The model Milky Way Galaxy would fill the Solar System nearly to the orbit of Saturn. The distance between the model Milky Way and Andromeda galaxies would fill the Solar System 20 times farther, out beyond humanity's most distant space probe. The model Laniakea Supercluster would fill the Solar System and go about one-eighth of the way to the nearest star.

When thinking about the distances in the universe, it can be helpful to discuss the time it takes to travel to various places. If someone asks you how far it is to the nearest city, you might say 100 km or you might say 1 hour. In either case, you will have given that person an idea of how far the city is. In astronomy, the speed of a car on the highway is far too slow to be useful. Instead, we use the fastest speed in the universe—the speed of light. Light travels at 300,000 kilometers per second (km/s). Light can circle Earth, a distance of 40,000 km, in just under $\frac{1}{7}$ of a second. So we say that the circumference of Earth is $\frac{1}{7}$ of a light-second. Even relatively small distances in astronomy are so vast that they are measured in units of **light-years (ly)**: the distance light travels in 1 year, about 9.5 trillion km, or 6 trillion miles.

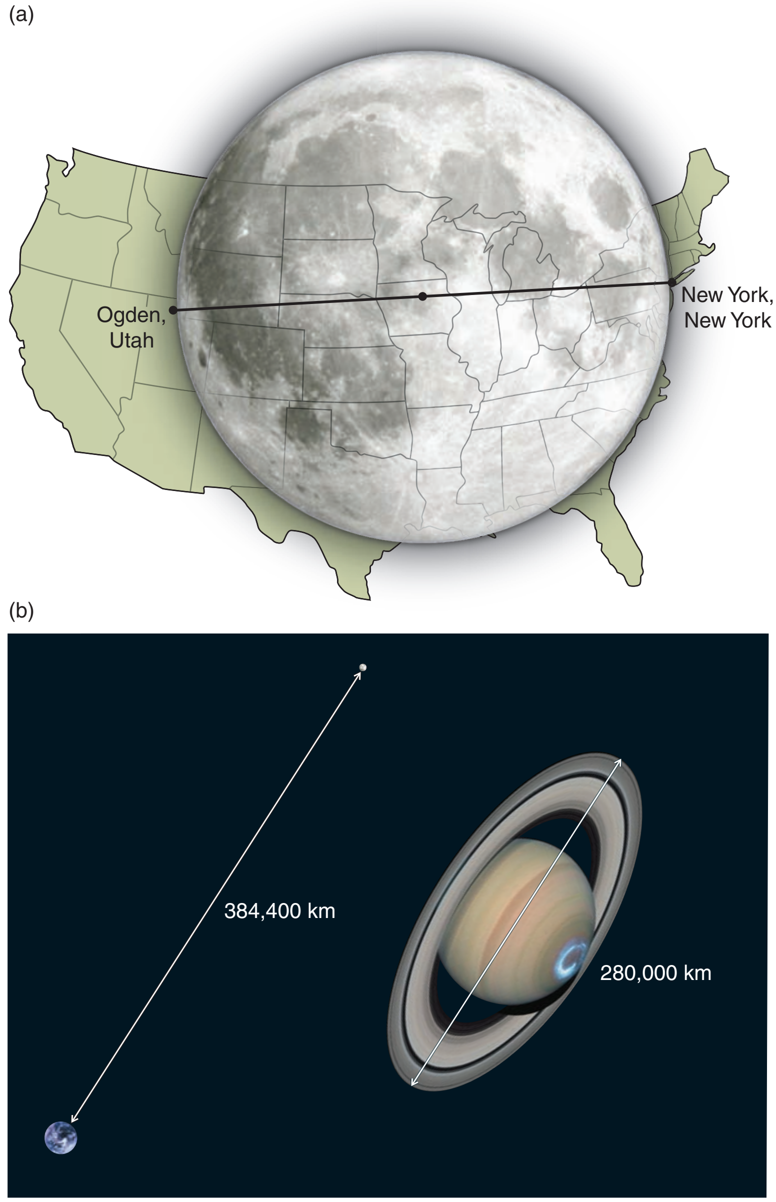


Figure 1.2 (a) The diameter of the Moon is about the same as the distance between New York, New York, and Ogden, Utah. (b) The size of Saturn, including the rings, is about 70 percent of the distance between Earth and the Moon.

Because light takes time to reach us, we see astronomical objects as they were in the past: the extent back in time depends on the object's distance from us. Because light takes $1\frac{1}{4}$ seconds to reach us from the Moon, we see the Moon as it was $1\frac{1}{4}$ seconds ago. Because light takes $8\frac{1}{3}$ minutes to reach us from the Sun, we see the Sun as it was $8\frac{1}{3}$ minutes ago. We see the nearest star as it was more than 4 years ago and objects across the Milky Way as they were tens of thousands of years ago. The light from the Virgo Cluster of galaxies has been traveling 50 million years to reach us. The light from the most distant observable objects has been traveling for almost the age of the universe—nearly 13.8 billion

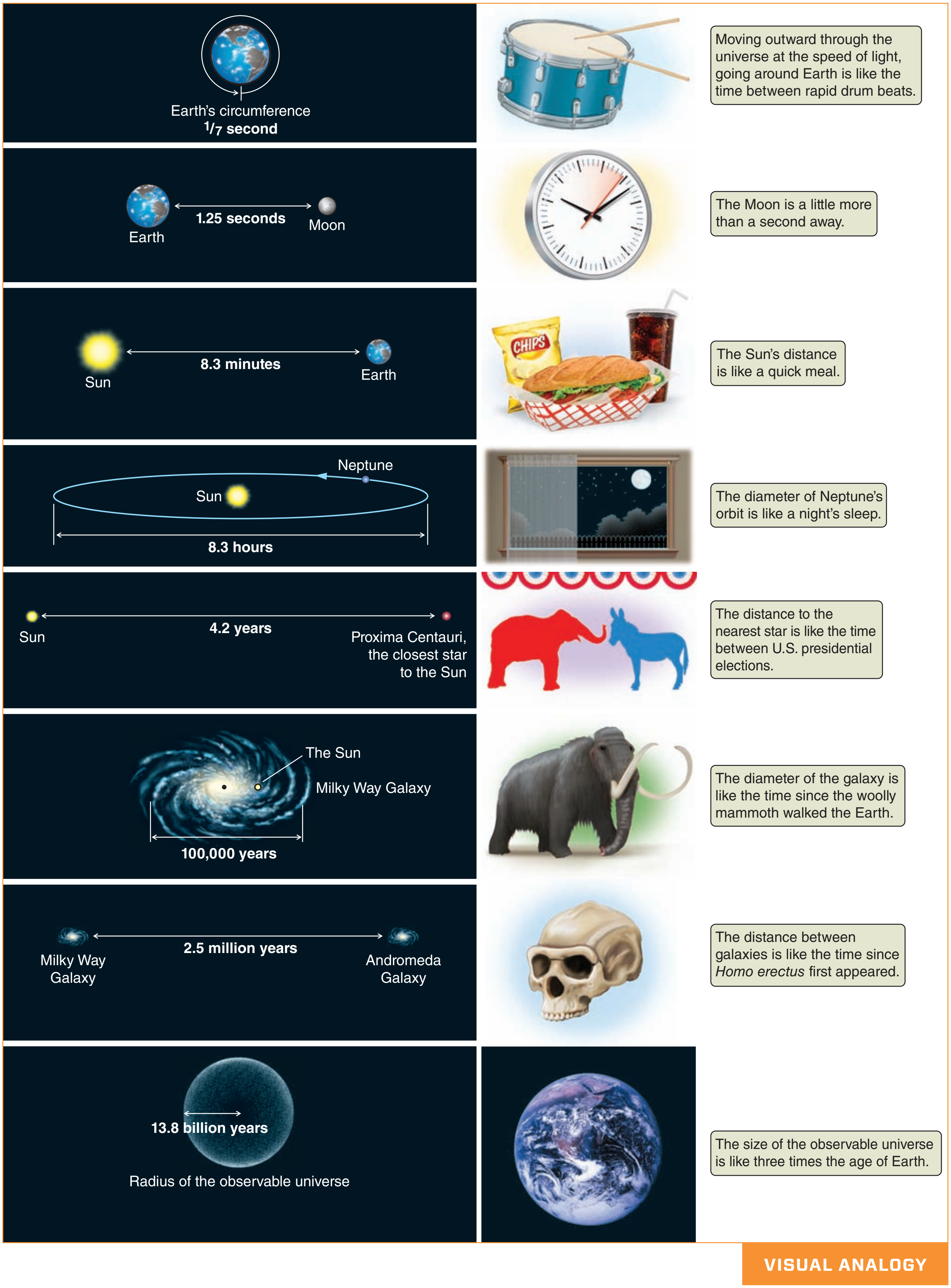


Figure 1.3 Thinking about the time it takes for light to travel between objects helps us comprehend the vast distances in the universe. (Figures such as this one, with "Visual Analogy" tags, are images that make analogies between astronomical phenomena and everyday objects more concrete.)

years. **Figure 1.3** begins with Earth and progresses outward to the observable universe.

The vast distances from Earth to other objects in the universe tell us that we occupy a very small part of the space in the universe and a very small part of time. Earth and the Solar System are only about one-third the age of the universe. Animals have existed on Earth for even less time. Imagine the age of the universe and the important events in it as if they took place within a single day, as illustrated in **Figure 1.4**. In this timeline, the Big Bang begins the cosmic day at midnight, and the original light chemical elements are created within the first 2 seconds. The first stars and galaxies appear within the first 10 minutes. Our Solar System formed from recycled gas and dust left over from previous generations of stars, at about 4 P.M. on this cosmic clock. The first bacterial life appears on Earth at 5:20 P.M., the first animals at 11:20 P.M., and modern humans at 11:59:59.8 P.M.—with only a fifth of a second to go in this cosmic day. We humans appeared quite recently in the history of the universe.

CHECK YOUR UNDERSTANDING 1.1

Rank the following in order of size: (a) a light-minute, (b) a light-year, (c) a light-hour, (d) the radius of Earth, (e) the distance from Earth to the Sun, (f) the radius of the Solar System.

1.2 Science Is a Way of Viewing the Universe

Humans have long paid attention to the sky and the stars and developed the dynamic science of astronomy. New discoveries happen frequently, and ideas about the universe are evolving rapidly. To view the universe through the eyes of an astronomer, you will need to understand how science itself works. Throughout this book, we will emphasize not only scientific discoveries but also the process of science. In this section, we will examine the scientific method.

The Scientific Method

The **scientific method** is a systematic way of testing new ideas or explanations. Often, scientists begin with a fact—an observation or a measurement. For example, you might observe that the weather changes in a predictable way each year and wonder why that happens. You then create a **hypothesis**, a testable explanation of the observation: "I think that it is cold in the winter and warm in the summer because Earth is closer to the Sun in the summer." You and your colleagues come up with a test: if it is cold in the winter and warm in the summer because Earth is closer to the Sun in the summer, then it will be cold in the winter everywhere on the planet—Australia should have winter at the same time of year as the United States. This test can be used to check your hypothesis. You travel from the United States to Australia in January and find that it is summer in Australia. Your hypothesis has just been proved incorrect, so we say that it has been **falsified**. This is different than the meaning in common usage, where one might think of "falsified" evidence as having been manipulated to misrepresent the truth. There are two important elements of your test that all scientific tests share. Your observation is reproducible: anyone who goes to Australia will find the same result.

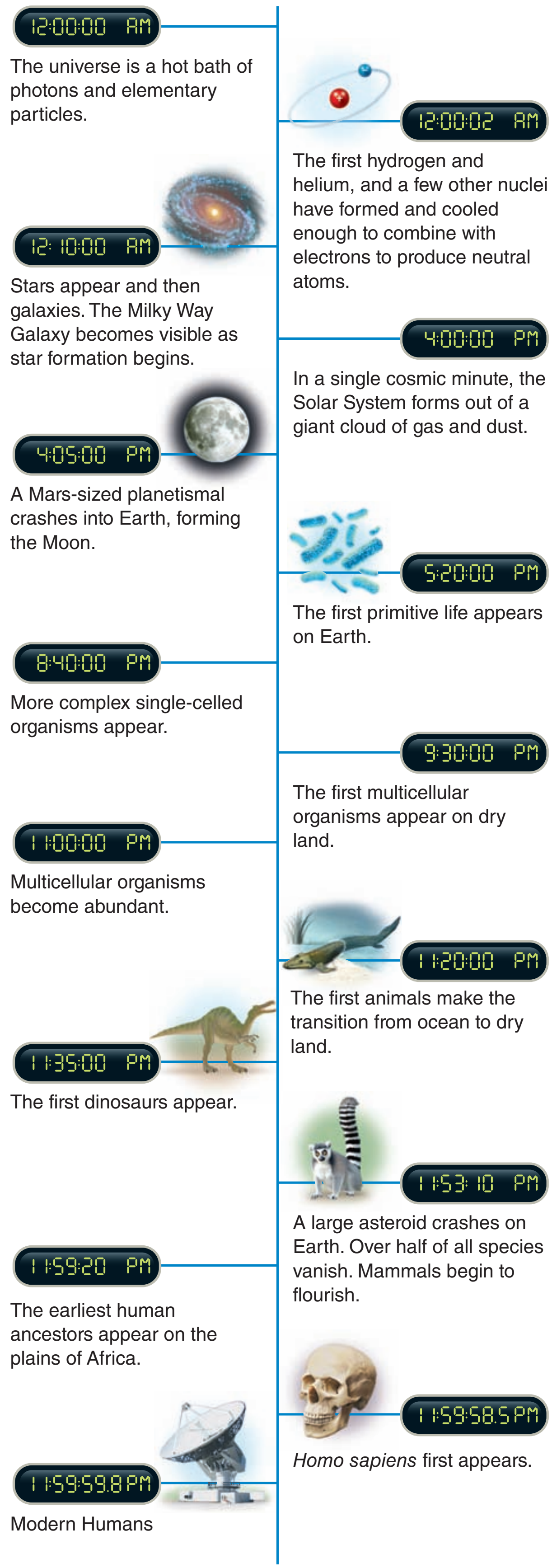


Figure 1.4 This cosmic timeline presents the history of the universe as a 24-hour day.

Nebraska Simulation: Lookback Time Simulator

Your result is also repeatable: if you conducted a similar test next year or the year after, you would get the same result. Because you have falsified your hypothesis, you must revise or completely change it to be consistent with the new data.

Any idea that is not testable—that is not falsifiable—must be accepted or rejected based on intuition alone, so it is not a scientific idea. A falsifiable hypothesis or idea does not have to be testable using current technology, but we must be able to imagine an experiment or observation that could prove the idea wrong if we could carry it out. As continuing tests support a hypothesis by failing to disprove it, scientists come to accept the hypothesis as a theory. A **theory** is a well-developed idea or group of ideas that is tied to known physical laws and makes testable predictions. As in the previous paragraph, the scientific meaning is different than the meaning in common usage. In everyday language, theory may mean a guess: "Do you have a theory about who did it?" In everyday language, a theory can be something we don't take too seriously. "After all," people say, "it's only a theory."

In stark contrast, scientists use the word *theory* to mean a carefully constructed proposition that takes into account every piece of relevant data as well as our entire understanding of how the world works. A theory has been used to make testable predictions, and all of those predictions have come true. Every attempt to prove it false has failed. A classic example is Einstein's theory of relativity, which we cover in some depth in Chapter 18. For more than a century, scientists have tested the predictions of the theory of relativity and have not been able to falsify it. Even after 100 years of verification, if a prediction of the theory of relativity failed tomorrow, the theory would require revision or replacement. As Einstein himself noted, a theory that fails only one test is proved false. In this sense, all scientific knowledge is subject to challenge.

In the loosely defined hierarchy of scientific knowledge, an *idea* is a notion about how something might be. Moving up the hierarchy we come to a *fact*, which is an observation or measurement. For example, the measured value of Earth's radius is a fact. A *hypothesis* is an idea that leads to testable predictions. A hypothesis may be the forerunner of a scientific theory, or it may be based on an existing theory, or both. At the top of the hierarchy is a *theory*: an idea that has been examined carefully, is consistent with all existing theoretical and observational knowledge, and makes testable predictions. Ultimately, the success of the predictions is the deciding factor between competing theories. A scientific *law* is a series of observations that leads to an ability to make predictions but has no underlying explanation of why the phenomenon occurs. So we might have a "law of daytime" that says the Sun rises and sets once each day. We could have a "theory of daytime" that says the Sun rises and sets once each day because Earth spins on its axis. Scientists themselves can be sloppy about the way they use these words, and you will sometimes see them used differently than we have defined them here.

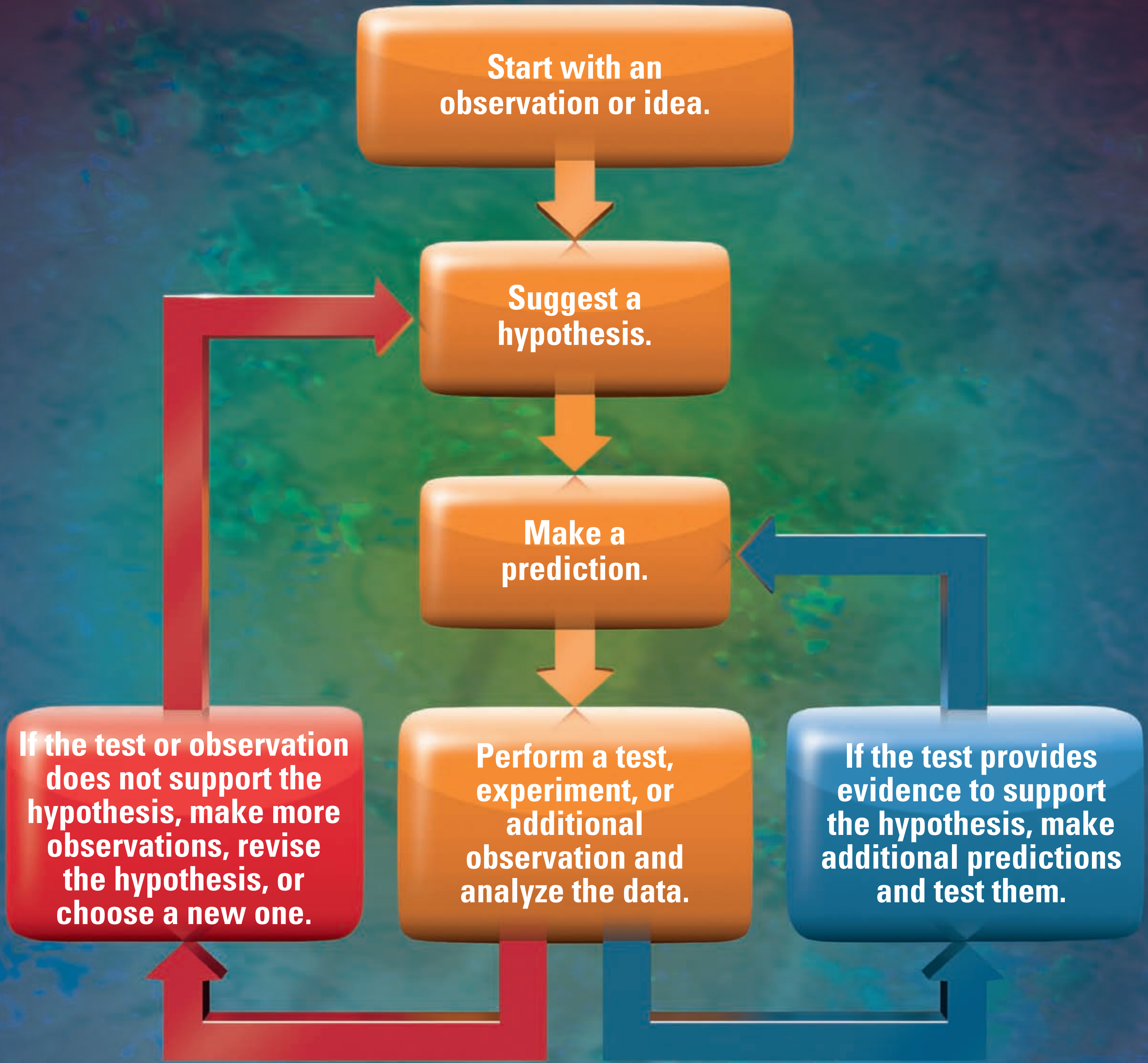
As shown in the **Process of Science Figure**, the scientific method follows a specific sequence. Scientists begin with an observation or idea, followed by careful analysis, followed by a hypothesis, followed by prediction, followed by further observations or experiments to test the prediction. A hypothesis may lead to a scientific theory, or it may be based on an existing theory, or both. Ultimately, the basis for deciding among competing theories is the success of their predictions. Scientists can use theories to take their knowledge a step further by building theoretical models. A **theoretical model** is a detailed description of the properties of a particular object or system in terms of known physical laws or theories, which are used to connect the theoretical model to the behavior of a complex system.

The construction of new theories is often guided by scientific **principles**, which are general ideas or a sense about the universe that will guide the

Process of Science

THE SCIENTIFIC METHOD

The scientific method is a formal procedure used to test the validity of scientific hypotheses and theories.



An idea or observation leads to a falsifiable hypothesis that is either accepted as a tested theory or rejected on the basis of observational or experimental tests of its predictions. The blue loop goes on indefinitely as scientists continue to test the theory.

construction of new theories. Two principles used in the study of astronomy are the *cosmological principle* and *Occam's razor*.

The **cosmological principle** is the testable assumption that the physical laws that apply here and now also apply everywhere and at all times. This principle also encompasses the assumption that there are no special locations or directions in the universe. By extension, the cosmological principle asserts that matter and energy obey the same physical laws throughout space and time as they do today on Earth. This principle means that the same physical laws that we observe and apply in laboratories on Earth can be used to understand what goes on in the centers of stars or in the hearts of distant galaxies. Each new theory that comes from applying the cosmological principle to observations of the universe around us adds to our confidence in the validity of this principle, which we will discuss in more detail in Chapter 21.

Occam's razor states that when we are faced with two hypotheses that explain all the observations equally well, we should use the one that requires the fewest assumptions until we have evidence to the contrary. For example, a hypothesis that atoms are constructed differently in the Andromeda Galaxy and in the Milky Way Galaxy would violate the cosmological principle. This hypothesis would also require a large number of assumptions to explain how atoms in the Andromeda Galaxy are constructed differently and yet still appear to behave in the same way as atoms in the Milky Way. For example, suppose you assume that the center of an atom in Andromeda is negatively charged, opposite to that in the Milky Way, where the center of an atom is positively charged. However, that assumption would require you to make an assumption about the location of the boundary between Andromeda-like matter and Milky Way–like matter and about why atoms on the boundary between the two regions did not destroy each other. You would also need an assumption about why atoms in the two regions are constructed so differently. If reasonable experimental evidence ever challenges the validity of the cosmological principle, scientists will construct a new description of the universe that takes this new data into account. Until then, the cosmological principle is the hypothesis that has the fewest assumptions, satisfying Occam's razor. To date, the cosmological principle has repeatedly been tested and remains valid.

In many sciences, researchers can conduct controlled experiments to test different hypotheses. This experimental method is often not available to astronomers: we cannot change the tilt of Earth or the temperature of a star to see what happens. Instead, astronomers work from observations or existing models. They make multiple observations using various methods and create mathematical and physical models based on established science to explain the observations.

For example, when astronomers first discovered planets orbiting other stars, these new *extrasolar planets* were most often giant gaseous planets (similar to Jupiter) in short-period orbits very close to their star. These planets are the easiest to discover because they have a strong pull on their star, as we will discuss in Chapter 7. However, their proximity to their star is completely unlike the situation in our own Solar System, where the giant planets are far from the Sun. These discoveries challenged existing ideas about how our Solar System formed. As different observers using multiple telescopes found more and more of these planets, astronomers realized they needed new explanations of planet formation to explain how such large planets could wind up so close to their star. Astronomers could not build different Solar Systems—but they could create computer simulations of planetary systems using the known laws of physics. When they did, they found that planets can migrate, moving to orbits closer to or farther from their star. Planetary scientists search for evidence to test this idea in our own Solar

System, where this may have occurred early in the life of the Sun. In this example, the observations occurred before the theory was constructed.

Alternatively, an astronomer might make predictions from an existing successful mathematical or physical model and then conduct observations and analyze data to test the predictions. One example is the discovery of black holes. In the late 18th century, two scientists hypothesized the existence of "dark stars": massive objects having such strong gravity that light could not escape. At that time, the scientists did not have a way to test this hypothesis. More than 100 years later, in the early 20th century, Karl Schwarzschild studied Einstein's relativity equations and calculated that these collapsed dark stars would be very small, with a radius of only a few kilometers. Fifty years later, these objects were named *black holes*. There was still no evidence of their existence until the 1970s and 1980s, when the new technology of space-based X-ray telescopes made possible the observations needed to test the hypothesis. Einstein's existing theory made the discovery of black holes possible.

The scientific method provides the rules for testing whether an idea is false, but it offers no insight into where the idea came from in the first place or how an experiment was designed. Scientists discussing their work use words such as *insight*, *intuition*, and *creativity*. Scientists speak of a beautiful theory in the same way that an artist speaks of a beautiful painting or a musician speaks of a beautiful performance. Science has an aesthetic that is as human and as profound as any found in the arts.

Yet science is not the same as art or music in one important respect. Whereas art and music are judged by a human jury alone, the validity of a scientific hypothesis or theory is subject to the natural world. Nature alone provides the final decisions about which theories can be kept and which theories must be discarded. It does not matter what we want to be true. In the history of science, many a beautiful and beloved theory has been abandoned.

Scientific Revolutions

Scientific inquiry is necessarily dynamic. Scientists do not have all the answers and must constantly refine their ideas in response to new data and new insights. The vulnerability of knowledge may seem like a weakness. "Gee, you really don't know anything," the cynical person might say. But this vulnerability is actually the greatest strength of the scientific process: it means that science self-corrects. Incorrect ideas are eventually overturned by new information. In science, even our most cherished ideas about the nature of the physical world remain fair game, subject to challenge by new evidence. Many of history's best scientists earned their status by falsifying a universally accepted idea. This is a powerful motivation for scientists to challenge old ideas constantly—to formulate and test new explanations for their observations.

For example, Sir Isaac Newton developed classical physics in the 17th century to explain motion, forces, and gravity. Newtonian physics (discussed in detail in Chapters 3 and 4) withstood the scrutiny of scientists for more than 200 years. Yet during the late 19th and early 20th centuries, a series of scientific revolutions completely changed our understanding of the nature of reality. The work of Albert Einstein (**Figure 1.5**) is representative of these scientific revolutions. Einstein's special and general theories of relativity replaced Newton's mechanics. Einstein did not prove Newton wrong but rather showed that Newton's theories were a special case of a far more general and powerful set of physical laws. Einstein's new ideas unified the concepts of mass and energy and destroyed the conventional notion of space and time as separate concepts.

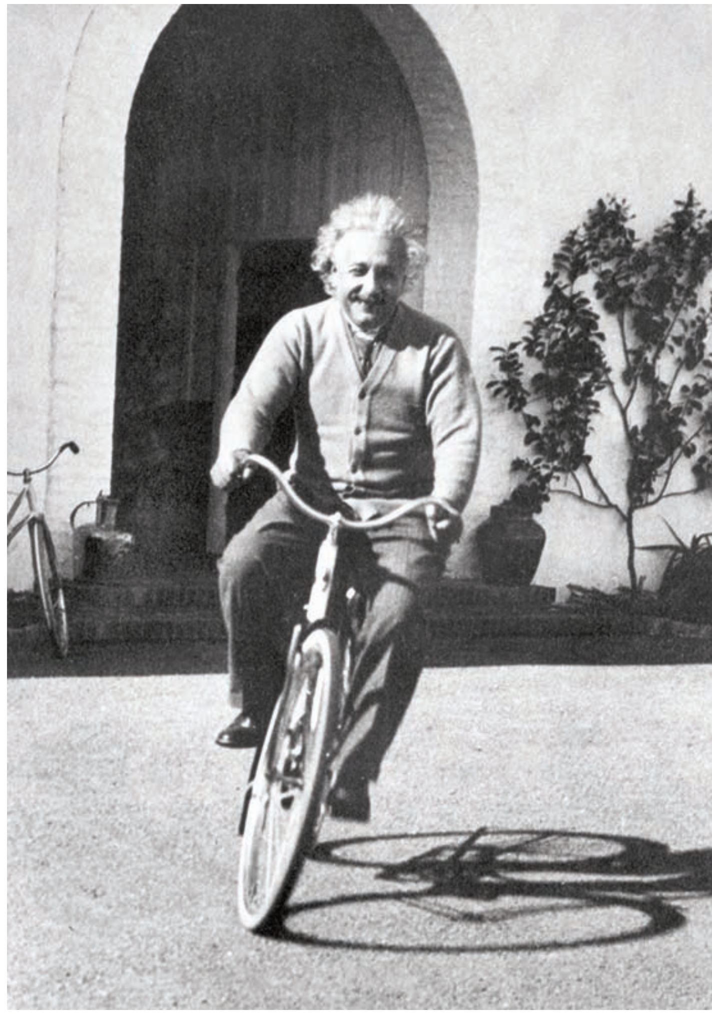


Figure 1.5 Albert Einstein is perhaps the most famous scientist of the 20th century, and he was *Time* magazine's selection for Person of the Century. Einstein helped to usher in two different scientific revolutions.

Throughout this text, you will encounter many other discoveries that forced scientists to abandon accepted theories. Einstein himself never embraced the view of the world offered by *quantum mechanics*—a second revolution he helped start. Yet quantum mechanics, a statistical description of the behavior of particles smaller than atoms, has held up for more than 100 years. In science, all authorities are subject to challenge, even Einstein.

Science is a way of thinking about the world. It is a search for the relationships that make our world what it is. Scientific inquiry assumes that nature operates by consistent, explicable, inviolate rules. Scientific knowledge is an accumulated collection of ideas about how the universe works, yet scientists are always aware that what is known today may be superseded tomorrow. A scientist assumes that there is an order in the universe and that the human mind is capable of grasping the essence of the rules underlying that order. Scientists build on these assumptions to make predictions and then test those predictions, finding the underlying rules that allow humanity to solve problems, invent new technologies, or find a new appreciation for the natural world. In the final analysis, science has found such a central place in our civilization because *science works*.

Figure 1.6 Since ancient times, people recognized that patterns in the sky change with the seasons. These and other patterns shape our lives. These star maps show the sky in the Northern Hemisphere during each season.

CHECK YOUR UNDERSTANDING 1.2

The scientific method is a process by which scientists: (a) prove theories to be known facts; (b) gain confidence in theories by failing to prove them wrong; (c) show all theories to be wrong; (d) survey what the majority of people think about a theory.

1.3 Astronomers Use Mathematics to Find Patterns

Scientific thinking allows scientists to make predictions. Once a pattern has been observed, for example the daily rising and setting of the Sun, scientists can predict what will happen next.

Imagine that the patterns in your life became disrupted, so that the world became entirely unpredictable. For example, what would life be like if you could not predict whether an object you dropped would fall up or down? Or what if one morning the Sun rises in the east and sets in the west, and the next day it rises in the west and sets in the east? In fact, objects do fall toward the ground. The Sun rises, sets, and then rises again at predictable times and in predictable locations. Spring turns into summer, summer turns into autumn, autumn turns into winter, and winter turns into spring. The rhythms of nature produce patterns in our lives, and these patterns give us clues about the nature of the physical world. Astronomers identify and characterize these patterns and use them to understand the world around us. Some of the most easily identified patterns in nature are those we see in the sky. What in the sky will look different or the same a week from now? A month from now? A year from now? As you can see in **Figure 1.6**, patterns in the sky mark the changing of the seasons. Because planting and harvesting times are determined by the seasons, it is no surprise that astronomy—which studies these patterns that are so important to agriculture—is the oldest of all sciences. We will see many other examples of patterns in the sky in the next chapter.

Astronomers use mathematics to analyze patterns and to communicate complex material compactly and accurately. Because the study of patterns in nature is so important to science, it should come as no surprise that mathematics is the language of science. Many people find mathematics to be a major obstacle that prevents them from appreciating the beauty and elegance of the world as seen through the eyes of a scientist. It is our goal in this book to explain any necessary math in everyday language. We will describe what equations mean and help you use them in a way that allows you to connect scientific concepts to the world. Your responsibility is to accept the challenge and make an honest effort to understand the material. **Working It Out 1.1** and **Working It Out 1.2** in this chapter review some basics of mathematical tools and graphs. At the back of the book, Appendix 1 explains some essential mathematical tools, and Appendix 2 contains physical constants of nature. Other appendixes contain data tables with key information about planets, moons, and stars.

CHECK YOUR UNDERSTANDING 1.3

When you see a pattern in nature, it is usually evidence of: (a) a theory being displayed; (b) a breakdown of random clustering; (c) an underlying physical law.

1.1 Working It Out Mathematical Tools

Mathematics provides scientists many of the tools that they need to understand the patterns they observe and to communicate that understanding to others. Following are a few tools that will be useful in our study of astronomy:

Scientific notation. Scientific notation is how we handle numbers of vastly different sizes. Writing out 7,540,000,000,000,000,000,000 in standard notation is very inefficient. Scientific notation uses the first few digits (the *significant* ones) and counts the number of decimal places to create the condensed form 7.54×10^{21}. Similarly, rather than writing out 0.000000000005, we write 5×10^{-12}. The exponent on the 10 is positive or negative depending on the direction that the decimal point was moved. For example, the average distance to the Sun is 149,600,000 km, but astronomers usually express it as 1.496×10^{8} km.

Ratios. Ratios are a useful way to compare things. A star may be "10 times as massive as the Sun" or "10,000 times as luminous as the Sun." These expressions are ratios.

Proportionality. Often, understanding a concept amounts to understanding the *sense* of the relationships that it predicts or describes. "If you have twice as far to go, it will take you twice as long to get here." "If you have half as much money, you will be able to buy only half as much gas." These are examples of proportionality.

Appendix 1 has a more detailed explanation of mathematical tools used in this book.

1.2 Working It Out Reading a Graph

Scientists often convey complex information and mathematical patterns in graphical form. Reading graphs is a skill that is important not only in astronomy but also in life. Economists, social and political scientists, mortgage brokers, financial analysts, retirement planners, doctors, and scientists all use graphs to evaluate and communicate important information.

Graphs typically have two axes: a horizontal axis (the *x*-axis) and a vertical axis (the *y*-axis). Typically, the *x*-axis shows an independent variable, which is the one you might have control over in an experiment. The *y*-axis shows the dependent variable, which—in many experiments—is the variable a researcher is studying.

Graphs can take different shapes. Suppose we plot the distance a car travels over a period of time, as shown in **Figure 1.7a**. In a linear graph, each interval on an axis represents the same-sized step. Each step on the horizontal axis of the graph in Figure 1.7a represents 5 minutes. Each step on the vertical axis represents a distance of 5 km traveled by the car. Data are plotted on the graph, with one dot for each observation; for example, the distance the car has traveled after 20 minutes is 20 km.

Drawing a line through these data indicates the trend of the data. To understand what the trend means, scientists often find the slope of the line, which is the relationship of the line's rise along the *y*-axis to its movement along the *x*-axis. To find the slope, we look at the change between two points on the vertical axis divided by the change between two points on the horizontal axis; for example, finding the slope of the line gives

$$\text{Slope} = \frac{\text{Change in vertical axis}}{\text{Change in horizontal axis}}$$

$$= \frac{(15 - 10)\text{ km}}{(15 - 10)\text{ min}}$$

$$= 1\text{ km/min}$$

In this case, the trend tells us that the car is traveling at 1 kilometer per minute (km/min), or 60 kilometers per hour (km/h). The slope of a line often contains extra information that is useful.

Many observations of natural processes do not result in a straight line on a graph. An example of this is an exponential process. Think about what happens when you catch a cold. When you get up in the morning at 7:00 A.M. you feel fine. At 9:00 A.M. you feel a little tired. By 11:00 A.M. you have a bit of a sore throat or a sniffle and think, "I wonder if I'm getting sick," and by 1:00 P.M. you have a runny nose and congestion and fever and chills. This is an exponential process, because the virus that has infected you reproduces exponentially.

For the sake of this discussion, suppose the virus produces one copy of itself each time it invades a cell. (In fact, viruses produce between 1,000 and 10,000 copies each time they invade a cell, so the exponential curve is actually much steeper.) One virus infects a cell and multiplies, so now there are two viruses—the original and a copy. These viruses invade two new cells, and each one produces a copy. Now there are four viruses. After the next cell invasion, there are eight. Then 16, 32, 64, 128, 256, 512, 1,024, 2,048, and so on. This behavior is plotted in Figure 1.7b.

It can be difficult to see what's happening in the early stages of an exponential curve, because the later numbers are so much larger than the earlier ones. For this reason, we sometimes plot this type of data *logarithmically*, by putting the logarithm (the power of 10) of the data on the vertical axis, as shown in Figure 1.7c. Now each step on the axis represents 10 times as many viruses as the previous step. Even though we draw all the steps the same size on the page, they represent different-sized steps in the data—the number of viruses, for example. We often use this technique in astronomy because it has a second, related advantage: very large variations in the data can easily fit on the same graph.

Each time you see a graph, you should first understand the axes—what data are plotted on this graph? Then you should check whether the axes are linear or logarithmic. Finally, you can look at the actual data or lines in the graph to understand how the system behaves.

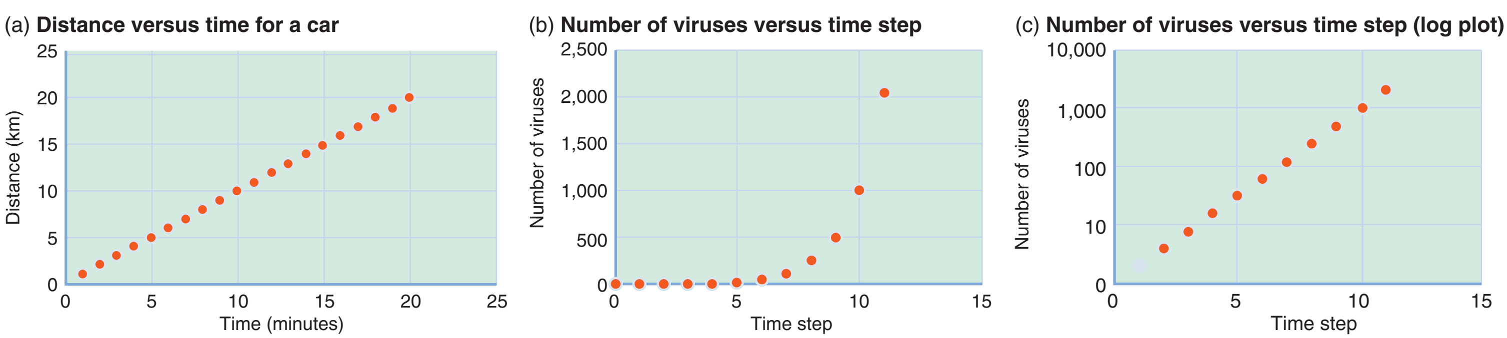


Figure 1.7 Graphs like these show relationships between quantities. (a) The time and distance traveled. (b, c) These graphs show the relationship between time and the number of viruses.

Origins

An Introduction

How and when did the universe begin? What combination of events led to the existence of humans as sentient beings living on a small rocky planet orbiting a typical middle-aged star? Are there others like us scattered throughout the galaxy?

Earlier in the chapter we mentioned the theme of origins. Throughout this book, you will see that this theme involves much more than how humans came to be on Earth. In these Origins sections, which conclude each chapter, we'll look into the origin of the universe and the origin of life on Earth. We will also examine the possibilities of life elsewhere in the Solar System and beyond—a subject called **astrobiology**. Our origins theme will include the discovery of planets around other stars and how they compare with the planets of our own Solar System.

Later in the book, we will present observational evidence that supports the **Big Bang** theory, which states that the universe started expanding from an infinitesimal size about 13.8 billion years ago. Only the lightest chemical elements were found in substantial amounts in the early universe: hydrogen and helium, and tiny amounts of lithium, and beryllium. However, we live on a planet with a central core consisting mostly of very heavy elements such as iron and nickel, surrounded by outer layers made up of rocks containing large amounts of silicon and various other elements, all heavier than the original elements. The human body contains carbon, nitrogen, oxygen, calcium, phosphorus, and a host of other chemical elements—except for hydrogen itself, all are heavier than hydrogen and helium. If these heavier elements that make up Earth and our bodies were not present in the early universe, where did they come from?

The answer to this question lies within the stars (**Figure 1.8**). In the core of a star, light elements, such as hydrogen, combine to form more massive atoms, which eventually leads to atoms such as carbon. When a star nears the end of its life, it often loses much of its material—including some of the new atoms formed in its interior—by blasting it back into interstellar space. This material combines with material lost from other stars—some of which produced even more massive atoms as they exploded—to form large clouds of dust and gas. Those clouds go on to make new stars and planets, similar to our Sun and Solar System. Prior "generations" of stars supplied the building blocks for the chemical processes that we see in the universe, including life. The atoms that make up much of what we see were formed in the cores of stars. The phrase "We are stardust" is not just poetry. We are actually made of recycled stardust.

The study of origins also provides examples of the process of science. Many of the physical processes in chemistry, geology, planetary science, physics, and astronomy that are seen on Earth or in the Solar System are observed across the galaxy and throughout the universe. But as of this writing, the only biology we know about is that existing on Earth. Thus, at this point in human history, much of what scientists can say about the origin of life on Earth and the possibility of life elsewhere is reasoned extrapolation and educated speculation. In these Origins sections, we'll address some of these hypotheses and try to be clear about which are speculative and which have been tested.

Figure 1.8 You and everything around you are composed of atoms forged in the interiors of stars that lived and died before the Sun and Earth were formed. The supermassive star Eta Carinae, shown here, is currently ejecting a cloud of chemically enriched material just as earlier generations of stars once did to enrich the gas that would become our Solar System.

ARTICLES QUESTIONS

This article illustrates how direct and indirect observations both contribute to new discoveries.

Probe Detects Southern Sea Under Ice on Saturnian Moon Enceladus

By **ALAN BOYLE, NBC News**

NASA's *Cassini* orbiter has detected the faint signature of a hidden southern ocean beneath the ice of the Saturnian moon Enceladus, confirming past suspicions and sparking fresh speculation about extraterrestrial marine life.

"It makes the interior of Enceladus a very attractive potential place to look for life," said Jonathan Lunine, a planetary scientist at Cornell University and a member of the science team reporting the discovery in this week's issue of the journal *Science*.

Astrobiologists have had Enceladus on their list since 2006, when *Cassini* detected geysers of water spewing up from fissures in the southern hemisphere (**Figure 1.9**). However, it took much more subtle observations to confirm the source.

"It was not a surprise to find a water reservoir . . . but the mass and geometry of this reservoir were unknown," Luciano Iess of Sapienza University of Rome, the *Science* study's lead author, told reporters during a teleconference.

Iess and his colleagues say the reservoir is a sea of liquid water, buried under 19 to 25 miles (30 to 40 kilometers) of ice. The sea is at least 6 miles (10 kilometers) deep and extends at least halfway up from the south pole toward the equator in every direction.

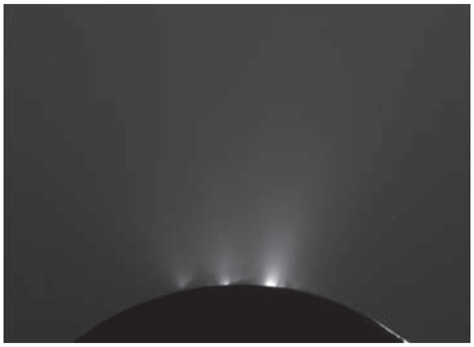


Figure 1.9 A backlit view of Enceladus from the *Cassini* orbiter shows illuminated jets of water spewing out from surface fissures.

"This means that it is as large, or larger, than Lake Superior," said Caltech's David Stevenson, another coauthor of the *Science* study.

How scientists know

It took masterful feats of observation and calculation to figure all that out.

Astronomers began by measuring slight variations in *Cassini*'s velocity as it sped past the 310-mile-wide (500-kilometer-wide) moon on three occasions between 2010 and 2012. Those changes amounted to mere millimeters per second, and could be detected only by analyzing the Doppler shifts in the radio transmissions from the spacecraft. (A classic example of Doppler shift is the rise and fall in the pitch of a train's whistle as it zooms past you.)

The velocity variations were caused by anomalies in Enceladus's gravitational field; that is, regions of the moon that had more or less mass than average. Astronomers had already known about a huge depression in Enceladus's southern hemisphere, so they expected the mass concentration to be less in the south. But after taking everything they knew into account, researchers determined that the concentration was more massive than it should have been.

The best way to explain the extra mass was to assume the existence of a sea in the south, lying between Enceladus's rocky core and icy shell (**Figure 1.10**). Liquid water is denser than water ice, as illustrated by the ice cubes floating in a glass of water.

Planetary physicist William McKinnon of Washington University in St. Louis told *Science* that the interpretation made sense. "You could create a model without water, but people wouldn't find it satisfying," he said.

Looking for life

The gravity measurements mesh nicely with the presence of those water geysers spewing out from Enceladus's southern fissures, which are also known as "tiger stripes." Enceladus's core undergoes tidal flexing as it circles Saturn, and that flexing is thought to generate heat that's concentrated at the poles.

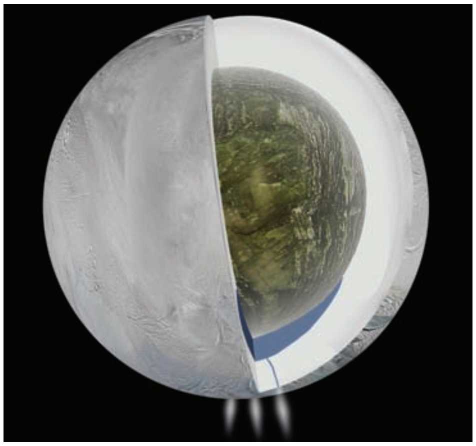


Figure 1.10 An illustration of one model of the interior of Enceladus, showing the rocky core and a southern sea, with water making its way up through cracks in the moon's icy shell and spewing out as jets of water vapor and ice.

Astronomers suggest that there's enough heat at the south pole to melt the ice and push seawater up to the surface through the fissures.

That scenario is exciting for astrobiologists, because it means the sea could be in contact with organic-rich silicate material at the bottom, at the right temperature for sustaining life.

Earlier observations from *Cassini* have shown that the water in Enceladus's geysers contains salts as well as organic molecules such as methane and ethane. However, the spacecraft's instruments aren't designed to detect the heavier organic molecules that would constitute evidence for life, Lunine said.

The easiest way to check for life would be to send a probe with the right kind of instruments through Enceladus's geysers to look for the right chemicals.

Enceladus isn't the only game in town when it comes to the search for life, however.

READING ASTRONOMY NEWS

Scientists say that Europa, one of Jupiter's moons, also appears to have an ice-covered sea. Last December, researchers reported evidence that Europa is also spewing geysers of water into space. Such findings have led NASA to seek $15 million to start work on a mission to Europa.

The Europa mission alone would require years to plan and at least $1 billion in funding. Right now, Enceladus is a lower priority for future exploration, and it's not clear when the moon's southern ocean will get a closer look. But the latest findings suggest that places like Enceladus and Europa (and perhaps Ganymede and Callisto, two more ice-covered moons of Jupiter) could represent astrobiological frontiers at least as promising as Mars.

"I look at this as a cornucopia of habitable environments in the outer solar system," Lunine said.

ARTICLES QUESTIONS

1. How large is Enceladus? How does this compare with the size of our Moon or with the distance between Chicago and St. Louis or between Santa Cruz and Los Angeles? How large is the ocean?
2. Was the original discovery of geysers on Enceladus in 2006 from an observation, a hypothesis, or a model?
3. How did scientists make this new discovery? Did they directly observe the water? If not, how did they conclude that it exists?
4. Why is it important to have multiple observations leading to a conclusion?
5. Why are scientists excited about the discovery of water on another world?

Summary

Astronomy seeks answers to many compelling questions about the universe. It uses all available tools to follow the scientific method. The process of science is based on objective reality, physical evidence, and testable hypotheses. Scientists continually strive to improve their understanding of the natural world and must be willing to challenge accepted truths as new information becomes available. We are a product of the universe: the very atoms we're made of were formed in stars that died long before the Sun and Earth were formed.

LG 1 **Describe the size and age of the universe and Earth's place in it.** We reside on a planet orbiting a star at the center of a solar system in a vast galaxy that is one of many galaxies in the universe. We occupy a very tiny part of the universe in space and time.

LG 2 **Use the scientific method to study the universe.** The scientific method is an approach to learning about the physical universe. It includes observations, forming hypotheses, making predictions to enable the testing and refining of those hypotheses, and repeated testing of theories. All scientific knowledge is provisional. Like art, literature, and music, science is a creative human activity; it is also a remarkably powerful, successful, and aesthetically beautiful way of viewing the world.

LG 3 **Demonstrate how scientists use mathematics, including graphs, to find patterns in nature.** Mathematics provides many of the tools that astronomers need to understand the patterns we see and to communicate that understanding to others.

? UNANSWERED QUESTIONS

- What makes up the universe? We have listed planets, stars, and galaxies as making up the cosmos, but astronomers now have evidence that 95 percent of the universe is composed of dark matter and dark energy, which we do not understand. Scientists are using the largest telescopes and particle colliders on Earth, as well as telescopes and experiments in space, to explore what makes up dark matter and what constitutes dark energy.
- Does life as we know it exist elsewhere in the universe? At the time of this writing, there is no scientific evidence that life exists on any other planet. Our universe is enormously large and has existed for a great length of time. What if life is too far away or existed too long ago for us ever to "meet"?

Questions and Problems

Test Your Understanding

1. Rank the following in order of increasing size.
   a. Local Group
   b. Milky Way
   c. Solar System
   d. universe
   e. Sun
   f. Earth
   g. Laniakea Supercluster
   h. Virgo Supercluster

2. If an event were to take place on the Sun, how long would it take for the light it generates to reach us?
   a. 8 minutes
   b. 11 hours
   c. 1 second
   d. 1 day
   e. It would reach us instantaneously.

3. *Understanding* in science means that
   a. we have accumulated lots of facts.
   b. we are able to connect facts through an underlying idea.
   c. we are able to predict events on the basis of accumulated facts.
   d. we are able to predict events on the basis of an underlying idea.

4. The cosmological principle states that
   a. on a large scale, the universe is the same everywhere at a given time.
   b. the universe is the same at all times.
   c. our location is special.
   d. all of the above

5. The Sun is part of
   a. the Solar System.
   b. the Milky Way Galaxy.
   c. the universe.
   d. all of the above

6. A light-year is a measure of
   a. distance.
   b. time.
   c. speed.
   d. mass.

7. Occam's razor states that
   a. the universe is expanding in all directions.
   b. the laws of nature are the same everywhere in the universe.
   c. if two hypotheses fit the facts equally well, the simpler one is the more likely to apply.
   d. patterns in nature are really manifestations of random occurrences.

8. The circumference of Earth is $\frac{1}{7}$ of a light-second. Therefore,
   a. if you were traveling at the speed of light, you would travel around Earth 7 times in 1 second.
   b. light travels a distance equal to Earth's circumference in $\frac{1}{7}$ of a second.
   c. neither a nor b
   d. both a and b

9. According to the graphs in Figures 1.7b and c, by how much did the number of viruses increase in four time steps?
   a. It doubled.
   b. It tripled.
   c. It quadrupled.
   d. It went up more than 10 times.

10. Any explanation of a phenomenon that includes a supernatural influence is not scientific because
    a. it does not have a hypothesis.
    b. it is wrong.
    c. people who believe in the supernatural are not credible.
    d. science is the study of the natural world.

11. "All scientific knowledge is provisional." In this context, *provisional* means
    a. "wrong."
    b. "relative."
    c. "temporary."
    d. "incomplete."

12. When we observe a star that is 10 light-years away, we are seeing that star
    a. as it is today.
    b. as it was 10 days ago.
    c. as it was 10 years ago.
    d. as it was 20 years ago.

13. Which of the following was *not* made in the Big Bang?
    a. hydrogen
    b. lithium
    c. beryllium
    d. carbon

14. "We are stardust" means that
    a. Earth exists because of the collision of two stars.
    b. the atoms in our bodies have passed through (and in many cases formed in) stars.
    c. Earth is primarily formed of material that used to be in the Sun.
    d. Earth and the other planets will eventually form a star.

15. The following astronomical events led to the formation of you. Place them in order of their occurrence over astronomical time.
    a. Stars die and distribute heavy elements into the space between the stars.
    b. Hydrogen and helium are made in the Big Bang.
    c. Enriched dust and gas gather into clouds in interstellar space.
    d. Stars are born and process light elements into heavier ones.
    e. The Sun and planets form from a cloud of interstellar dust and gas.

Thinking about the Concepts

16. Suppose you lived on the planet named "Tau Ceti e" that orbits Tau Ceti, a nearby star in our galaxy. How would you write your cosmic address?

17. Imagine yourself living on a planet orbiting a star in a very distant galaxy. What does the cosmological principle tell you about the physical laws at this distant location?

18. If the Sun suddenly exploded, how soon after the explosion would we know about it?

19. If a star exploded in the Andromeda Galaxy, how long would it take that information to reach Earth?

20. Give an example of a scientific theory that has been superseded by a newer theory. As scientists developed this new theory, where on the Process of Science Figure did a change occur so that the old theory became invalid and the new theory was accepted?

21. Some people have proposed the theory that Earth was visited by extraterrestrials (aliens) in the remote past. Can you think of any tests that could support or refute that theory? Is it falsifiable? Would you regard this proposal as science or pseudoscience?

22. What does the word *falsifiable* mean? Give an example of an idea that is not falsifiable. Give an example of an idea that is falsifiable.

23. Explain how the word *theory* is used differently in the context of science than in common everyday language.

24. What is the difference between a *hypothesis* and a *theory* in science?

25. Suppose the tabloid newspaper at your local supermarket claimed that children born under a full Moon become better students than children born at other times.
    a. Is this theory falsifiable?
    b. If so, how could it be tested?

26. A textbook published in 1945 stated that light takes 800,000 years to reach Earth from the Andromeda Galaxy. In this book, we assert that it takes 2,500,000 years. What does this difference tell you about a scientific "fact" and how our knowledge evolves with time?

27. Astrology makes testable predictions. For example, it predicts that the horoscope for your star sign on any day should fit you better than horoscopes for other star signs. Read the daily horoscopes for all of the astrological signs in a newspaper or online. How many of them might fit the day you had yesterday? Repeat the experiment every day for a week and keep a record of which horoscopes fit your day each day. Was your horoscope sign consistently the best description of your experiences?

28. A scientist on television states that it is a known fact that life does not exist beyond Earth. Would you consider this scientist reputable? Explain your answer.

29. Some astrologers use elaborate mathematical formulas and procedures to predict the future. Does this show that astrology is a science? Why or why not?

30. Why can it be said that we are made of stardust? Explain why this statement is true.

Applying the Concepts

31. Review Working It Out 1.1. Convert the following numbers to scientific notation:
    a. 7,000,000,000
    b. 0.00346
    c. 1,238

32. Review Working It Out 1.1. Convert the following numbers to standard notation:
    a. 5.34×10^8
    b. 4.1×10^3
    c. 6.24×10^{-5}

33. If a car is traveling at 35 km/h, how far does it travel in
    a. 1 hour?
    b. half an hour?
    c. 1 minute?

34. Review Appendix 1.7. The surface area of a sphere is proportional to the square of its radius. How many times larger is the surface area if the radius is
    a. doubled?
    b. tripled?
    c. halved (divided by 2)?
    d. divided by 3?

35. The average distance from Earth to the Moon is 384,400 km. How many days would it take you, traveling at 800 km/h—the typical speed of jet aircraft—to reach the Moon?

36. The average distance from Earth to the Moon is 384,400 km. In the late 1960s, astronauts reached the Moon in about 3 days. How fast (on average) must they have been traveling (in kilometers per hour) to cover this distance in this time? Compare this speed to the speed of a jet aircraft (800 km/h).

37. (a) If it takes about 8 minutes for light to travel from the Sun to Earth, and Neptune is 30 times farther from Earth than the Sun is, how long does it take light to reach Earth from Neptune? (b) Radio waves travel at the speed of light. What does this fact imply about the problems you would have if you tried to conduct a two-way conversation between Earth and a spacecraft orbiting Neptune?

38. The distance from Earth to Mars varies from 56 million km to 400 million km. How long does it take a radio signal traveling at the speed of light to reach a spacecraft on Mars when Mars is closest and when Mars is farthest away?

39. The surface area of a sphere is proportional to the square of its radius. The radius of the Moon is only about one-quarter that of Earth. How does the surface area of the Moon compare with that of Earth?

40. A remote Web page may sometimes reach your computer by going through a satellite orbiting approximately 3.6×10^4 km above Earth's surface. What is the minimum delay, in seconds, that the Web page takes to show up on your computer?

41. Imagine that you have become a biologist, studying rats in Indonesia. Most of the time, Indonesian rats maintain a constant population. Every half century, however, these rats suddenly begin to multiply exponentially! Then the population crashes back to the constant level. Sketch a graph that shows the rat population over two of these episodes.

42. New York is 2,444 miles from Los Angeles. What is that distance in car-hours? In car-days? (Assume a travel speed of 70 mph.)

43. Some theorize that a tray of hot water will freeze more quickly than a tray of cold water when both are placed in a freezer.
    a. Does this theory make sense to you?
    b. Is the theory falsifiable?
    c. Do the experiment yourself. Note the results. Was your intuition borne out?

44. A pizzeria offers a 9-inch-diameter pizza for \$12 and an 18-inch-diameter pizza for \$24. Are both offerings equally economical? If not, which is the better deal? Explain your reasoning.

45. The circumference of a circle is given by $C = 2\pi r$, where r is the radius of the circle.
    a. Calculate the approximate circumference of Earth's orbit around the Sun, assuming that the orbit is a circle with a radius of 1.5×10^8 km.
    b. Noting that there are 8,766 hours in a year, how fast, in kilometers per hour, does Earth move in its orbit?
    c. How far along in its orbit does Earth move in 1 day?

USING THE WEB

46. Go to the interactive "Scale of the Universe" Web page at the Astronomy Picture of the Day website (http://apod.nasa.gov/apod/ap140112.html). Start at 10^0 (human size) and scale upward; clicking on an object gives you its exact size. What astronomical bodies are about the size of the United States? What objects are about the size of Earth? What stars are larger than the distance from Earth to the Sun? How many light-days is the distance of *Voyager 1* to the Earth? What objects are about the size of the distance from the Sun to the nearest star? How much larger is the Milky Way than the size of the Solar System? How much larger is the Local Group than the Milky Way? How much larger is the observable universe than the Local Group?

47. a. For a video representation of the scale of the universe, view the short video *The Known Universe* at the Hayden Planetarium website (http://www.haydenplanetarium.org/universe), which takes the viewer on a journey from the Himalayan mountains to the most distant galaxies. How far have broadcast radio programs from Earth traveled? Is the Sun a particularly luminous star compared to others? Do you think the video is effective for showing the size and scale of the universe?
    b. A similar film produced in 1996 in IMAX format, *Cosmic Voyage*, can be found online at http://topdocumentaryfilms.com/cosmic-voyage. Watch the "powers of ten" zoom out to the cosmos, starting at the 7-minute mark, for about 5 minutes. Do the "powers of ten" circles add to your understanding of the size and scale of the universe? (The original film *Powers of Ten* can be viewed online at http://apod.nasa.gov/apod/ap150324.html, but notably it extends a few powers of ten less than the newer film.)

48. Go to the Astronomy Picture of the Day (APOD) app or website (http://apod.nasa.gov/apod) and click on "Archive" to look at the recent pictures and videos. Submissions to this website come from all around the world. Pick one and read the explanation. Was the image or video taken from Earth or from space? Is it a combination of several images? Does it show Earth, our Solar System, objects in our Milky Way Galaxy, more distant galaxies, or something else? Is the explanation understandable to someone who has not studied astronomy? Do you think this website promotes a general interest in astronomy?

49. Throughout this book, we will examine how discoveries in astronomy and space are covered in the media. Go to your favorite news website (or to one assigned by your instructor) and find a recent article about astronomy or space. Does this website have a separate section for science? Is the article you selected based on a press release, on interviews with scientists, or on an article in a scientific journal? Use Google News or the equivalent to see how widespread the coverage of this story is. Have many newspapers carried it? Has it been picked up internationally? Has it been discussed in blogs? Do you think this story was interesting enough to be covered?

50. Go to a blog about astronomy or space. Is the blogger a scientist, a science writer, a student, or an enthusiastic amateur astronomer? What is the current topic of interest? Is it controversial? Are readers making many comments? Is this blog something you would want to read again?

smartwork5

If your instructor assigns homework in Smartwork5, access your assignments at digital.wwnorton.com/astro5.

digital.wwnorton.com/astro5

Logic is fundamental to the study of science and to scientific thinking. A logical fallacy is an error in reasoning, which good scientific thinking avoids. For example, "because Einstein said so" is not an adequate argument. No matter how famous the scientist is (even if he is Einstein), he or she must still supply a logical argument and evidence to support a claim. Anyone who claims that something must be true because Einstein said it has committed the logical fallacy known as an *appeal to authority*. There are many types of logical fallacies, but a few of them crop up often enough in discussions about science that you should be aware of them.

Ad hominem. In an ad hominem fallacy, you attack the person who is making the argument, instead of the argument itself. Here is an extreme example of an ad hominem argument: "A famous politician says Earth is warming. But I think this politician is an idiot. So Earth can't be warming."

Appeal to belief. This fallacy has the general pattern "Most people believe X is true; therefore X is true." For example, "Most people believe Earth orbits the Sun. Therefore, Earth orbits the Sun." Note that even if the conclusion is correct, you may still have committed a logical fallacy in your argument.

Begging the question. In this fallacy, also known as circular reasoning, you assume the claim is true and then use this assumption as evidence to prove the claim is true. For example, "I am trustworthy; therefore I must be telling the truth." No real evidence is presented for the conclusion.

Biased sample. If a sample drawn from a smaller pool has a bias, then conclusions about the sample cannot be applied to a larger pool. For example, imagine you poll students at your university and find that 30 percent of them visit the library one or more times per week. Then you conclude that 30 percent of Americans visit the library one or more times per week. You have committed the biased sample fallacy, because university students are not a representative sample of the American public.

Post hoc ergo propter hoc. *Post hoc ergo propter hoc* is Latin for "after this, therefore because of this." Just because one thing follows another doesn't mean that one caused the other. For example, "There was an eclipse and then the king died. Therefore, the eclipse killed the king." This fallacy is often connected to related inverse reasoning: "If we can prevent an eclipse, the king won't die."

Slippery slope. In this fallacy, you claim that a chain reaction of events will take place, inevitably leading to a conclusion that no one could want. For example, "If I don't get A's in all of my classes, I will not ever be able to get into graduate school, and then I won't ever be able to get a good job, and then I will be living in a van down by the river until I'm old and starve to death." None of these steps actually follows inevitably from the one before.

Following are some examples of logical fallacies. Identify the type of fallacy represented. Each of the fallacies we just discussed is represented once.

1 You get a chain email threatening terrible consequences if you break the chain. You move it to your spam box. Later that day you get in a car accident. The following morning, you retrieve the chain email and send it along.

____

____

2 If I get question 1 on the assignment wrong, then I'll get question 2 wrong as well, and before you know it, I will never catch up in the class.

____

____

3 All my friends love the band Degenerate Electrons. Therefore, all people my age love this band.

____

____

4 Eighty percent of Americans believe in the tooth fairy. Therefore, the tooth fairy exists.

____

____

5 My professor says that the universe is expanding. But my professor is a geek, and I don't like geeks. So the universe can't be expanding.

____

____

6 When applying for a job, you use a friend as a reference. Your prospective employer asks you how she can be sure your friend is trustworthy, and you say, "I can vouch for him."

____

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2 Patterns in the Sky—Motions of Earth and the Moon

Ancient peoples learned that they could use the patterns they observed in the sky to predict the changing length of day, the change of seasons, and the changes in the appearance of the Moon. Some people understood these patterns well enough to create complicated calendars and predict rare eclipses. But now we can see these patterns with the perspective of centuries of modern science, and we can explain these changes as a consequence of the motions of Earth and the Moon. Discovering what causes these patterns has shown us the way outward into the universe.

LEARNING GOALS

In this chapter, we will examine the patterns in the sky and on Earth and the underlying motions that cause these patterns. By the conclusion of this chapter, you should be able to:

LG 1 Describe how Earth's rotation about its axis and revolution around the Sun affect our perception of celestial motions as seen from different places on Earth.

LG 2 Explain why there are different seasons throughout the year.

LG 3 Describe the factors that create the phases of the Moon.

LG 4 Sketch the alignment of Earth, the Moon, and the Sun during eclipses of the Sun and the Moon

The changing seasons bring noticeable variations to the landscape. ▶▶▶


What causes
the seasons?

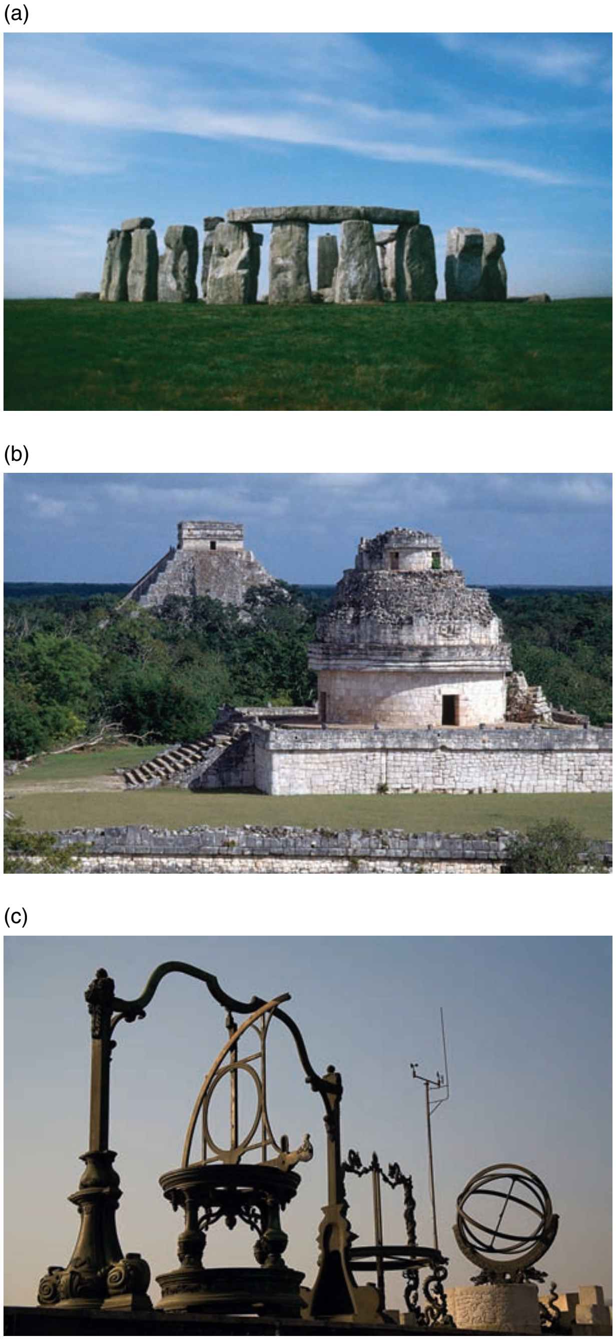


Figure 2.1 (a) One of the suspected uses of Stonehenge 4,000 years ago was to keep track of celestial events. (b) The Mayan El Caracol at Chichén Itzá in Mexico (906 CE) is believed to have been designed to align with the planet Venus. (c) The Beijing Ancient Observatory in China (1442 CE) includes ancient astronomical instruments as well as some brought by European Jesuits in the 17th and 18th centuries.

▶II **AstroTour:** The Celestial Sphere and the Ecliptic

2.1 Earth Spins on Its Axis

Ancient humans may not have known that they were "stardust," but they did sense that there was a connection between their lives on Earth and the sky above. Before our modern technological civilization, people's lives were more attuned to the ebb and flow of nature, which includes the patterns in the sky. By watching the repeating patterns of the Sun, Moon, and stars in the sky, people found that they could predict when the seasons would change and when the rains would come and the crops would grow. Ancient astronomers with knowledge of the sky—priests and priestesses, natural philosophers and explorers—all had knowledge of the world that others did not, and knowledge of the world was power. Some of these early observations and ideas about these patterns live on today in the names of stars and the apparent grouping of stars we call **constellations**, in calendars based on the Moon and Sun that are still in use by many cultures, and in the astronomical names of the days of the week.

From Mesopotamia to Africa, from Europe to Asia, from the Americas to the British Isles, the archaeological record holds evidence that ancient cultures built structures that were sometimes used to study astronomical positions and events. **Figure 2.1** shows some examples of these. Pre-telescopic astronomical observatories from the 8th through 17th centuries were used to study the sky for timekeeping and navigation. Many of these structures and observatories are now national historical or UNESCO World Heritage sites.

The Celestial Sphere

Long before Christopher Columbus sailed, Aristotle and other Greek philosophers knew that Earth is a sphere. However, because Earth seems stationary, they did not realize that the changes they observed in the sky from day to day and year to year are caused by Earth's motions. As we will see in this subsection, Earth's rotation on its axis determines the passage of day and night, which dictates the rhythm of life on Earth.

One reason the ancients did not suspect that Earth rotates was that they could not perceive Earth's spinning motion. As Earth rotates about its axis, its surface is moving quite fast—about 1,674 kilometers per hour (km/h) at the equator. We do not "feel" that motion any more than we would feel the motion of a car with a perfectly smooth ride cruising down a straight highway. Nor do we feel the direction of Earth's spin, although the hourly motion of the Sun, Moon, and stars across the sky reveals it. Earth's **North Pole** is at the north end of Earth's rotation axis. Imagine you are in space far above Earth's North Pole. From there you would see Earth complete a counterclockwise rotation, once each 24-hour period, as shown in **Figure 2.2**. As the rotating Earth carries an observer on the surface from west to east, objects in the sky appear to move in the other direction, from east to west. As seen from Earth's surface, the path each object takes across the sky is called its **apparent daily motion**.

To help visualize the apparent daily motions of the Sun and stars, it is useful to think of the sky as a huge sphere with the stars painted on its surface and Earth at its center. From ancient Greek times to the Renaissance, most people believed this to be a true representation of the heavens. Astronomers call this imaginary sphere, shown in **Figure 2.3**, the **celestial sphere**. The celestial sphere is a useful concept because it is easy to visualize, but never forget that it is, in fact, imaginary.

Each point on the celestial sphere indicates a direction in space. Directly above Earth's North Pole is the **north celestial pole (NCP)**. Directly above Earth's **South Pole**, which is at the south end of Earth's rotation axis, is the **south celestial pole (SCP)**. Directly above Earth's **equator** is the **celestial equator**, an imaginary circle that divides the sky into a northern half and a southern half. Just as the north celestial pole is the projection of the direction of Earth's North Pole into the sky, the celestial equator is the projection of the plane of Earth's equator into the sky. Just as Earth's North Pole is 90° away from Earth's equator, the north celestial pole is 90° away from the celestial equator. If you are in the Northern Hemisphere and you point one arm toward the celestial equator and one arm toward the north celestial pole, your arms will always form a right angle, so the north celestial pole is 90° away from the celestial equator. If you are in the Southern Hemisphere, the same holds true there: the angle between the celestial equator and the south celestial pole is always 90° as well.

Between the celestial poles and the equator, objects have positions on the celestial sphere with coordinates analogous to latitude and longitude on Earth. **Latitude** is an indication of distance north or south from Earth's equator. On the celestial sphere, **declination** similarly indicates the distance of an object north or south of the celestial equator (from 0° to ±90°). On Earth, **longitude** measures how far east or west you are from the Royal Observatory in Greenwich, England. **Right ascension** on the celestial sphere is similar to longitude on Earth and measures the angular distance of a celestial body eastward along the celestial equator from the point where the Sun's path crosses the celestial equator from south to north. These coordinates are used to locate objects in the sky quickly. The **ecliptic** is the path of the Sun in the sky throughout the year. Detailed descriptions and illustrations of latitude and longitude, and of celestial coordinates used with the celestial sphere, can be found in Appendix 7.

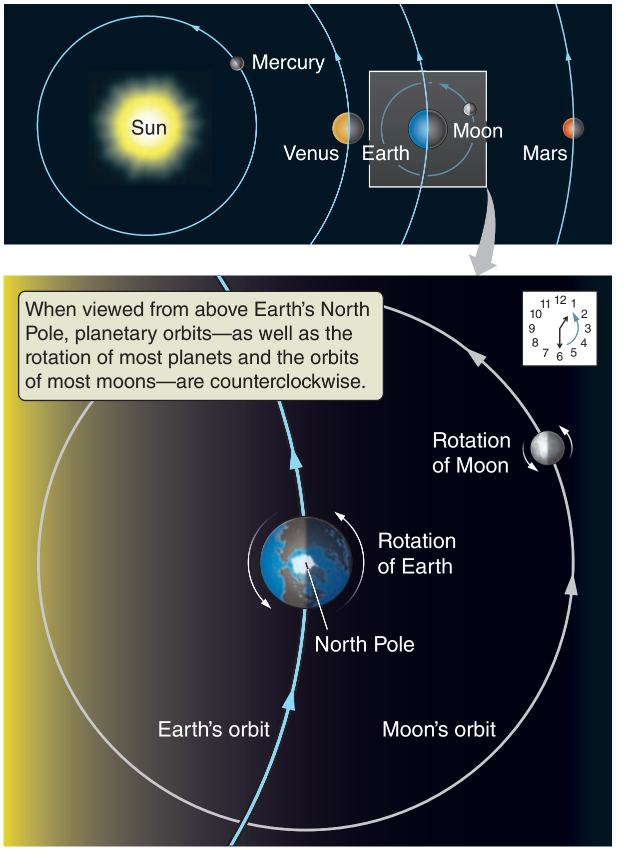


Figure 2.2 Motions in the Solar System, as viewed from above Earth's North Pole. (Not drawn to scale.)

The **zenith** is the point in the sky directly above you wherever you are, as shown in **Figure 2.3a**. You can find the **horizon** by standing up and pointing your right hand at the zenith and your left hand straight out from your side. Turn in a complete circle. Your left hand has traced out the entire horizon. You can divide the sky into an east half and a west half with a line that runs from the horizon at due north through the zenith to the horizon at due south. This imaginary north–south line is called the **meridian**, shown as a dashed line in Figure 2.3a. Figure 2.3b shows these locations on the celestial sphere. The meridian line continues around the far side of the celestial sphere, through the **nadir** (the point directly below you), and back to the starting point due north.

Take a moment to visualize all these locations in space. To see how to use the celestial sphere, consider the Sun at noon and at midnight. Local noon occurs when the Sun crosses the meridian at your location. This is the highest point above the horizon that the Sun will reach on any given day. The highest point is almost never the zenith. You have to be in a specific place on a specific day for the Sun to be directly over your head at noon, for example, at a latitude 23.5° north of the

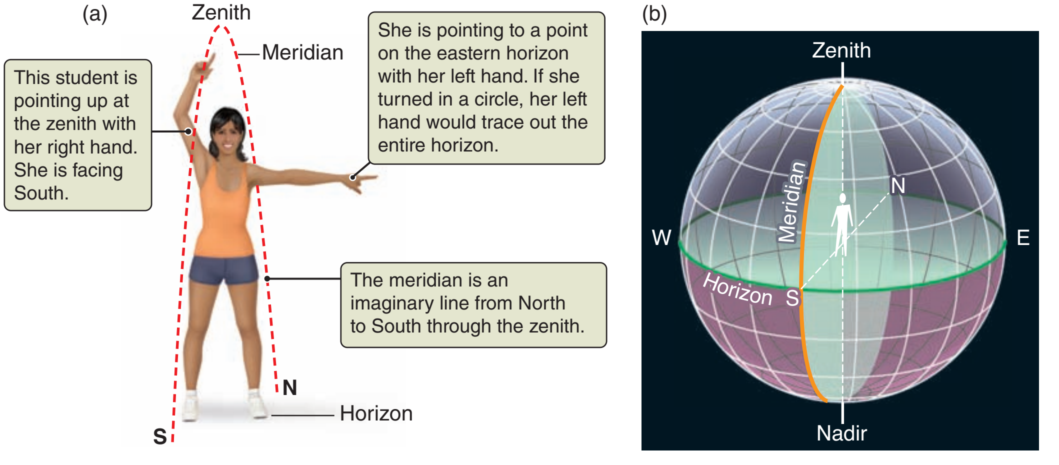


Figure 2.3 (a) The meridian is a line on the celestial sphere that runs from north to south, dividing the sky into an east half and a west half. (b) At any location on Earth, the sky is divided into an east half and a west half by an imaginary meridian projected onto the celestial sphere.

Astronomy in Action: Vocabulary of the Celestial Sphere

Nebraska Simulations: Celestial and Horizon Systems Comparison; Rotating Sky Explorer

AstroTour: The View from the Poles

equator on June 20. Local midnight occurs when the Sun is precisely opposite from its position at local noon. From our perspective on Earth, the celestial sphere appears to rotate, carrying the Sun across the sky to its highest point at noon, over toward the west to set in the evening. In *reality*, the Sun remains in the same place in space through the entire 24-hour period, and Earth rotates so that any given location on Earth faces a different direction at every moment. When it is noon where you live, Earth has rotated so that you face most directly toward the Sun. Half a day later, at midnight, your location on Earth has rotated to face most directly away from the Sun.

The View from the Poles

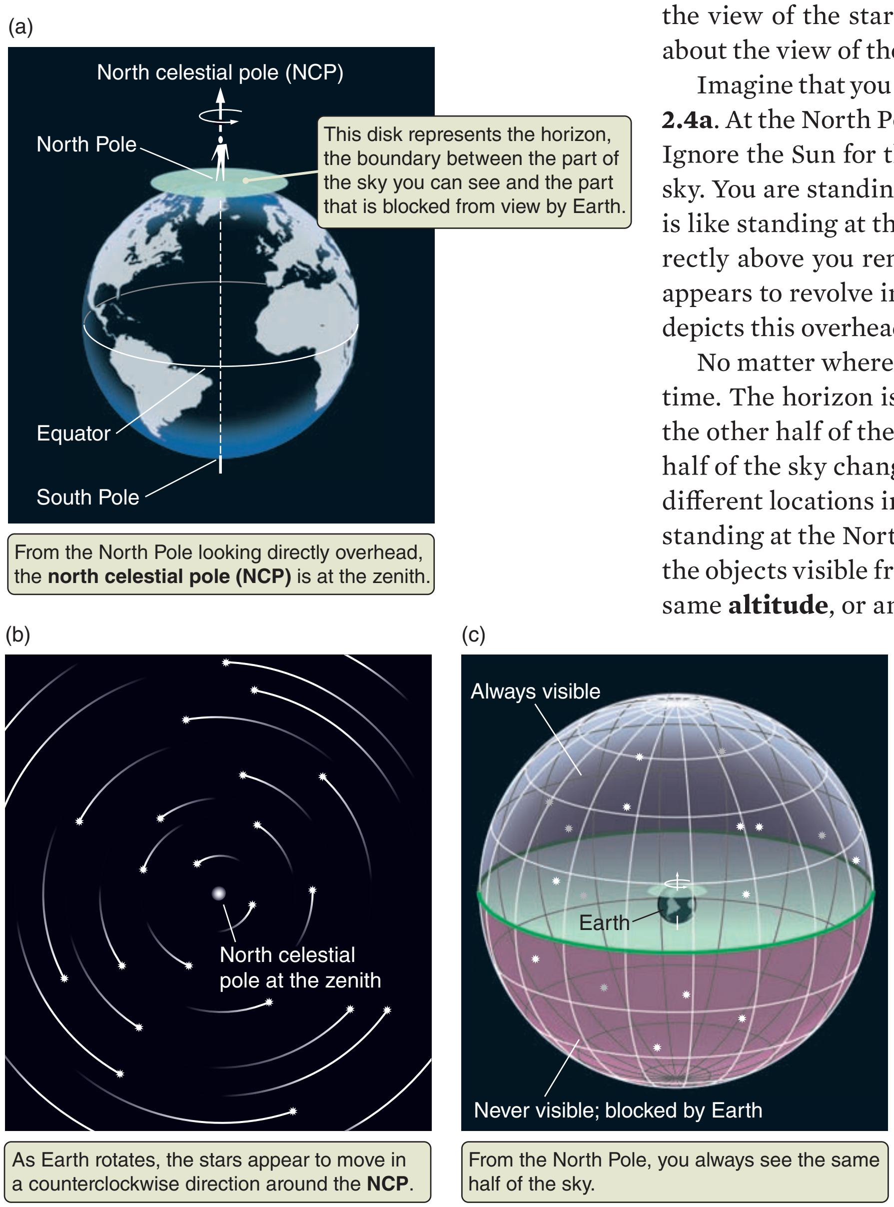
The apparent daily motions of the stars and the Sun depend on where you live. For example, the apparent daily motions of celestial objects in a northern place such as Alaska are quite different from the apparent daily motions seen from a tropical island such as Hawaii. To understand why your location matters, let's examine the view of the stars from the poles—and then use these to guide our thinking about the view of the stars from other latitudes.

Imagine that you are standing on the North Pole watching the sky as in **Figure 2.4a**. At the North Pole, the north celestial pole is directly overhead at the zenith. Ignore the Sun for the moment and pretend that you can always see stars in the sky. You are standing where Earth's axis of rotation intersects its surface, which is like standing at the center of a rotating carousel. As Earth rotates, the spot directly above you remains fixed over your head while everything else in the sky appears to revolve in a counterclockwise direction around this spot. Figure 2.4b depicts this overhead view.

No matter where you are on Earth, you can see only half of the sky at any one time. The horizon is the boundary between the part of the sky you can see and the other half of the sky that is blocked by Earth. Except at the poles, the visible half of the sky changes constantly as Earth rotates, because the zenith points to different locations in the sky as Earth carries you around. In contrast, if you are standing at the North Pole, the zenith is always in the same location in space, so the objects visible from the North Pole follow circular paths that always have the same **altitude**, or angle above the horizon. Objects close to the zenith appear to follow small circles, while objects near the horizon follow the largest circles (Figure 2.4b). The view from the North Pole is special because from there, nothing rises or sets each day as Earth turns: from there you will always see the *same* half of the celestial sphere (Figure 2.4c).

The view from Earth's South Pole is much the same—with two major differences. First, the South Pole is on the opposite side of Earth from the North Pole, so the visible half of the sky at the South Pole is precisely the half that is hidden from view at the North Pole. The second difference is that stars appear to move clockwise around the south celestial pole rather than counterclockwise as they do at the north celestial pole. To visualize why these motions are different, stand up and spin around from right to left. As you look at the ceiling, things appear to move in a counterclockwise direction, but as you look at the floor, they appear to be moving clockwise.

Figure 2.4 As viewed from (a) Earth's North Pole, (b) stars move throughout the night in counterclockwise, circular paths about the zenith. (c) The same half of the sky is always visible from the North Pole.



CHECK YOUR UNDERSTANDING 2.1

No matter where you are on Earth, stars appear to rotate about a point called the: (a) zenith; (b) celestial pole; (c) nadir; (d) meridian.

The View Away from the Poles

Suppose that you leave the North Pole to travel south to lower latitudes. Imagine a line from the center of Earth to your location on the surface of the planet, as in **Figure 2.5**. Now imagine a second line from the center of Earth to the point on the equator closest to you. The angle between these two lines is your latitude. At the North Pole, for example, these two imaginary lines form a 90° angle. At the equator, they form a 0° angle. So the latitude of the North Pole is 90° north, and the latitude of the equator is 0°. The South Pole is at latitude 90° south.

Your latitude determines the part of the sky that you can see throughout the year. As you move south from the North Pole, your zenith moves away from the north celestial pole, and so the horizon moves as well. At the North Pole, the horizon makes a 90° angle with the north celestial pole, which is at the zenith. At a latitude of 60° north, as in Figure 2.5, your horizon is tilted 60° from the north celestial pole. The angle between your horizon and the north celestial pole is equal to your latitude no matter where you are on Earth. The situation is the same in the Southern Hemisphere—your latitude is the altitude of the south celestial pole. At the equator, at a latitude of 0°, the north and south celestial poles would be at the northern and southern horizons, respectively.

One way to solidify your understanding of the view of the sky at different latitudes is to draw pictures like the one in Figure 2.5. If you can draw a picture like this for any latitude—filling in the values for each angle in the drawing and imagining what the sky looks like from that location—then you will be well on your way to developing a working knowledge of the appearance of the sky. That knowledge will prove useful later, when we discuss a variety of phenomena, such as the changing of the seasons.

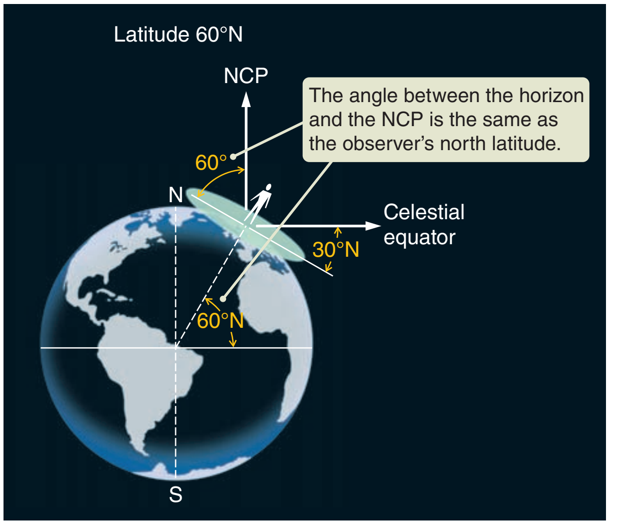


Figure 2.5 Your perspective on the sky depends on your location on Earth. The locations of the celestial poles and the celestial equator in an observer's sky depend on the observer's latitude. In this case, an observer at latitude 60° north sees the north celestial pole at an altitude of 60° above the northern horizon and the celestial equator 30° above the southern horizon.

Motions of the Stars and the Celestial Poles

Figure 2.6 shows two time-lapse views of the sky from different latitudes. The apparent motions of the stars about the celestial poles also differs from latitude to latitude. The visible part of the sky constantly changes, as stars rise and set with Earth's rotation. From this perspective the horizon appears fixed, while the stars appear to move. From these different latitudes, if we focus our attention on the north celestial pole, we see much the same thing we saw from Earth's North Pole. The north celestial pole remains fixed in the sky, and all of the stars appear to move throughout the night in counterclockwise, circular paths around that point. But because the north celestial pole is no longer directly overhead as it was at the North Pole, the apparent circular paths of the stars are now tipped relative to the horizon. (More correctly, your horizon is now tipped relative to the apparent circular paths of the stars.)

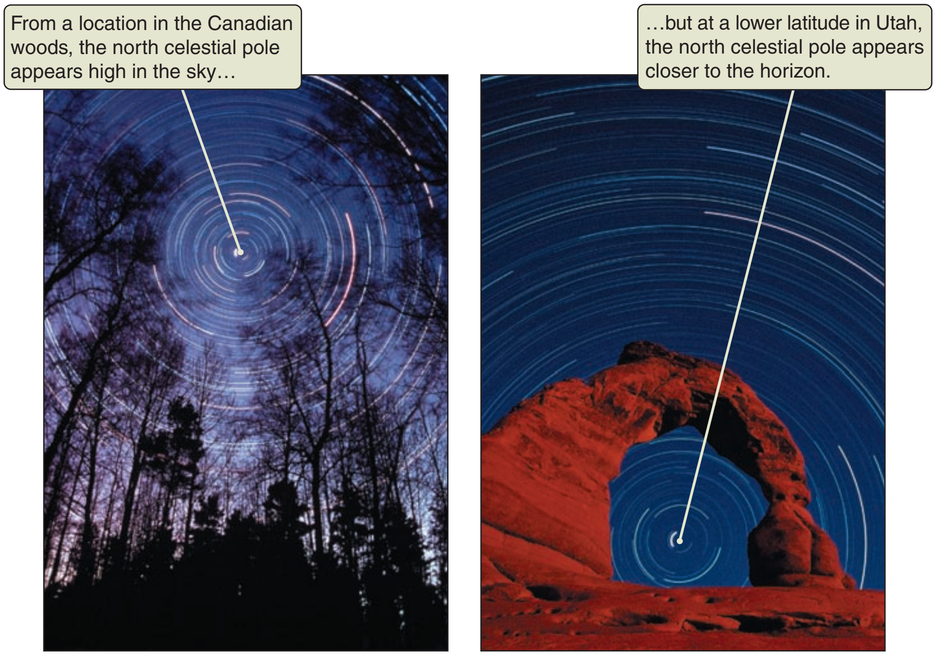


Figure 2.6 Time exposures of the sky showing the apparent motions of stars through the night. Note the difference in the circumpolar portion of the sky as seen from the two different northern latitudes.

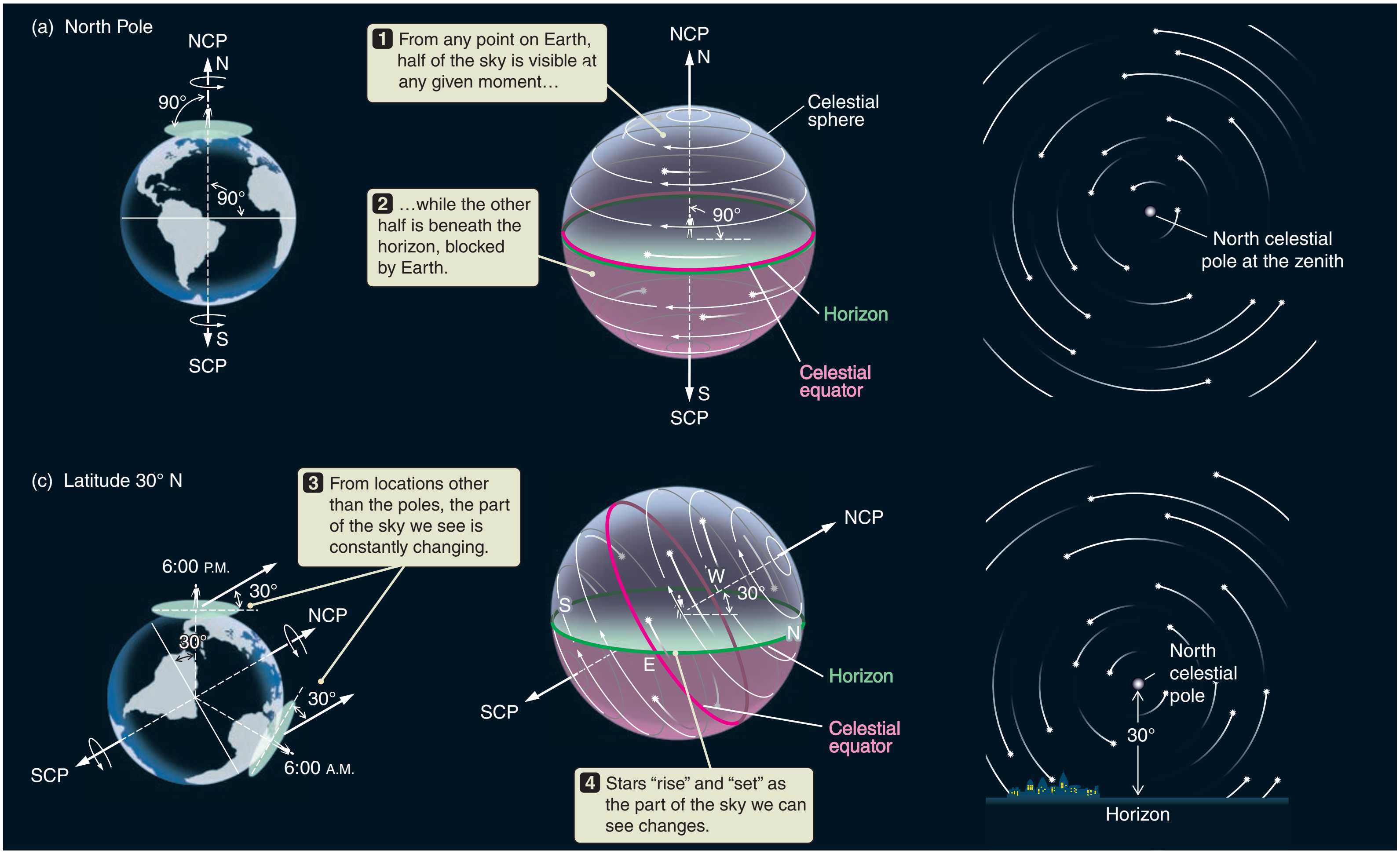


Figure 2.7 The celestial sphere is shown here as viewed by observers at four different latitudes. At all locations other than the poles, stars rise and set as the part of the celestial sphere that we see changes during the day.

From the vantage point of an observer in the Northern Hemisphere, stars near the north celestial pole never dip below the horizon and thus stay visible all night. Recall from Figure 2.5 that the latitude is equal to the altitude of the north celestial pole. Stars closer to the north celestial pole than this angle never dip below the horizon as they complete their apparent paths around the pole. These stars are called **circumpolar** ("around the pole") stars. Another group of stars, near the south celestial pole, never rise above the horizon in the Northern Hemisphere. Stars between those that never rise and those in the circumpolar region can be seen for *only part* of each 24-hour day. These stars appear to rise and set as Earth turns. The only place on Earth where you can see the entire sky over the course of 24 hours is the equator. From the equator, the north and south celestial poles sit on the northern and southern horizons, respectively, and all of the stars move through the sky each 24-hour day. (Even though the Sun lights the sky for roughly half of this time, the stars are still there.)

Figure 2.7 shows the orientation of the sky as seen by observers at four different latitudes. For an observer at the North Pole (Figure 2.7a), the celestial equator lies exactly along the horizon. The north celestial pole is at the zenith, and the

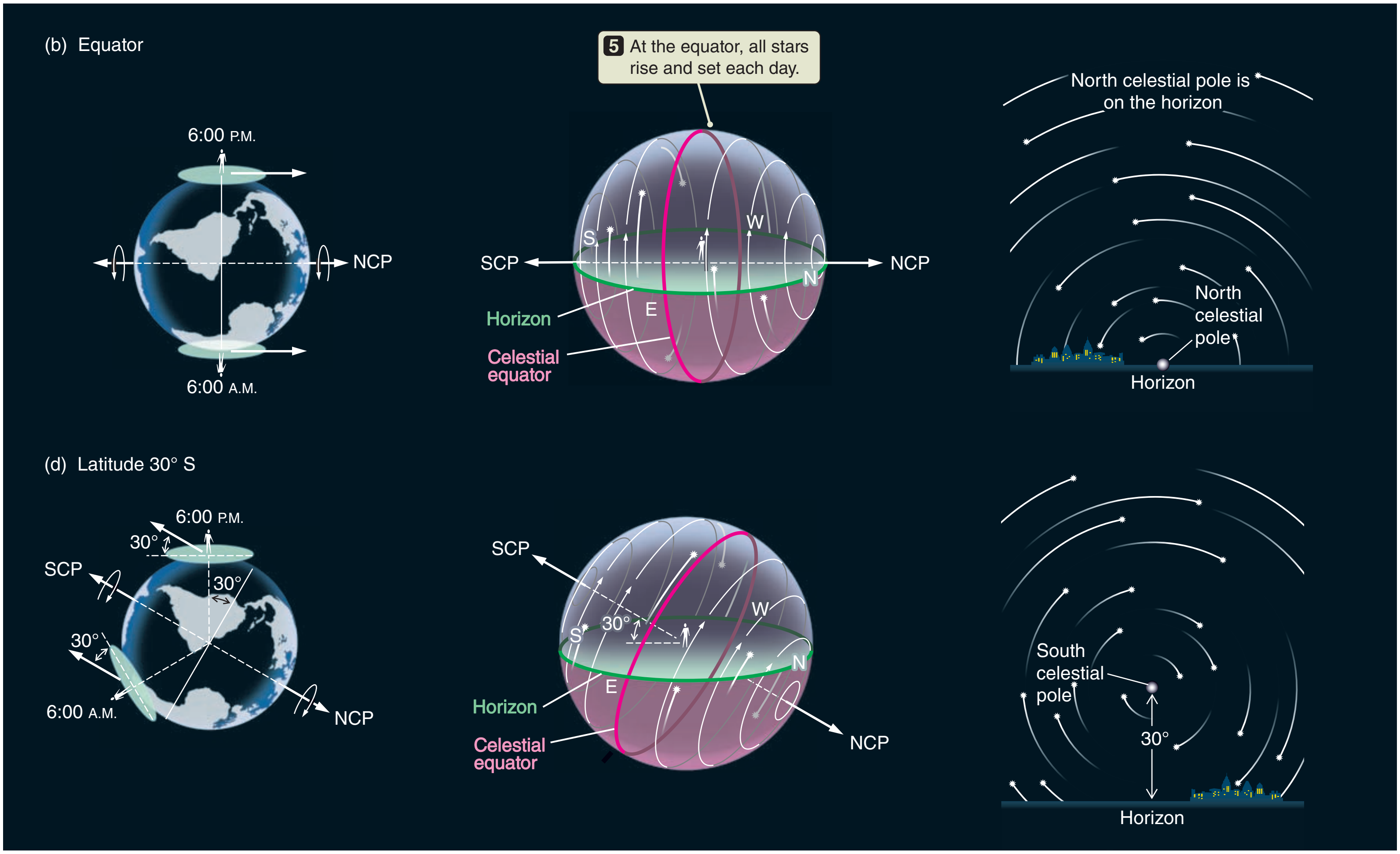


Figure 2.7 Continued.

southern half of the sky is never visible. Stars neither rise nor set; their paths form circles parallel to the horizon. For an observer at the equator (Figure 2.7b), the celestial poles are both at the horizon, and all the stars are visible in a 24-hour period, rising straight up and setting straight down each day.

At other latitudes, the celestial equator intersects the horizon due east and due west. Therefore, a star on the celestial equator rises due east and sets due west. Stars located north of the celestial equator rise north of east and set north of west. Stars located south of the celestial equator rise south of east and set south of west.

From everywhere else on Earth (except at the poles), half of the celestial equator is always visible above the horizon. Therefore, any object located on the celestial equator is visible half of the time—above the horizon for 12 hours each day. Objects that are not on the celestial equator are above the horizon for differing amounts of time. Figures 2.7c and d show that stars in the observer's hemisphere are visible for more than half the day because more than half of each star's path in the sky is above the horizon. In contrast, stars in the opposite hemisphere are visible for less than half the day because less than half of each star's path in the sky is above the horizon.

Nebraska Simulations: Meridional Altitude Simulator

Nebraska Simulation: Declination Ranges Simulator

For example, as seen from the Northern Hemisphere, stars north of the celestial equator remain above the horizon for more than 12 hours each day. The farther north the star is, the longer it stays up. Circumpolar stars are the extreme example of this phenomenon; they are always above the horizon. In contrast, stars south of the celestial equator are above the horizon for less than 12 hours each day. The farther south a star is, the less time it is visible. For an observer in the Northern Hemisphere, stars located close to the south celestial pole never rise above the horizon.

Using the Stars for Navigation Since ancient times, travelers have used the stars for navigation. They would find the north or south celestial poles by recognizing the stars that surround them. In the Northern Hemisphere, a moderately bright star happens to be located close to the north celestial pole (**Figure 2.8a**). This star is called Polaris, the "North Star." The altitude of Polaris in the sky is nearly equal to your latitude. If you are in Phoenix, Arizona, for example (latitude 33.5° north), the north celestial pole has an altitude of 33.5°. In Fairbanks, Alaska (latitude 64.6° north), the north celestial pole sits much higher, with an altitude of 64.6°. Similarly in the Southern Hemisphere, the constellation Crux (commonly called the Southern Cross) points to a star near the south celestial pole (Figure 2.8b). A navigator who has located a pole star can identify north and south, and therefore east, west, and her latitude. This enables the navigator to determine which direction to travel. The location of the north celestial pole in the sky was used to measure the size of Earth, as described in **Working It Out 2.1**. Determining your longitude by astronomical methods is much more complicated because of Earth's rotation. Longitude cannot be determined from astronomical observation alone.

Nebraska Simulations: Big Dipper Clock

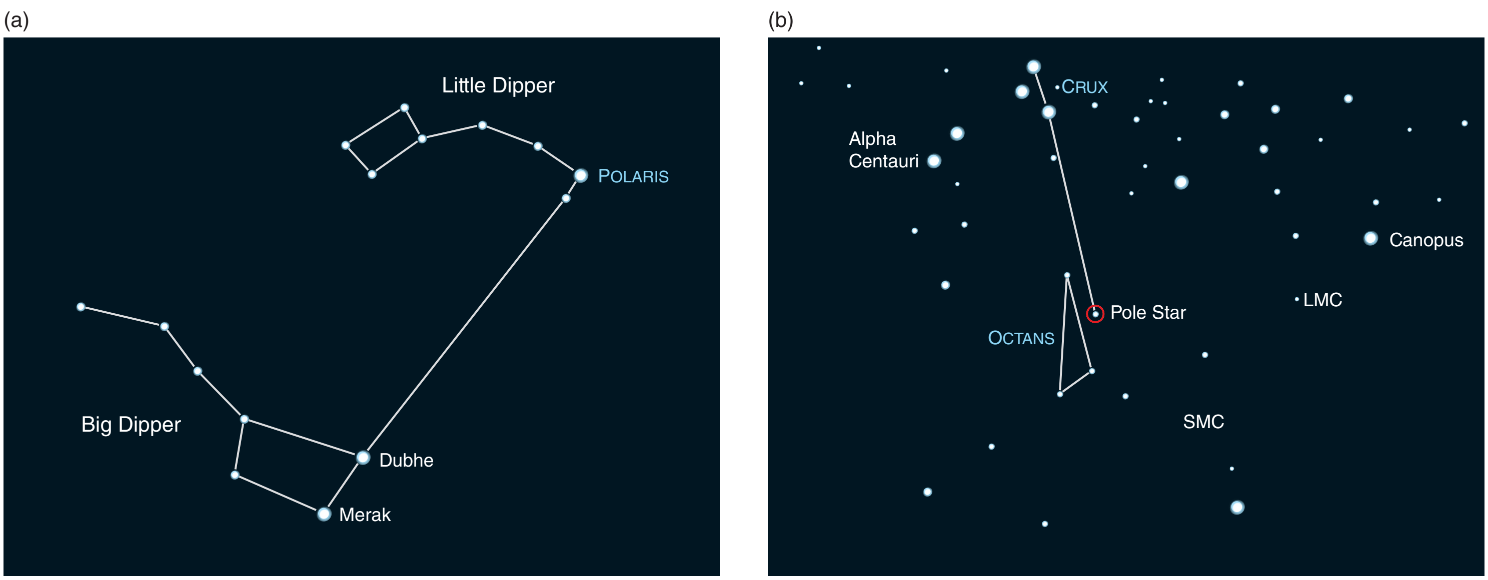


Figure 2.8 Groups of stars near the pole stars in the sky can be used to locate a pole star. (a) Two bright "pointer stars" stars in the cup of the Big Dipper point toward Polaris, the "North Star." (b) In the Southern Hemisphere, the constellation Crux and two of its bright "pointer stars" can be used to locate the relatively faint southern pole star.

2.1 Working It Out How to Estimate the Size of Earth

We can use the location of the north celestial pole in the sky to estimate the size of Earth. Suppose we start out in Phoenix, Arizona, and we observe the north celestial pole to be 33.5° above the horizon. If we head north, by the time we reach the Grand Canyon, about 290 kilometers (km) from Phoenix, we notice that the north celestial pole has risen to about 36° above the horizon. This difference between 33.5° and 36° (2.5°) is 1/144 of the way around a circle. (A circle is 360°, and 2.5°/360° = 1/144.)

This means that we must have traveled 1/144 of the way around the circumference, C, of Earth by traveling the 290 km between Phoenix and the Grand Canyon. In other words,

$$\frac{1}{144} \times C = 290 \text{ km}$$

Rearranging the expression, the circumference of Earth is given by

$$C = 144 \times 290 \text{ km} \approx 42{,}000 \text{ km}$$

The actual circumference of Earth is just over 40,000 km, so our simple calculation was close. The circumference of a circle is equal to 2π multiplied by its radius. So, the radius of Earth is given by

$$\text{Radius} = \frac{C}{2\pi} = \frac{40{,}000 \text{ km}}{2\pi} = 6{,}400 \text{ km}$$

It was in much this same way that the Greek astronomer Eratosthenes (276–194 BCE) made the first accurate measurements of the size of Earth in about 230 BCE. As illustrated in **Figure 2.9**, Eratosthenes used the distance between his home city of Alexandria and the city of Syene (currently Aswân, in Egypt), which was 5,000 "stadia." He noticed that on the first day of summer in Syene, the sunlight reflected directly off the water in a deep well, so the Sun must have been nearly at the zenith. By measuring the shadow of the Sun from an upright stick in Alexandria, he saw that the Sun was about 7.2° south of the zenith on the same date. Assuming Earth was spherical and Syene was directly south of Alexandria, he determined the distance between the two cities to be 7.2° divided by 360, or 1/50 of the circumference of Earth.

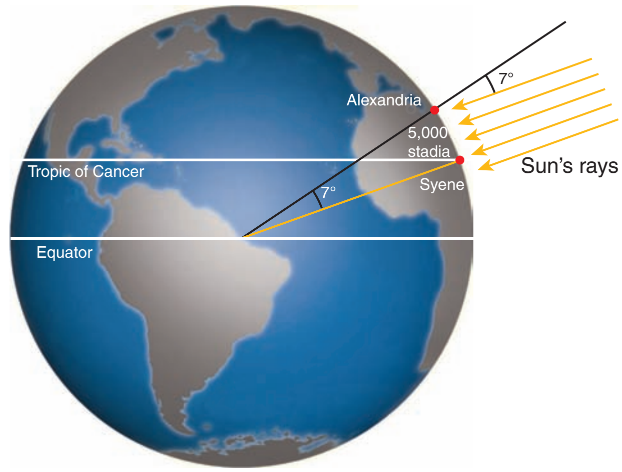


Figure 2.9 Eratosthenes estimated the size of Earth using observations and basic calculations.

It was difficult to estimate distances accurately in those days, and although historians know Eratosthenes concluded that the cities were 5,000 stadia apart, they are still not at all sure of the value of his stadion unit. If the stadion was 185 meters, then Eratosthenes would have worked the math in a similar way:

$$\frac{1}{50} \times C = 5{,}000 \text{ stadia} \times 185 \text{ meters/stadion}$$
$$= 925{,}000 \text{ meters} = 925 \text{ km}$$

Eratosthenes would have found the circumference of Earth to be

$$C = 50 \times 925 \text{ km} = 46{,}250 \text{ km}$$

only about 16 percent higher than the modern value.

Relative Motions and Frame of Reference

Why don't we feel the motion of Earth as it spins on its axis and moves through space in its orbit around the Sun? Astronomers use the concept of a **frame of reference**, which is a coordinate system within which an observer measures positions and motions. The difference in motion between two individual frames of reference is called the **relative motion**. For example, imagine that you are riding in a car traveling down a straight section of highway at a constant speed. If you are not looking out the window or feeling road vibrations, there is no experiment you can easily do to tell the difference between riding in a car down a straight section of highway at constant speed and sitting in the car while it is parked in

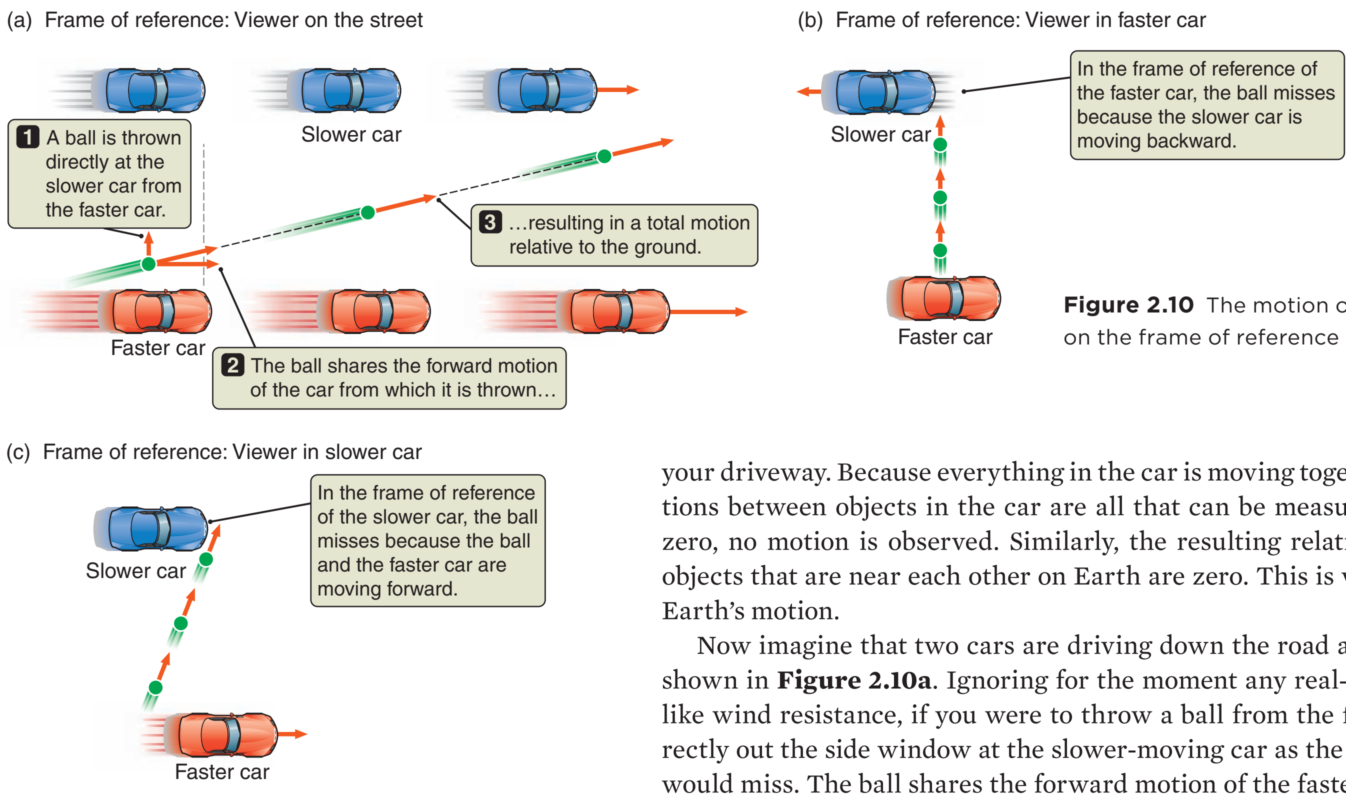


Figure 2.10 The motion of an object depends on the frame of reference of the observer.

your driveway. Because everything in the car is moving together, the relative motions between objects in the car are all that can be measured, and they are all zero, no motion is observed. Similarly, the resulting relative motions between objects that are near each other on Earth are zero. This is why we do not notice Earth's motion.

Now imagine that two cars are driving down the road at different speeds, as shown in **Figure 2.10a**. Ignoring for the moment any real-world complications, like wind resistance, if you were to throw a ball from the faster-moving car directly out the side window at the slower-moving car as the two cars passed, you would miss. The ball shares the forward motion of the faster car, so the ball outruns the forward motion of the slower car. As shown in Figure 2.10b, from your perspective in the faster car, the slower car lagged behind the ball. From the slower car's perspective, represented in Figure 2.10c, your car and the ball sped on ahead.

Although we cannot feel Earth's rotation, it influences things as diverse as the motion of weather patterns on Earth and how an artillery gunner must aim at a distant target. An object on the surface of Earth moves in a circle each day around Earth's rotation axis. This circle is larger for objects near Earth's equator and smaller for objects closer to one of Earth's poles. But all objects must complete their circular motion in exactly 1 day. As you can see in **Figure 2.11**, the surface of Earth moves faster at the equator than at higher latitudes. An object closer to the equator has farther to go each day than does an object nearer a pole. Therefore, the object nearer the equator must be moving faster than the object at higher latitude. If an object starts out at one latitude and then moves to another, its apparent motion over the surface of Earth is influenced by this difference in speed.

Now consider two locations at different latitudes. Imagine that a cannonball is launched directly north from a point in the Northern Hemisphere, as shown in Figure 2.11a. Because the cannon is located nearer to the equator than its target is, the cannonball is moving toward the east faster than its target. Even though the cannonball is fired toward the north, it shares the eastward velocity of the cannon itself. This means that the cannonball is *also* moving toward the east faster than

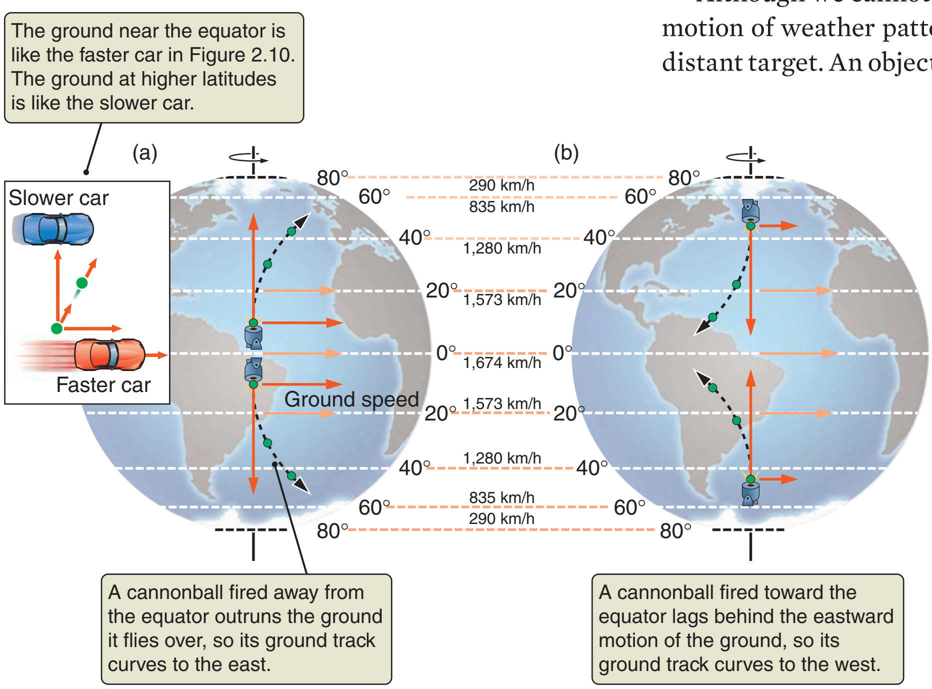


Figure 2.11 The Coriolis effect causes objects to be deflected as they move across the surface of Earth. The green dashed line shows the path of the cannonball as measured by a local observer.

its target. Recall how the ball thrown from the faster car outpaced the slower-moving car in Figure 2.10. Similarly, as the cannonball flies north, it moves toward the east faster than the ground underneath it does. To an observer on the ground, the cannonball appears to curve toward the east as it outruns the eastward motion of the ground it is crossing. The farther north the cannonball flies, the greater the difference between its eastward velocity and the eastward velocity of the ground. Thus, the cannonball follows a path that appears to curve more and more to the east the farther north it goes. If you are located in the Northern Hemisphere and fire a cannonball *south* toward the equator, as shown in Figure 2.11b, the opposite effect will occur. Now the cannon is moving toward the east more slowly than its target. As the cannonball flies toward the south, its eastward motion lags behind that of the ground underneath it, and the cannonball appears to curve toward the west.

This curving motion of objects from the difference in Earth's rotation speeds at different latitudes is called the **Coriolis effect**. In the Northern Hemisphere, the Coriolis effect causes a cannonball fired north to drift to the east as seen from the surface of Earth. In other words, the cannonball appears to curve to the right. A cannonball fired south appears to curve to the west, which also gives it the appearance of curving to the right. In the Northern Hemisphere, the Coriolis effect seems to deflect things to the *right*. If you think through this example for the Southern Hemisphere, you will see that south of the equator, the Coriolis effect seems to deflect things to the *left*. In between, at the equator itself, the Coriolis effect vanishes.

On Earth the effect is enough to deflect a fly ball hit north or south into deep left field in a stadium in the northern United States by about a half a centimeter. At some time or other, the Coriolis effect from the rotation of Earth has probably determined the outcome of a ball game.

CHECK YOUR UNDERSTANDING 2.2

If the star Polaris has an altitude of 35°, then we know that: (a) our longitude is 55° east; (b) our latitude is 55° north; (c) our longitude is 35° west; (d) our latitude is 35° north.

2.2 Revolution about the Sun Leads to Changes during the Year

Earth orbits (or **revolves**) around the Sun in the same direction that Earth spins about its axis—counterclockwise as viewed from above Earth's North Pole (see **Figure 2.12**). A **year** is the time it takes for Earth to complete one revolution around the Sun. The motion of Earth around the Sun is responsible for many of the patterns of change we see in the sky and on Earth, including changes in the stars we see overhead. Because of this motion, the stars in the night sky change throughout the year, and Earth experiences seasons.

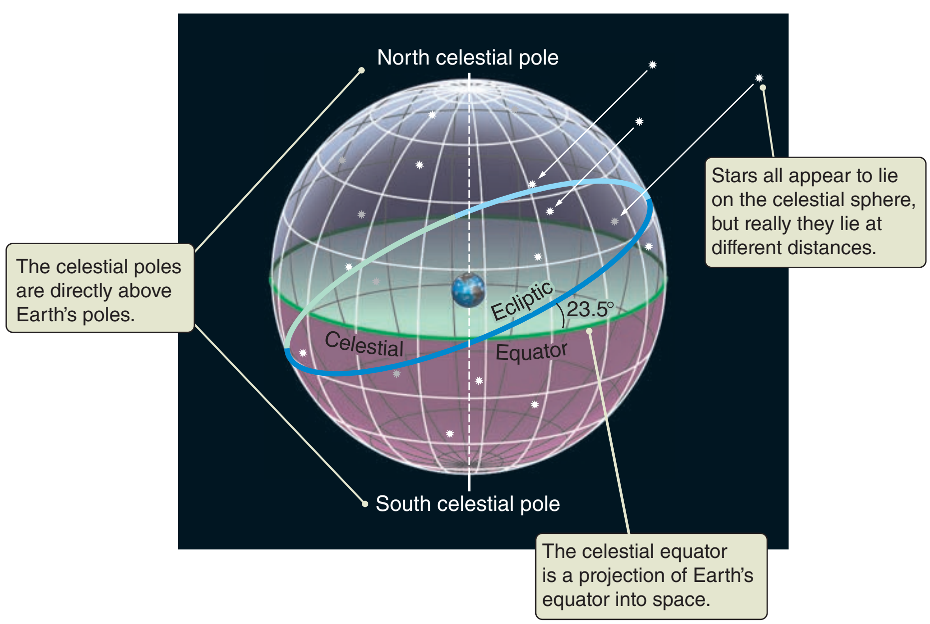


Figure 2.12 The celestial sphere is a useful fiction for thinking about the appearance and apparent motion of the stars in the sky.

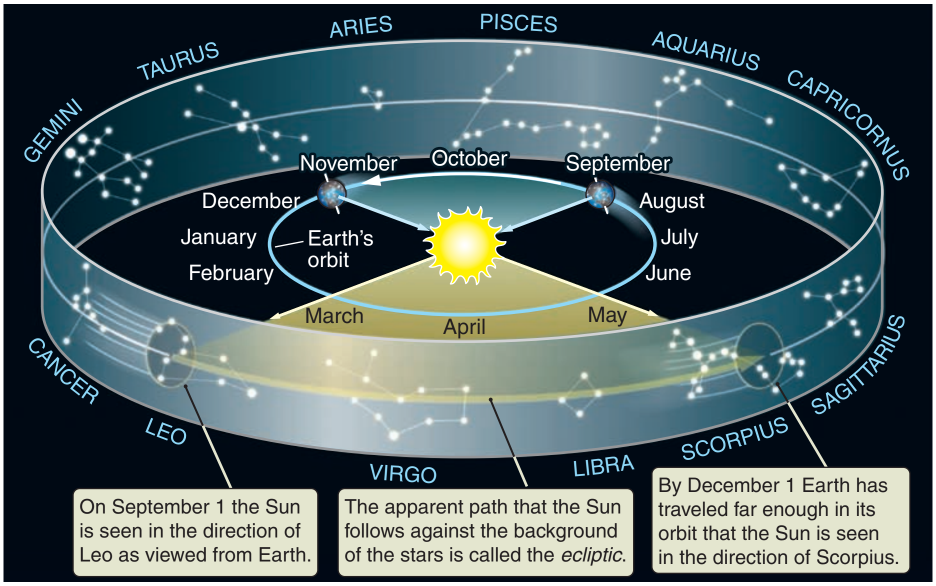


Figure 2.13 As Earth orbits around the Sun, the Sun's apparent position against the background of stars changes. The imaginary circle traced by the annual path of the Sun is called the ecliptic. The blue band shows 12 of the zodiacal constellations along the ecliptic.

Constellations and the Zodiac

As shown in **Figure 2.13**, as Earth orbits the Sun, our view of the night sky changes. Six months from now, Earth will be on the other side of the Sun. The stars that are overhead at midnight 6 months from now are those that are near overhead at noon today. In order to follow the patterns of the Sun and the stars, early humans grouped together stars that formed recognizable patterns, called **constellations**. But people from different cultures saw different patterns and projected ideas from their own cultures onto what they saw in the sky. Constellations named for winged horses, dragons, and other imaginary images, and the stories that go with them, are creations of the human imagination. If you look at the sky, no obvious pictures of these images emerge. Instead, there is only the random pattern of stars—about 5,000 of them visible to the naked eye—spread out across the sky.

Modern constellations visible from the Northern Hemisphere draw heavily from the list of constellations compiled 2,000 years ago by the Alexandrian astronomer Ptolemy. Modern constellation names in the southern sky come from European explorers visiting the Southern Hemisphere during the 17th and 18th centuries. Today, astronomers use an officially sanctioned set of 88 constellations as a kind of road map of the sky. Every star in the sky lies within the borders of a single constellation, and the names of constellations are used in naming the stars that lie within their boundaries. For example, Sirius, the brightest star in the sky, lies within the boundaries of the constellation Canis Major (meaning "big dog"). Following the Greek alphabet, the brightest star in a constellation is called *alpha*, the second brightest is called *beta*, and so forth. The official name of Sirius is Alpha Canis Majoris, indicating that it is the brightest star in Canis Major. Appendix 6 provides sky maps showing the constellations.

Nebraska Simulations: Ecliptic (Zodiac) Simulator

If you could note the position of the Sun relative to the stars each day for a year, you would find that the Sun traces out a great circle against the background of the stars. On September 1, the Sun appears to be in the direction of the constellation Leo. Six months later, on March 1, Earth is on the other side of the Sun, and the Sun appears from our perspective on Earth to be in the direction of the constellation Aquarius. Recall that the apparent path that the Sun follows against the background of the stars is called the ecliptic and is illustrated as the yellow band in Figure 2.13. The 13 constellations that lie along the ecliptic through which the Sun appears to move are called the constellations of the **zodiac**.

The Tilt of Earth's Axis and the Seasons

We have discussed the rotation of Earth on its axis and the revolution of Earth around the Sun. To understand why the seasons change, we need to consider the combined effects of these two motions. Many people believe that Earth is closer to the Sun in the summer and farther away in the winter, and this change in distance causes the seasons. Can this hypothesis be falsified? We can make a prediction that if the distance from Earth to the Sun caused the seasons, then all of Earth should experience summer at the same time of year. But the United States experiences

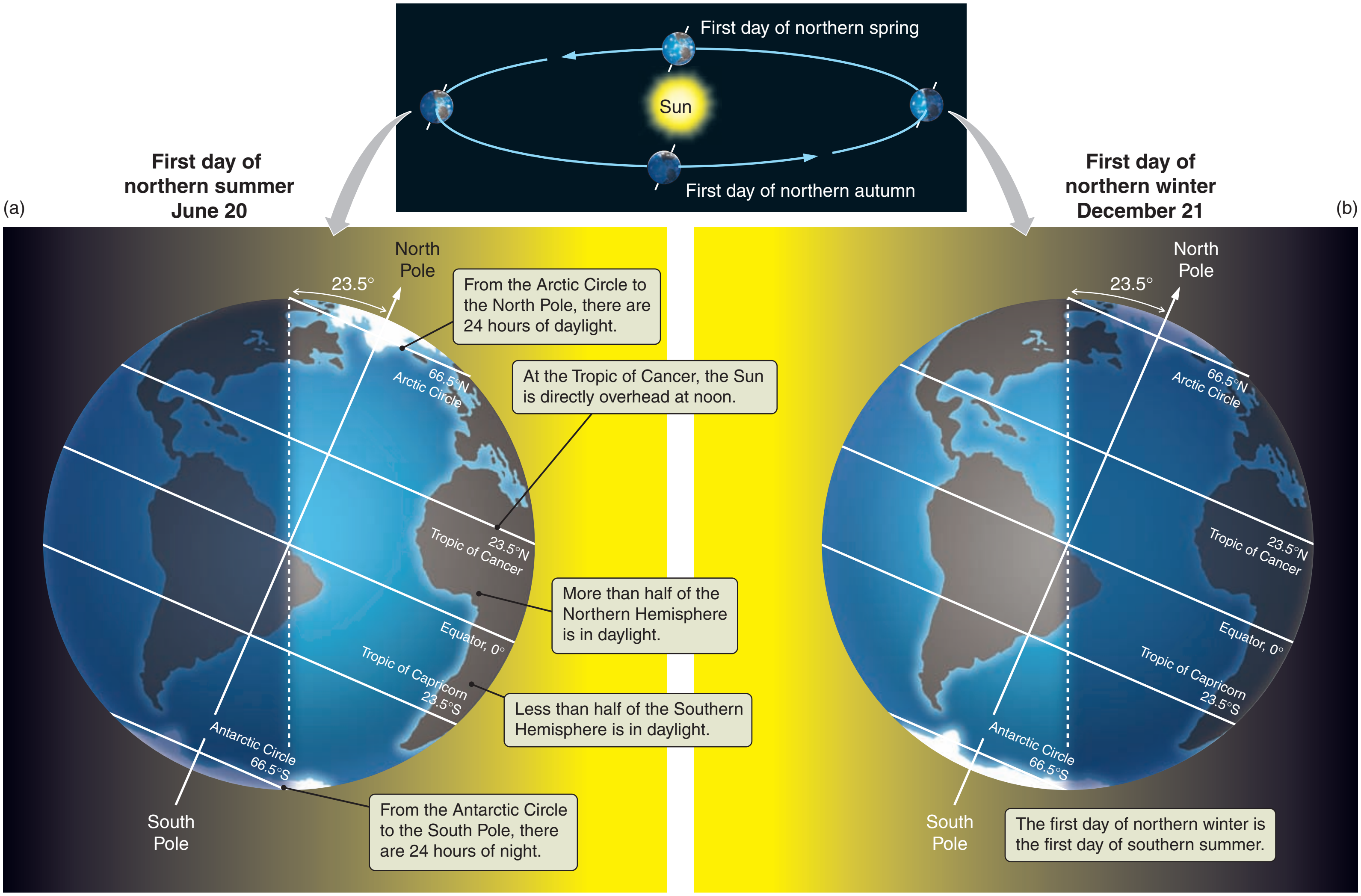


Figure 2.14 (a) On the first day of the northern summer (around June 20, the summer solstice), the northern end of Earth's axis is tilted most nearly toward the Sun, while the Southern Hemisphere is tipped away. (b) Six months later, on the first day of the northern winter (around December 21, the winter solstice), the situation is reversed. Seasons are opposite in the two hemispheres.

summer in June, while Australia experiences summer in December. In modern times, we can directly measure the distance, and we find that Earth is actually closest to the Sun at the beginning of January. We have just falsified this hypothesis, and we need to look for another one that explains all of the available facts.

We observe that as Earth orbits the Sun, the Sun appears to move along the ecliptic, which is tilted 23.5° with respect to the celestial equator. This occurs because Earth's axis of rotation is tilted by 23.5° from the perpendicular to Earth's orbital plane. We notice that during the summer, the days are longer than in winter, and the Sun is higher in the sky as it crosses the meridian in summer than in winter.

Figure 2.14 shows that as Earth moves around the Sun, its axis always points towards Polaris, in the same direction in space. During its orbit, sometimes Earth is on one side of the Sun, and sometimes on the other side. Therefore, sometimes Earth's North Pole is tilted more toward the Sun, and other times the South Pole is tilted more towards the Sun. When Earth's North Pole is tilted toward the Sun, an observer on Earth views the Sun north of the celestial equator; for observers in the Northern Hemisphere, the Sun is above the horizon more than 12 hours each day, thus the days are longer than 12 hours. Six months later, when Earth's North

▶II **AstroTour:** The Earth Spins and Revolves

Nebraska Simulations: Seasons and Ecliptic Simulator

Astronomy in Action: The Cause of Earth's Seasons

Nebraska Simulations: Daylight Hours Explorer

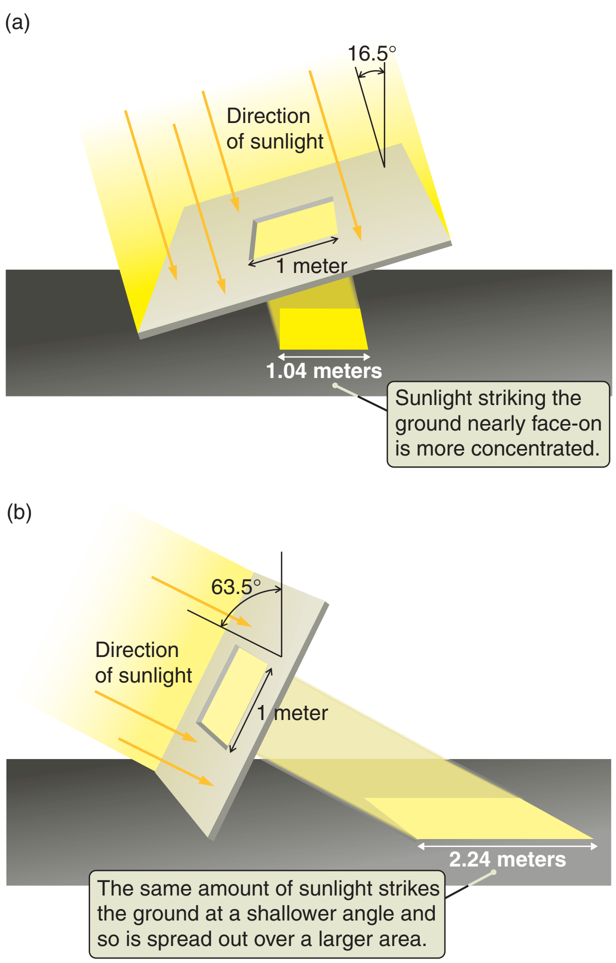


Figure 2.15 Local noon at latitude 40° north. (a) On the first day of northern summer, sunlight strikes the ground almost face-on. (b) On the first day of northern winter, sunlight strikes the ground more obliquely, and less than half as much sunlight falls on each square meter of ground each second.

Pole is tilted away from the Sun, an observer in the same place views the Sun south of the celestial equator.

In the preceding paragraph, we were careful to specify the *Northern* Hemisphere because seasons are opposite in the Southern Hemisphere. Look again at Figure 2.14. Around June 20, while the Northern Hemisphere is enjoying the long days and short nights of summer, Earth's South Pole is tilted away from the Sun. It is winter in the Southern Hemisphere; less than half of the Southern Hemisphere is illuminated by the Sun, and the days are shorter than 12 hours. On December 21, Earth's South Pole is tilted toward the Sun. It is summer in the Southern Hemisphere; the days are long and the nights are short there.

To understand how the combination of Earth's axial tilt and its path around the Sun creates seasons, consider a limiting case. If Earth's spin axis were exactly perpendicular to the plane of Earth's orbit (the **ecliptic plane**), then the Sun would always be on the celestial equator. At every latitude, the Sun would follow the same path through the sky every day, rising due east each morning and setting due west each evening. The Sun would be above the horizon exactly half the time, and days and nights would always be exactly 12 hours long everywhere on Earth. In short, if Earth's spin axis were exactly perpendicular to the plane of Earth's orbit, each day would be just like the last, and there would be no seasons.

The differing length of days through the year is part of the explanation for seasonal temperature changes, but it is not the whole story. Another important effect relates to the angle at which the Sun's rays strike Earth. The Sun is higher in the sky during the summer than it is during the winter, and sunlight strikes the ground *more directly* during the summer than during the winter. To see why this is important, study **Figure 2.15**. During the summer, Earth's surface is more nearly face-on to the incoming sunlight. More energy falls on each square meter of ground each second; the light is concentrated and bright. During the winter, the surface of Earth is more tilted with respect to the sunlight, so the light is more diffuse. Less energy falls on each square meter of the ground each second. This is the main reason why it is hotter in the summer and colder in the winter. As you can see in the **Process of Science Figure**, determining the causes of seasonal change requires accounting for all the known facts.

We can compare the average temperatures found at different latitudes on Earth to see the effect of the height of the Sun in the sky. Near the equator, the Sun passes high overhead every day, regardless of the season. As a result, the average temperatures are warm throughout the year. At high latitudes, however, the Sun is *never* high in the sky, and the average temperatures can be cold and harsh even during the summer. In between, at latitude 40° north, which stretches across the United States from northern California to New Jersey, more than twice as much solar energy falls on each square meter of ground per second at noon on June 20 as falls there at noon on December 21. These two effects—the directness of sunlight and the differing length of the night—mean that the Sun heats a hemisphere more during summer than winter.

The Solstices and the Equinoxes

Four days during Earth's orbit mark unique moments in the year. The day when the Sun is highest in the sky as it crosses the meridian—the line from due north to due south that passes overhead—is called the **summer solstice**. On this day, the Sun rises farthest north of east and sets farthest north of west. This occurs each year near June 20, the first day of summer in the Northern Hemisphere. This orientation of Earth and Sun is shown in Figure 2.14a.

Process of Science

THEORIES MUST FIT ALL THE KNOWN FACTS

Many people misunderstand the phenomenon of changing seasons because they do not account for all the relevant facts.

Take 1

The Hypothesis
We have seasons because Earth is closer to the Sun in summer and farther away in winter.

The Test
If this is true, both the Northern and Southern hemispheres would have summer in July.

The Northern and Southern hemispheres experience opposite seasons.

The Conclusion
The hypothesis is falsified.

Take 2

The Hypothesis
We have seasons because the tilt of Earth's axis causes one hemisphere to be significantly closer to the Sun than the other.

The Test
If this is true, the distances must be very different to cause such a large effect. Earth is tiny compared to its distance from the Sun: the difference in distance between hemispheres is less than 0.004 percent of the distance from the Sun.

The Conclusion
The hypothesis is falsified.

Take 3

The Hypothesis
We have seasons because Earth's tilt changes the distribution of energy—one hemisphere receives more light than the other.

The Test
If this is true, the amount of sunlight striking the ground in the summer should be more than in the winter, and the days should be longer in summer.

The Conclusion
Seasons are caused primarily by a change in illumination due to Earth's tilt. During winter, less energy falls on each square meter of ground per second.

New information often challenges misconceptions.

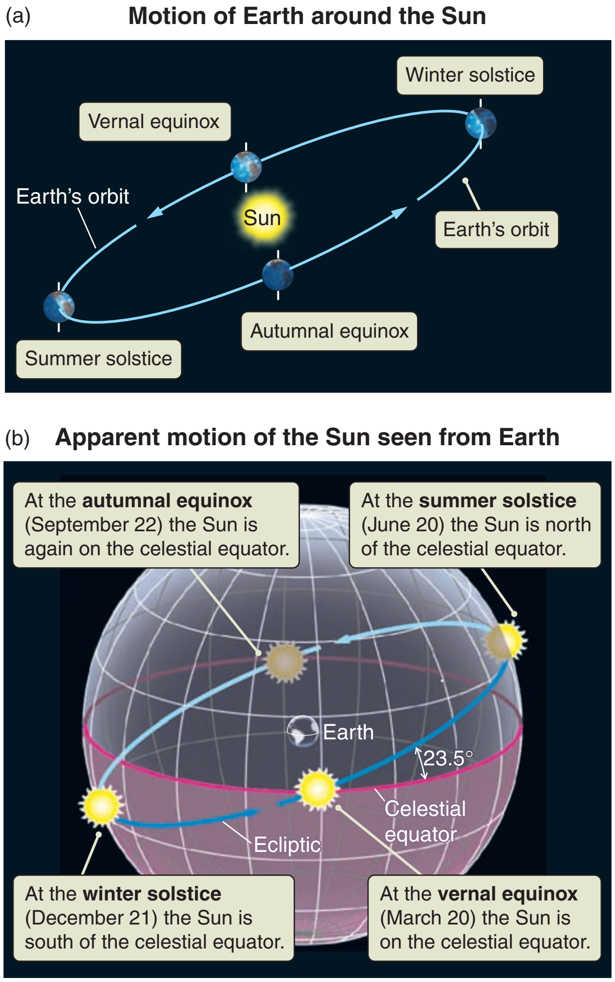


Figure 2.16 The motion of Earth around the Sun is shown from the frame of reference of (a) the Sun and (b) Earth.

Astronomy in Action: The Earth-Moon-Sun System

Six months after the summer solstice, the North Pole is tilted away from the Sun. This day is the **winter solstice** in the Northern Hemisphere, shown in Figure 2.14b. The winter solstice occurs each year about December 21, the shortest day of the year and the first day of winter in the Northern Hemisphere. Almost all cultural traditions in the Northern Hemisphere include a major celebration of some sort in late December. These winter festivals celebrate the return of the source of Earth's light and warmth. The days have stopped growing shorter and are beginning to get longer, and spring will come again.

Between the two solstices, there are two days when the ecliptic crosses the celestial equator. On these days, the Sun lies directly above Earth's equator. We call these days *equinoxes*, which means "equal night," because the entire Earth experiences 12 hours of daylight and 12 hours of darkness. Halfway between summer solstice and winter solstice, the **autumnal equinox** marks the beginning of fall in the Northern Hemisphere; it occurs around September 22. Halfway between winter solstice and summer solstice, the **vernal equinox** marks the beginning of spring in the Northern Hemisphere; it occurs around March 20.

Figure 2.16 shows the solstices and equinoxes from two perspectives. Figure 2.16a shows Earth in orbit around a stationary Sun, and Figure 2.16b shows the Sun's apparent motion along the celestial sphere, which is how it appears to observers on Earth. In both cases, we are looking at the plane of Earth's orbit from the side, so that it is shown in perspective and looks quite flattened. We have also tilted the images so that the North Pole of Earth points straight up. The equinoxes correspond to the points in the sky where the celestial equator meets the ecliptic. Practice shifting between these two perspectives. You will know that you understand these differing perspectives when you are able to look at a position in either panel and predict the corresponding positions of the Sun and Earth in the other panel.

Just as it takes time for a pot of water on a stove to heat up when the burner is turned up and time for the pot to cool off when the burner is turned down, it takes time for Earth to respond to changes in heating from the Sun. The hottest months of northern summer are usually July and August, which come after the summer solstice, when the days are growing shorter. Similarly, the coldest months of northern winter are usually January and February, which occur after the winter solstice, when the days are growing longer. Temperature changes on Earth lag behind changes in the amount of heating we receive from the Sun.

This picture of the seasons must be modified somewhat near Earth's poles. At latitudes north of 66.5° north and south of 66.5° south, the Sun is circumpolar for

Figure 2.17 This composite photo shows the midnight Sun, which can be seen in latitudes above 66.5° north (or south). In the 360-degree panoramic view, the Sun moves 15° each hour.

a part of the year surrounding the first day of summer. These lines of latitude are the **Arctic Circle** and the **Antarctic Circle** (see Figure 2.14). When the Sun is circumpolar, it is above the horizon 24 hours a day, earning the polar regions the nickname "land of the midnight Sun" (**Figure 2.17**). There is an equally long period surrounding the first day of winter when the Sun never rises and the nights are 24 hours long. The Sun never rises high in the Arctic or Antarctic sky, so the sunlight is never very direct. Even with the long days at the height of summer, the Arctic and Antarctic regions remain relatively cool.

In contrast, on the equator, *all* stars are above the horizon 12 hours a day, and the Sun is no exception. On the equator, days and nights are 12 hours long throughout the year. The Sun passes directly overhead on the first day of spring and the first day of autumn because these are the days when the Sun is on the celestial equator. Sunlight is most direct, perpendicular to the ground, at the equator on these days. On the summer solstice, the Sun is at its northernmost point along the ecliptic. On this day, and on the winter solstice, the Sun is farthest from the zenith at noon, and therefore sunlight is least direct at the equator.

As shown in Figure 2.14, latitude 23.5° north is called the Tropic of Cancer, and latitude 23.5° south is called the Tropic of Capricorn. The band between these two latitudes is called the **Tropics**. If you live in the tropics—in Rio de Janeiro or Honolulu, for example—the Sun will be directly overhead at noon twice during the year.

Precession of the Equinoxes

When the Alexandrian astronomer Ptolemy and his associates were formalizing their knowledge of the positions and motions of objects in the sky 2,000 years ago, the Sun appeared in the constellation Cancer on the first day of northern summer and in the constellation Capricornus on the first day of northern winter. Today, the Sun is in Taurus on the first day of northern summer and in Sagittarius on the first day of northern winter. Why have the constellations in which solstices appear changed? There are actually two motions associated with Earth and its axis: Earth spins on its axis, but its axis also wobbles like the axis of a spinning top (**Figure 2.18**). The wobble is very slow: it takes about 26,000 years for the north celestial pole to complete one trip around a large circle centered on the north ecliptic pole. Currently, Polaris is the star we see near the north celestial pole. However, if you could travel several thousand years into the past or future, you would find that the point about which the northern sky appears to rotate is no longer near Polaris, but instead the stars rotate about another point on the path shown in Figure 2.18b. This figure shows the path of the north celestial pole through the sky during one cycle of this wobble.

The celestial equator is perpendicular to Earth's axis. Therefore, as Earth's axis wobbles, the celestial equator must also wobble. As the celestial equator wobbles, the locations where it crosses the ecliptic—the equinoxes—change as well. During each 26,000-year wobble of Earth's axis, the locations of the equinoxes make one complete circuit around the celestial equator. This change of the position of the equinox, due to the wobble of Earth's axis, is called the **precession of the equinoxes**.

CHECK YOUR UNDERSTANDING 2.3

If Earth's axis were tilted by 45°, instead of its actual tilt, how would the seasons be different than they are currently? (a) The seasons would remain the same. (b) Summers would be colder. (c) Winters would be shorter. (d) Winters would be colder.

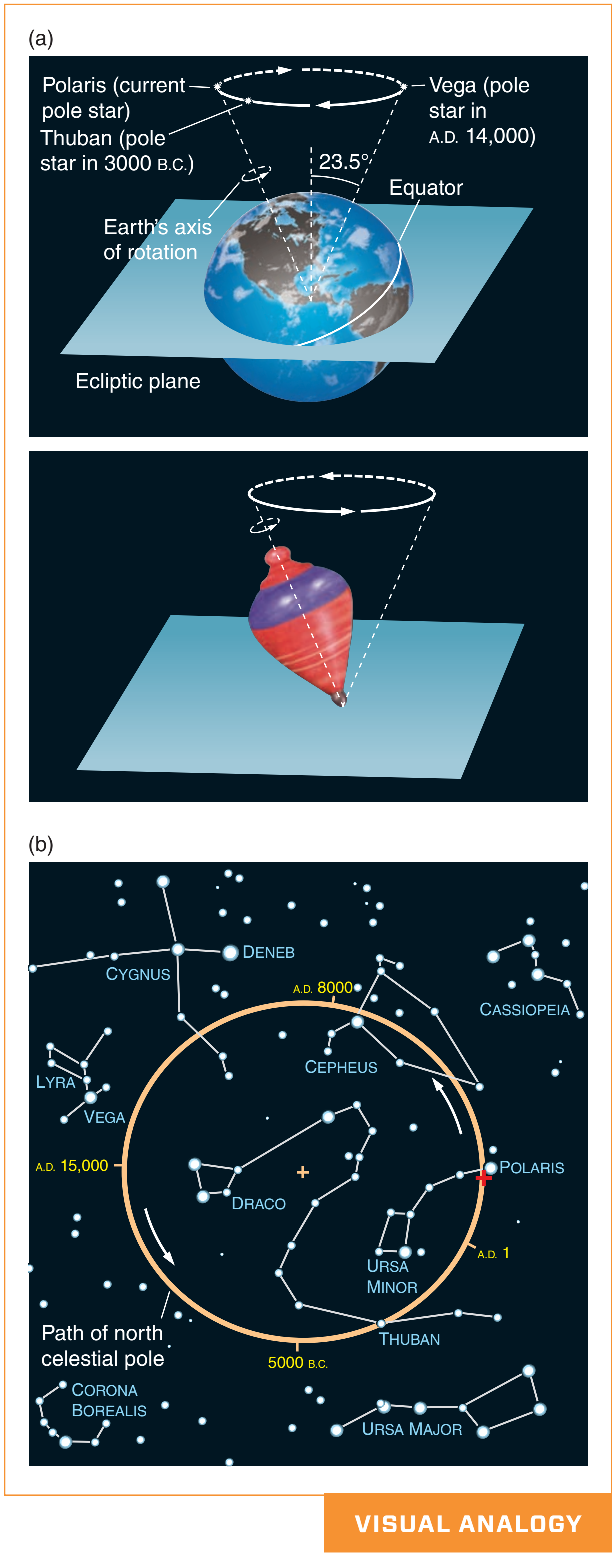


Figure 2.18 (a) Earth's axis of rotation changes orientation in the same way that the axis of a spinning top changes orientation. (b) This precession causes the projection of Earth's rotation axis to move in a circle, centered on the north ecliptic pole (orange cross in the center). The red cross marks the projection of Earth's axis on the sky in the early 21st century.

VISUAL ANALOGY

Figure 2.19 An orange and a lamp can help you visualize the changing phases of the Moon.

2.3 The Moon's Appearance Changes as It Orbits Earth

The most prominent object in our sky after the Sun is the Moon. Just as Earth orbits around the Sun, the Moon orbits around Earth once every 27.3 days. In this section, we will discuss the phases of the Moon as seen from Earth.

The Changing Phases of the Moon

The Moon and its changing aspects have long fascinated humans. We speak of the "man in the Moon," the "harvest Moon," and sometimes a "blue Moon." In mythology, the Moon was the Roman goddess Diana, the Greek goddess Artemis, and the Inuit god Igaluk. The Moon has been the frequent subject of mythology, art, literature, and music.

Unlike the Sun, the Moon has no light source of its own; it shines by reflected sunlight. As the Moon orbits Earth, our view of the illuminated portion of the Moon is constantly changing. These different appearances of the Moon are called **phases** of the Moon. As the Moon orbits Earth, our view of the illuminated portion of the Moon is constantly changing. During a new Moon, when the Moon is between Earth and the Sun, the side facing away from us is illuminated, and during a full Moon, when the Earth is between the Sun and the Moon, the side facing toward us is illuminated. The rest of the time, only part of the illuminated portion can be seen from Earth. Sometimes the Moon appears as a circular disk in the sky. Other times it is nothing more than a thin sliver or its face appears dark.

To help you visualize the changing phases of the Moon, use an orange, a lamp, and your head. Your head is Earth, the orange is the Moon, and the lamp is the Sun (**Figure 2.19**). Turn off all the other lights in the room, and step back as far from the lamp as you can. Hold up the orange slightly above your head so that it is illuminated from one side by the lamp. Move the orange clockwise around your head and watch how the appearance of the orange changes. When you are between the orange and the lamp, the face of the orange that is toward you is fully illuminated. The orange appears to be a bright, circular disk. As the orange moves around its circle, you will see a progression of lighted shapes, depending on how much of the bright side and how much of the dark side of the orange you can see. This progression of shapes exactly mimics the changing phases of the Moon.

Astronomy in Action: Phases of the Moon

Figure 2.20 shows the changing phases of the Moon. The **new Moon** occurs when the Moon is between Earth and the Sun. The far side is illuminated, but the near side is in darkness and we cannot see it. The new Moon appears close to the Sun in the sky, so it is up in the daytime with the Sun: it rises in the east at sunrise, crosses the meridian near noon, and sets in the west near sunset. A new Moon is never above the horizon in the nighttime sky.

AstroTour: The Moon's Orbit: Eclipses and Phases

A few days after a new Moon, as the Moon orbits Earth, a sliver of its illuminated half, called a **waxing crescent Moon**, becomes visible. *Waxing* here means "growing in size and brilliance"; the name refers to the fact that the Moon appears to be "filling out" from night to night at this time. From our perspective, the Moon has also moved away from the Sun in the sky. Because the Moon travels around Earth in the same direction in which Earth rotates, we now see the Moon trailing the Sun, so it is east of the Sun in the sky. A waxing crescent Moon is

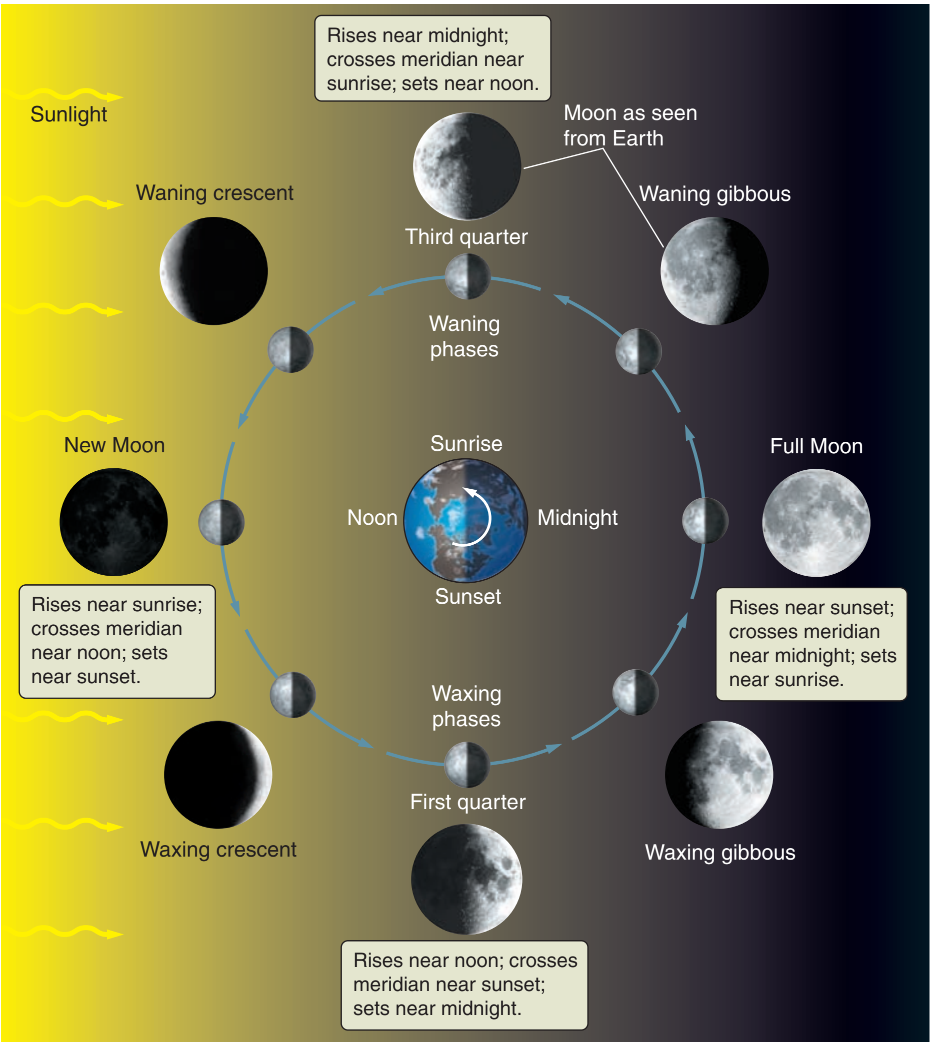


Figure 2.20 The inner circle of images (connected by blue arrows) shows the Moon as it orbits Earth, as seen by an observer far above Earth's North Pole. The Sun is on the left. The outer ring of images shows the corresponding phases of the Moon as seen from Earth.

visible in the western sky in the evening, near the setting Sun but remaining above the horizon after the Sun sets. The "horns" of the crescent always point directly away from the Sun.

As the Moon moves farther along in its orbit, and the angle between the Sun and Moon grows, more and more of its near side becomes illuminated. About a week after the new Moon, half of the near side of the Moon is illuminated and half is in darkness. This phase is called a **first quarter Moon** because the Moon has moved a quarter of the way around Earth and has completed the first quarter of its cycle from new Moon to new Moon. A look at Figure 2.20 shows that the first quarter Moon rises at noon, crosses the meridian at sunset, and sets at midnight.

As the Moon moves beyond first quarter, more than half of its near side is illuminated. This phase is called a **waxing gibbous Moon**, from the Latin *gibbus*, meaning, "hump." The waxing gibbous Moon continues nightly to "grow" until finally we see the entire near side of the Moon illuminated—a **full Moon**. Earth is now between the Sun and the Moon, which appear opposite each other in the sky when viewed from Earth. The full Moon rises as the Sun sets, crosses the meridian at midnight, and sets in the morning as the Sun rises.

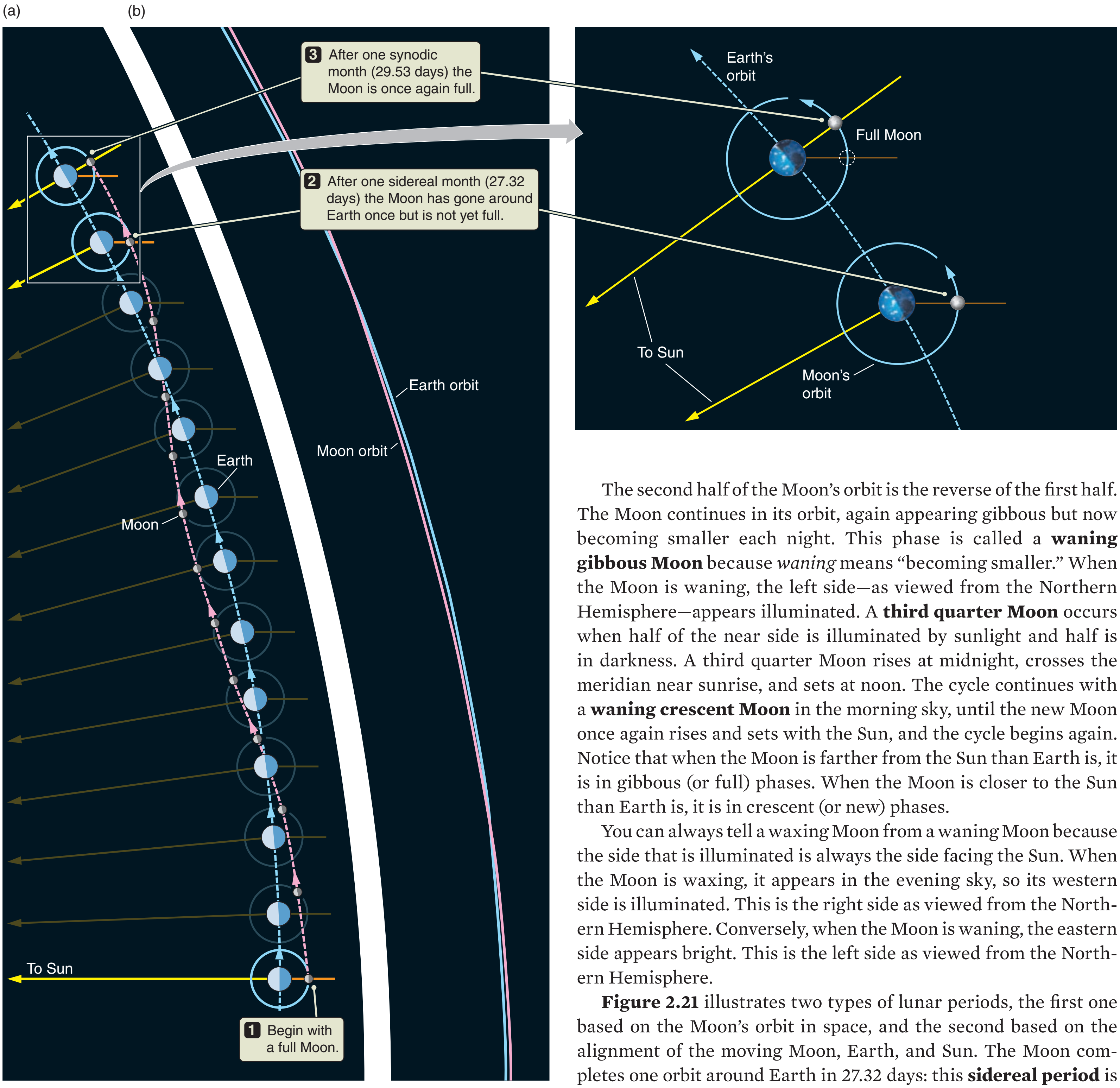


Figure 2.21 (a) The Moon completes one sidereal orbit in 27.32 days, but the synodic period (the period between phases seen from Earth) from one full Moon to the next is 29.53 days. The horizontal orange line to the right of the Moon indicates a fixed direction in space. (b) The orbits of Earth and the Moon are shown here to scale although the sizes of Earth and the Moon are not.

The second half of the Moon's orbit is the reverse of the first half. The Moon continues in its orbit, again appearing gibbous but now becoming smaller each night. This phase is called a **waning gibbous Moon** because *waning* means "becoming smaller." When the Moon is waning, the left side—as viewed from the Northern Hemisphere—appears illuminated. A **third quarter Moon** occurs when half of the near side is illuminated by sunlight and half is in darkness. A third quarter Moon rises at midnight, crosses the meridian near sunrise, and sets at noon. The cycle continues with a **waning crescent Moon** in the morning sky, until the new Moon once again rises and sets with the Sun, and the cycle begins again. Notice that when the Moon is farther from the Sun than Earth is, it is in gibbous (or full) phases. When the Moon is closer to the Sun than Earth is, it is in crescent (or new) phases.

You can always tell a waxing Moon from a waning Moon because the side that is illuminated is always the side facing the Sun. When the Moon is waxing, it appears in the evening sky, so its western side is illuminated. This is the right side as viewed from the Northern Hemisphere. Conversely, when the Moon is waning, the eastern side appears bright. This is the left side as viewed from the Northern Hemisphere.

Figure 2.21 illustrates two types of lunar periods, the first one based on the Moon's orbit in space, and the second based on the alignment of the moving Moon, Earth, and Sun. The Moon completes one orbit around Earth in 27.32 days: this **sidereal period** is how long it takes to return to the same location in its orbit. However, because of the changing relationships among Earth, the Moon, and the Sun due to Earth's orbital motion, it takes 29.53 days to go from one full Moon to the next. This is known as its **synodic period** and is the basis for our "month" because it is what we can easily observe from Earth.

Do not try to memorize all possible combinations of where the Moon is in the sky at what phase and at what time of day. Instead, work on understanding the motion and phases of the Moon, and then use your understanding to figure out the specifics of any given case. To study the phases of the Moon, draw a picture like Figure 2.20, and use it to follow the Moon around its orbit. From your drawing, figure out what phase you would see and where it would appear in the sky at a given time of day. You might also try the simulations described in "Exploration: The Phases of the Moon" at the end of the chapter.

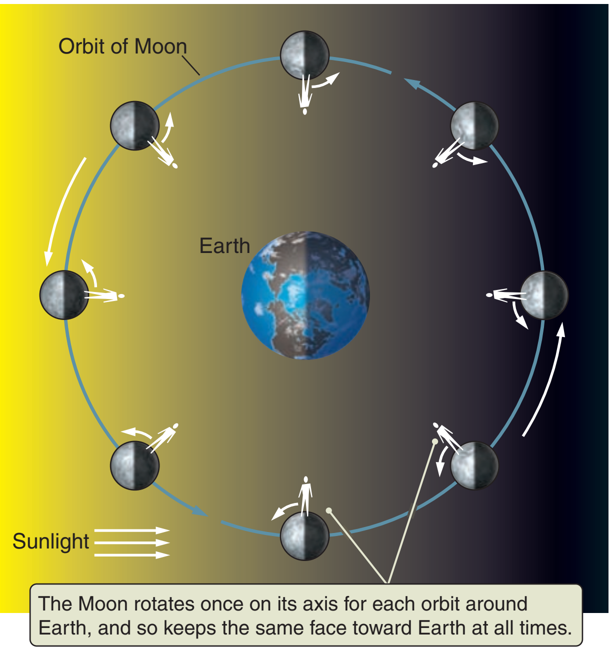


Figure 2.22 The Moon rotates once on its axis for each orbit around Earth—an effect called synchronous rotation. In this illustration, the Sun is far to the left of the Earth-Moon system.

The Visible Face of the Moon

Although the Moon's illumination varies at different parts of its orbit, one aspect of the Moon's appearance that does not change is the face of the Moon that we see. If we were to go outside next week or next month, or 20 years from now, or 20,000 centuries from now, we would still see the same side of the Moon that we see tonight. This happens because the Moon rotates on its axis exactly once for each revolution that it makes around Earth.

Imagine walking around the Washington Monument while keeping your face toward the monument at all times. By the time you complete one circle around the monument, your head has turned completely around once. When you were south of the monument, you were facing north; when you were east of the monument, you were facing west; and so on. But someone looking at you from the monument would always see your face. The Moon does exactly the same thing, rotating on its axis once per revolution around Earth, always keeping the same face toward Earth (**Figure 2.22**). When an object's revolution and rotation are synchronized (or in sync) with each other, its called **synchronous rotation**. We will see other examples of this in our Solar System.

The Moon's *far side*, facing away from Earth, is often called the "dark side of the Moon." In fact, there is no side of the Moon that is always dark. At any given time, half of the Moon is in sunlight and half is in darkness—just as at any given time, half of Earth is in sunlight and half is in darkness. The side of the Moon that faces away from Earth, the "far side," spends just as much time in sunlight as the side of the Moon that faces toward Earth does.

Nebraska Simulations: Lunar Phase Simulator

CHECK YOUR UNDERSTANDING 2.4

You see the Moon rising just as the Sun is setting. What phase is the Moon in?

2.4 Calendars Are Based on the Day, Month, and Year

Archeologists tell us that the development of agriculture was crucial for the rise of human civilization, and keeping track of the seasons and best times of the year to plant and harvest was critical to successful farming. Records going back to the dawn of humanity suggest that people kept track of time by following the patterns in the sky, especially those of the Sun, the Moon and the stars. Some anthropologists have speculated that notches on fragments of bone found in southern France represent a 33,000-year-old lunar calendar. In this section, we will examine some different calendars.

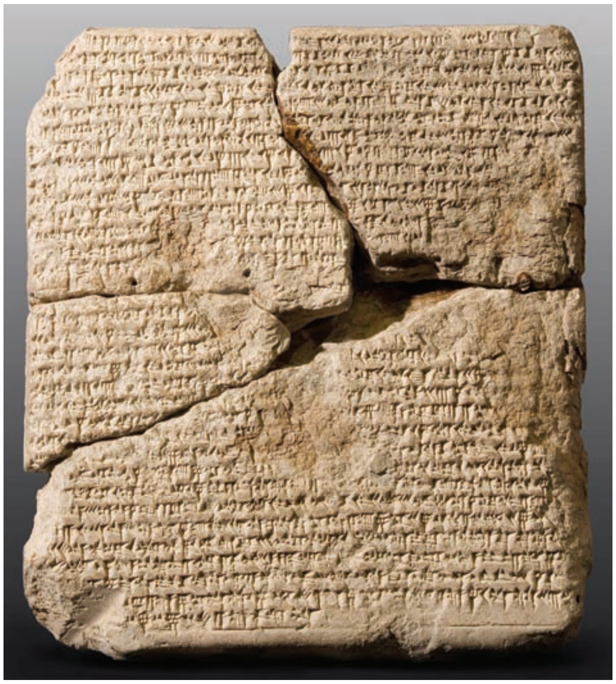


Figure 2.23 The ancient Egyptian calendar used a system of 12 months, plus festival days.

Lunar and Lunisolar Calendars

As civilizations developed around the globe, different cultures tried to solve the "problem" of the calendar. The rates of rotation of Earth and revolutions of the Moon around Earth and Earth around the Sun are not even multiples of each other. A lunar cycle (full Moon to full Moon) is 29.5 days, and a solar cycle—the time it takes for the Sun to appear to move from and return to its highest possible point in the sky at noon on the summer solstice—is 365.24 days. One solar cycle has 12.38 lunar cycles. These fractions of days and months are what make calendars complicated.

Some of the oldest known calendars come from the Egyptians, the Babylonians, and the Chinese. The ancient Egyptians used a system of 12 months of 30 days each—which added up to 360 days—and then added five "festival days" to the end of the year (**Figure 2.23**). Without leap years, this 365-day year led to a drift of the seasons, so an extra month was added when necessary. When we consider how we celebrate the days between the modern December holidays and the New Year, an end-of-year calendar break for festivals seems like a good solution!

The Babylonians started the 24-hour day and 7-day week—7 for the Sun, the Moon, and the 5 planets visible with the naked eye. They created the first *lunisolar* calendar, in which a month began with the first sighting of the lunar crescent, and a 13th month was added when needed to catch up to the solar year. As the Babylonians developed mathematics, they discovered that 235 lunar months equals 19 solar years (and 6,940 days). Then they created a calendar cycle that consisted of 19 years, in which 12 of the years have 12 months and 7 of the years have 13 months, and then the cycle repeats. The ancient Hebrew calendar adopted this cycle, and the Jewish calendar still uses it today. This type of calendar keeps holidays in the same season from year to year, even though the dates are different.

The ancient Chinese calendar dating back several thousand years occasionally added a 13th month. By about 500 BCE, the Chinese were using a year of 365.25 days and a system similar to the Babylonians of adding a 13th month into some years. A few cultures used stellar calendars, for example following the position of a bright star like Sirius or certain prominent groups of stars in their sky, such as the Pleiades or the Big Dipper, to mark out a year.

The Islamic calendar is a purely lunar calendar, with no 13th lunar month added in. Their 12 months of 29 or 30 days each add up to 354 days—11.24 days short of the solar year. For this reason, the Islamic New Year and all other holidays drift earlier in each successive solar year. In the Islamic calendar, a holiday may fall in the winter in some years, and then a few years later it will have moved back to autumn.

The Modern Civil Calendar

The international civil calendar used today is a solar calendar known as the **Gregorian calendar**. It is based on the **tropical year**, which measures the 365.242 solar days from one vernal equinox to the next. A **solar day** is the 24-hour period of Earth's rotation that brings the Sun back to the same local meridian. This is in contrast to the **sidereal day**, which is the time it takes for Earth to make one rotation and face the exact same star on the meridian. The sidereal day is about 23 hours 56 minutes and differs from the solar day because of Earth's motion around the Sun.

Nebraska Simulations: Synodic Lag

The Gregorian calendar includes a system of **leap years**—years in which a 29th day is added to the month of February—decreed by Julius Caesar in 45 BCE to make up for the extra fraction of a day. Leap years prevent the seasons from slowly sliding through the year to become increasingly out of sync with the months, so we don't end up experiencing winter in December one year and in August other years.

The Gregorian calendar is named for Pope Gregory XIII. He was concerned that the Easter holiday, which falls on the first Sunday after the first full Moon following March 21, was drifting away from the vernal (spring) Equinox. Julius Caesar's rule of one leap year every 4 years resulted in an average year of 365.25 days, but the actual year is 365.242 days. This difference of 0.008 day is about 11.5 minutes per year, or 3 days every 400 years, and by Gregory's time it had caused the date of the vernal equinox to drift in the Julian calendar by about 10 days. So in 1582, Pope Gregory decreed that 10 days would be deleted from the calendar to move the vernal equinox back to March 21. To make this work out better in the future, he declared that only century years divisible by 400 are leap years, thereby deleting 3 leap years (and the 3 days) every 400 years. Catholic countries followed this system immediately, but Protestant countries did not adopt it until the 1700s. Eastern Orthodox countries, including Russia, did not switch from the Julian to the Gregorian calendar until the 1900s. One slight further revision—making years divisible by 4,000 into common 365-day years—has been proposed so the modern Gregorian calendar will slip by about only 1 day in 20,000 years.

Despite international adoption of the Gregorian calendar, billions of people still celebrate holidays and festivals according to a lunisolar or lunar calendar. Chinese New Year, Passover, Easter, Ramadan, Rosh Hashanah, and Diwali, among others, have dates that change from one year to the next because they are based on lunar months from lunisolar or lunar calendars. The astronomy of people from long ago is still in use today.

CHECK YOUR UNDERSTANDING 2.5

Suppose that the astronomical cycles were even multiples of each other, so that a month was precisely 30 days, and a year was precisely 12 months. How would this change the dates of "wandering" holidays such as Chinese New Year or Ramadan?

2.5 Eclipses Result from the Alignment of Earth, Moon, and the Sun

For ancient peoples attuned to the patterns of the sky, it must have been terrifying to look up to see the Sun being eaten away as if by a giant dragon or the full Moon turning the color of blood. An **eclipse** is the total or partial obscuration of one celestial body, or the light from that body, by another celestial body. Archaeological evidence suggests that ancient peoples put great effort into trying to figure out the pattern of eclipses and thereby bring them into the orderly scheme of the heavens. Stonehenge, pictured in Figure 2.1a, may have enabled its builders to predict when eclipses might occur. Ancient Chinese, Babylonian, and Greek astronomers had figured out that eclipses occur in cycles, and they were able to use their knowledge to make predictions about when and where eclipses would occur. In this section, we will describe the different types of eclipses and their frequency.

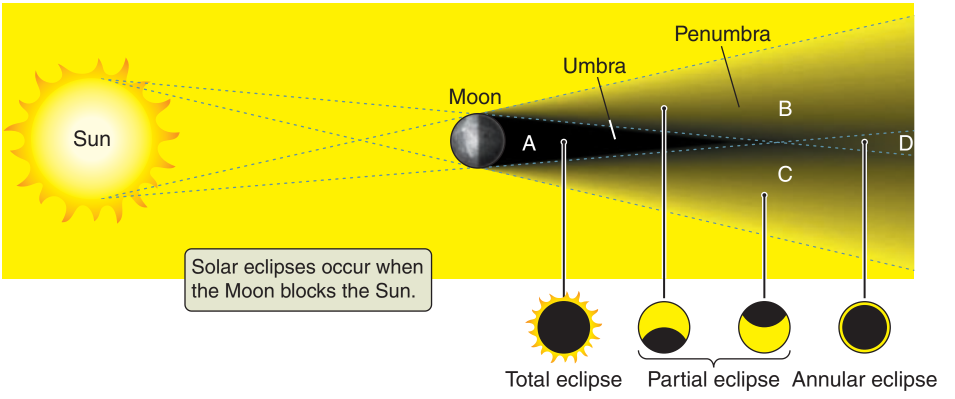


Figure 2.24 Different parts of the Sun are blocked at different places within the Moon's shadow. An observer on Earth in the umbra (point A) sees a total solar eclipse, observers in the penumbra (points B and C) see a partially eclipsed Sun, and observers at point D see an annular solar eclipse.

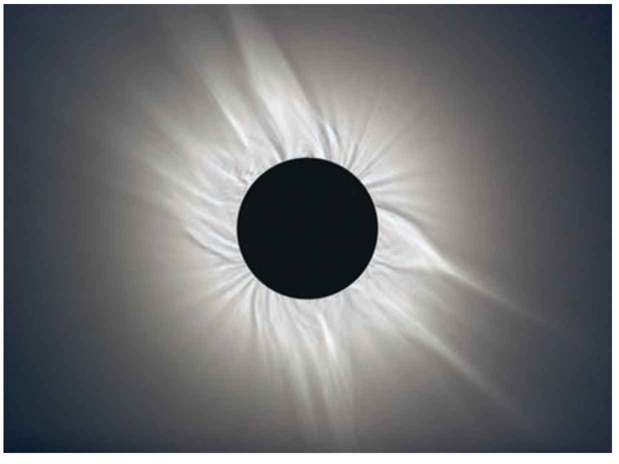


Figure 2.25 The full spectacle of a total eclipse of the Sun.

Solar Eclipses

A **solar eclipse** occurs when the Moon passes between Earth and the Sun; observers on Earth in the shadow of the Moon will see the eclipse. There are three different types of solar eclipses: *total*, *partial*, and *annular*. Consider the structure of the shadow of the Sun cast by a round object such as the Moon, as shown in **Figure 2.24**. An observer at point A would be unable to see any part of the surface of the Sun. This darkest, inner part of the shadow is called the **umbra**. If a location on Earth passes through the Moon's umbra, the Sun's light is totally blocked by the Moon, and a **total solar eclipse** will be observed (**Figures 2.25 and 2.26a**). At points B and C in Figure 2.24, an observer can see one side of the disk of the Sun but not the other. This outer region, which is only partially in shadow, is the **penumbra**. If a location on the surface of Earth passes through the Moon's penumbra, viewers at that location will observe a **partial solar eclipse**, in which the disk of the Moon blocks the light from a portion of the Sun's disk.

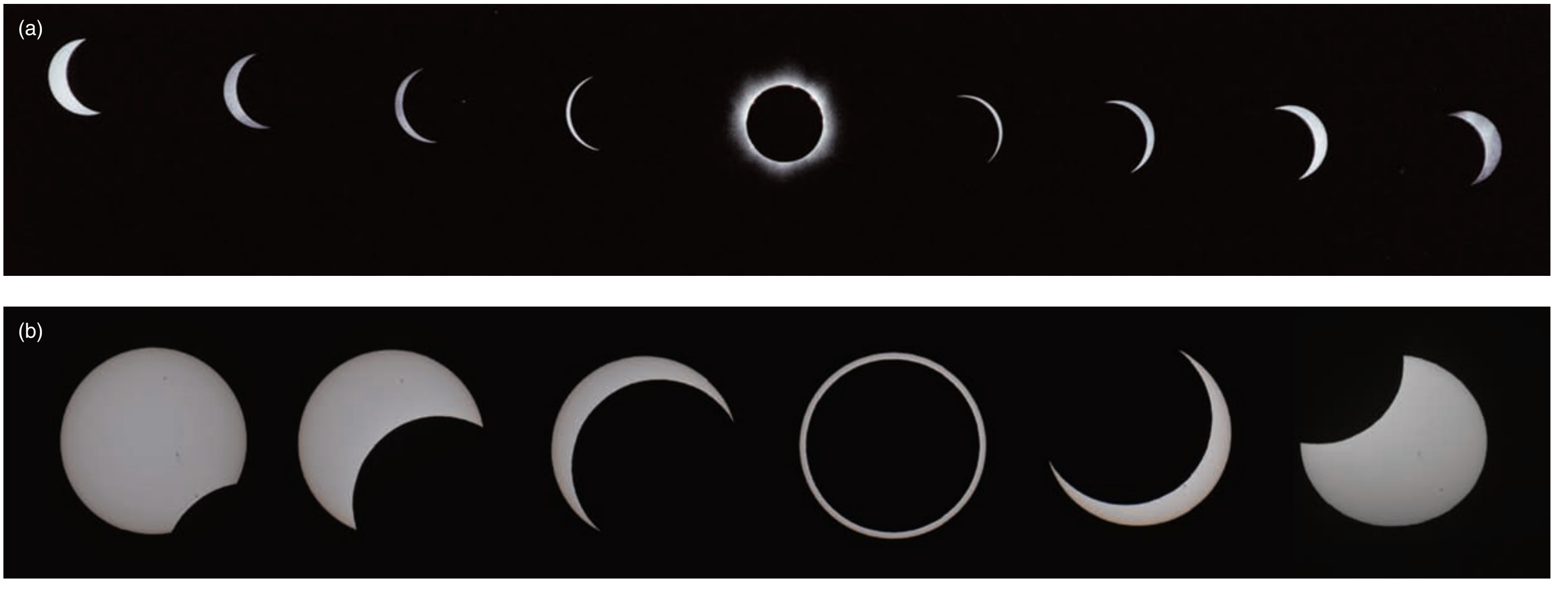


Figure 2.26 Time sequences of images of the Sun taken (a) during a total solar eclipse and (b) during the annular solar eclipse of May 20, 2012. The Sun set during the ending phases.

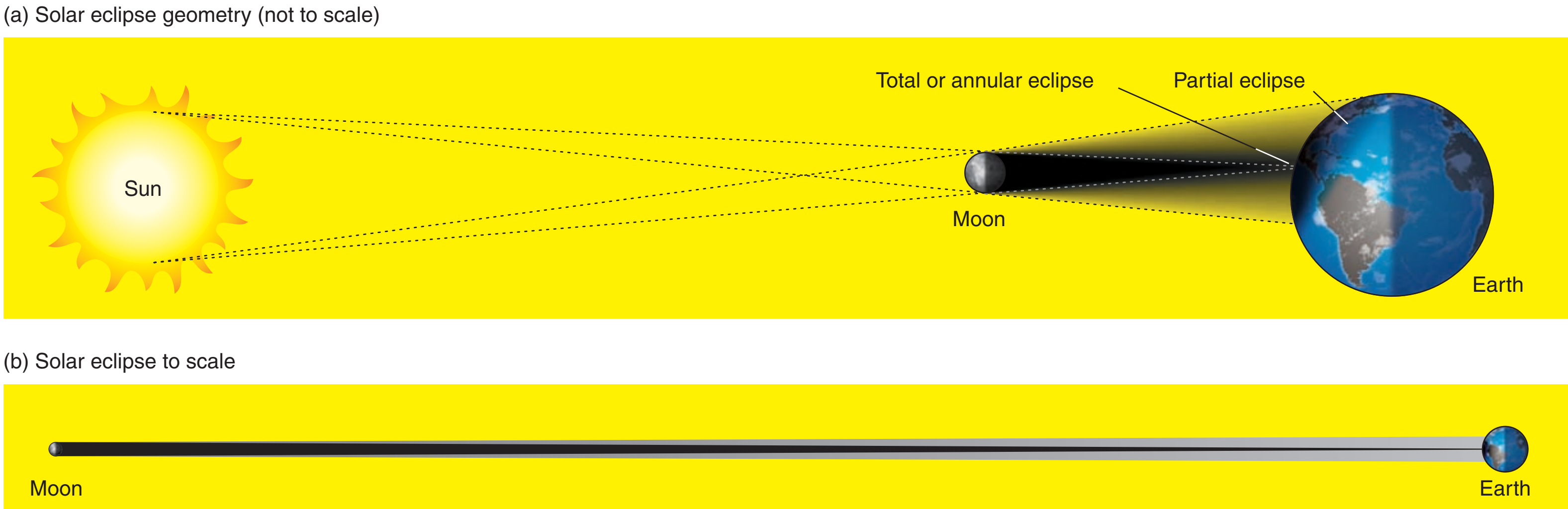


Figure 2.27 (a, b) A solar eclipse occurs when the shadow of the Moon falls on the surface of Earth. Note that (b) is drawn to proper scale.

In the third type of solar eclipse, called an **annular solar eclipse**, the Sun appears as a bright ring surrounding the dark disk of the Moon (Figure 2.26b). An observer at point D in Figure 2.24 is far enough from the Moon that the Moon's apparent size in the sky is smaller than the Sun's. The apparent size of an object in the sky depends on the object's actual size and its distance from us. The Sun is about 400 times the diameter of the Moon, and the distance between the Sun and Earth is about 400 times more than the distance between the Moon and Earth. As a result, the Moon and Sun have almost exactly the same apparent size in the sky. Another factor is that the Moon's orbit is not a perfect circle. When the Moon and Earth are a bit closer together than average, the Moon appears slightly larger in the sky than the Sun. An eclipse occurring at that time will be total for some observers. When the Moon and Earth are farther apart than average, the Moon appears smaller than the Sun, so eclipses occurring during this time will be annular for some observers. Among all solar eclipses, one-third are total at some location on the surface of Earth, one-third are annular, and one-third are seen only as a partial eclipse.

Figure 2.27 shows the geometry of a solar eclipse when the Moon's shadow falls on the surface of Earth. Figures like this usually show Earth and the Moon much closer together than they really are. The page is too small to draw them correctly and still see the critical details. The relative sizes and distances between Earth and the Moon are roughly equivalent to the difference between a basketball and a tennis ball placed 7 meters apart. Figure 2.27b shows the geometry of a solar eclipse with Earth, the Moon, and the separation between them drawn to the correct scale. Compare this drawing to Figure 2.27a and you will understand why drawings of Earth and the Moon are rarely drawn to the correct scale. If the Sun were drawn to scale in Figure 2.27a, it would be bigger than your head and located almost 64 meters off the left side of the page.

From any particular location, you are more likely to observe a partial solar eclipse than a total solar eclipse. Where the Moon's penumbra touches Earth, it has a diameter of almost 7,000 km—large enough to cover a substantial fraction of Earth. Thus, a partial solar eclipse is often visible from many locations on

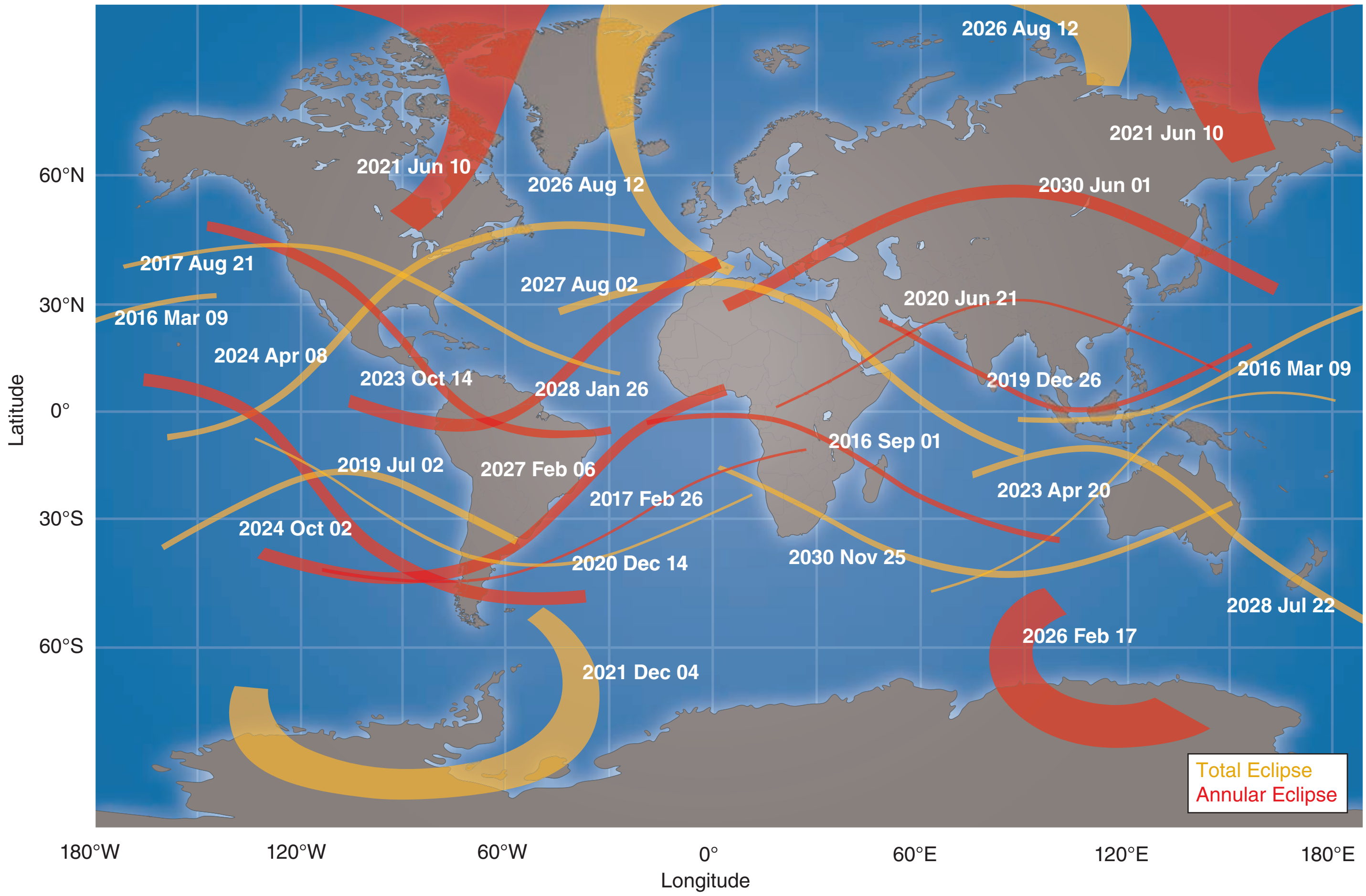


Figure 2.28 The paths of total solar eclipses through 2020. Solar eclipses occurring in Earth's polar regions cover more territory because the Moon's shadow hits the ground obliquely.

Earth. In contrast, the path along which a total solar eclipse can be seen, shown in **Figure 2.28**, covers only a tiny fraction of Earth's surface. Even when the distance between Earth and the Moon is at a minimum, the umbra is only 270 km wide at the surface of Earth. As the Moon moves along in its orbit, this tiny shadow sweeps across the face of Earth at speeds of a few thousand kilometers per hour. Additionally, the Moon's shadow falls on the curved surface of Earth, causing the region shaded by the Moon during a solar eclipse to be elongated by differing amounts. The curvature can even cause an eclipse that started out as annular to become total.

The result is that a total solar eclipse can never last longer than 7½ minutes and is usually significantly shorter. Even so, it is one of the most amazing sights in nature. People all over the world flock to the most remote corners of Earth to witness the fleeting spectacle of the bright disk of the Sun blotted out of the daytime sky. Perhaps you saw some of the annular eclipse that was visible from much of the United States in May 2012. The first total solar eclipse since 1979 that will be visible in the continental United States will take place in August 2017 (followed by another in 2024). Annular eclipses will be visible from parts of the United States in 2021 and 2023. Viewing a solar eclipse should be on your lifetime to-do list!

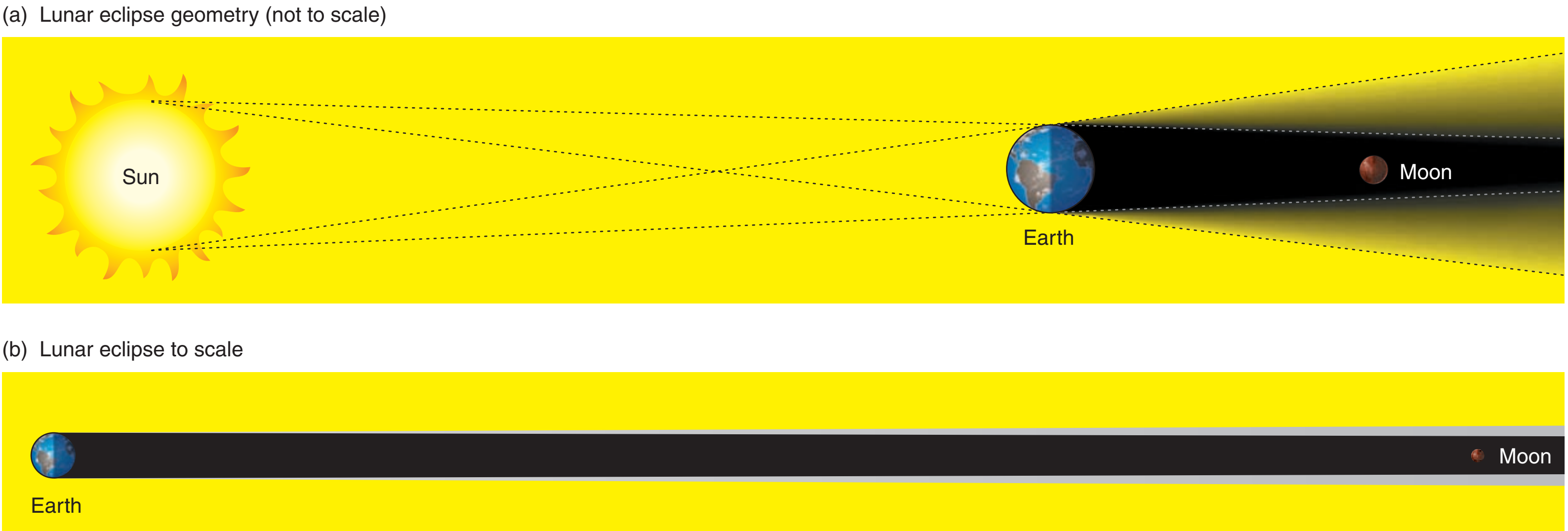


Figure 2.29 (a, b) A lunar eclipse occurs when the Moon passes through Earth's shadow. Note that (b) is drawn to proper scale.

Lunar Eclipses

Lunar eclipses occur when the Moon moves through the shadow of Earth. The geometry of a lunar eclipse is shown in **Figure 2.29a** and is drawn to scale in Figure 2.29b. Here Earth is between the Sun and the Moon. Because Earth is much larger than the Moon, the dark umbra of Earth's shadow at the distance of the Moon is more than 2½ times the diameter of the Moon. A **total lunar eclipse**, when the Moon is entirely within Earth's shadow, lasts as long as 1 hour 40 minutes. In a total lunar eclipse, the Moon often appears red (**Figure 2.30a**). This "blood-red Moon," as it has been called in literature and poetry, occurs because the Moon is being illuminated by red light from the Sun that is bent as it travels through Earth's atmosphere and hits the Moon. Other colors of light are absorbed or scattered away from the Moon by Earth's atmosphere and therefore do not illuminate it.

A **penumbral lunar eclipse** occurs when the Moon passes through the penumbra of Earth's shadow; these are noticeable only from a very dark location or when the Moon passes within about 1,000 km of the umbra. If Earth's shadow incompletely covers the Moon, some of the disk of the Moon remains bright and some of it is in shadow. This is called a **partial lunar eclipse**. Figure 2.30b shows a composite of images taken at different times during a partial lunar eclipse. In the center image, the Moon is nearly completely eclipsed by Earth's shadow.

Many more people have observed a total lunar eclipse than have observed a total solar eclipse. To see a total solar eclipse, you must be located within that very narrow band of the Moon's shadow as it moves across Earth's surface. In contrast, when the Moon is immersed in Earth's shadow, anyone located in the hemisphere of Earth that is facing the Moon can see it. As a result, from any location, total eclipses of the Moon are relatively common, and you may have seen at least one.

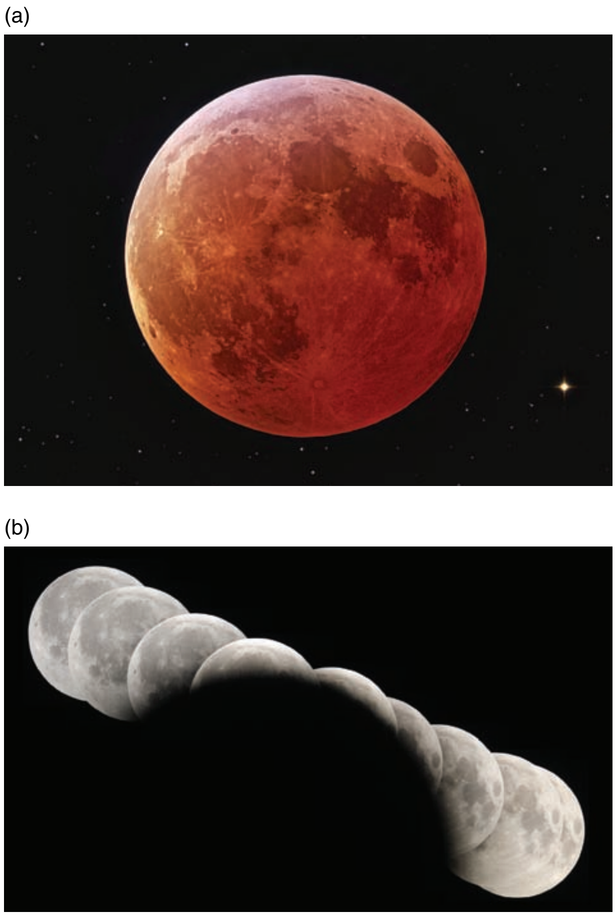


Figure 2.30 (a) During a total lunar eclipse, the Moon often appears blood red. (b) A time-lapse series of photographs of a partial lunar eclipse clearly shows Earth's shadow. Note the size of Earth's shadow compared to the size of the Moon.

Frequency of Eclipse Seasons

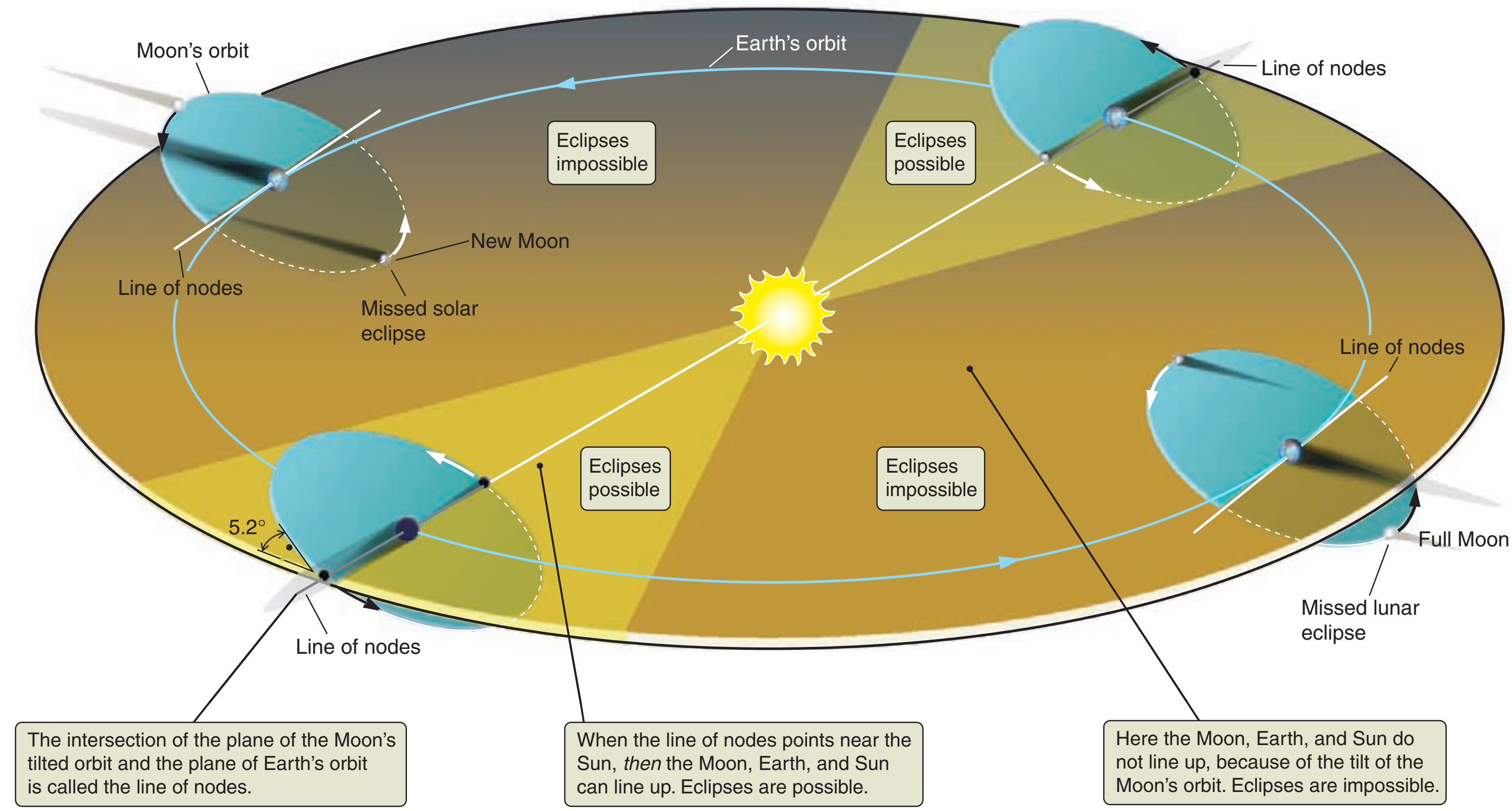
How did some people in ancient cultures successfully predict eclipses? From their understanding of lunar and solar cycles for making calendars, they were able to compute cycles of eclipses. Imagine Earth, the Moon, and the Sun all sitting on the same flat tabletop. If the Moon's orbit were in exactly the same plane as the orbit of Earth, then the Moon would pass directly between Earth and the Sun at every new Moon. The Moon's shadow would pass across the face of Earth, and we would see a solar eclipse. Similarly, Earth would pass directly between the Sun and the Moon every synodic month, and a lunar eclipse would occur at each full Moon. However, you know from experience that you don't see a lunar eclipse every time the Moon is full, nor do you observe a solar eclipse every time the Moon is new. These observations tell us something about how the Moon's orbit around Earth is oriented with respect to Earth's orbit around the Sun.

Nebraska Simulations: Moon Inclinations; Eclipse Shadow Simulator

Solar and lunar eclipses do not happen every month because the Moon's orbit does not lie in exactly the same plane as the orbit of Earth. As you can see in **Figure 2.31**, the plane of the Moon's orbit around Earth is inclined by about 5.2° with respect to the plane of Earth's orbit around the Sun. The line along which the orbital plane of the Sun and the orbital plane of the Moon intersect is called the **line of nodes**. For part of the year, the line of nodes points in the general direction of the Sun. During these times, called **eclipse seasons**, a new Moon passes directly between the Sun and Earth, casting its shadow on Earth's surface and causing a solar eclipse. Similarly, a full Moon occurring during an eclipse season passes through Earth's shadow, and a lunar eclipse results. An eclipse season lasts only 38 days. That's how long the Sun is close enough to the line of nodes for eclipses to occur. Most of the time the line of nodes points farther away from the Sun, and Earth, Moon, and Sun cannot line up closely enough for an eclipse to occur. At these times, a solar eclipse cannot take place because the shadow of a new Moon passes "above" or "below" Earth. Similarly, no lunar eclipse can occur because a full Moon passes "above" or "below" the shadow of Earth.

If the plane of the Moon's orbit always had the same orientation, then eclipse seasons would occur twice a year, as suggested by Figure 2.31. In actuality, eclipse

Figure 2.31 Eclipses are possible only when the Sun, Moon, and Earth lie along (or very close to) an imaginary line known as the line of nodes. When the Sun does not lie along the line of nodes, Earth passes under or over the shadow of a new Moon, and a full Moon passes under or over the shadow of Earth.



seasons occur about every 5 months 20 days. The roughly 10-day difference is due to the fact that the plane of the Moon's orbit slowly wobbles, much like the wobble of a spinning plate balanced on the end of a circus performer's stick. As it does so, the line of nodes changes direction. This wobble rotates in the direction opposite the direction of the Moon's motion in its orbit. That is, the line of nodes moves clockwise as viewed from above Earth's orbital plane. One wobble of the Moon's orbit takes 18.6 years, so we say that the line of nodes regresses at a rate of 360° every 18.6 years, or 19.4° per year. This amounts to about a 20-day regression each year. If January 1 marks the middle of an eclipse season, the next eclipse season will be centered around June 20, and the one after that around December 10.

Nebraska Simulations: Eclipse Table

CHECK YOUR UNDERSTANDING 2.6

If the Moon were in its same orbital plane but twice as far from Earth, which of the following would happen? (a) The Moon would not go through phases. (b) Total eclipses of the Sun would not be possible. (c) Annular eclipses of the Sun would not be possible. (d) Total eclipses of the Moon would not be possible.

Origins

The Obliquity of Earth

The various motions of Earth give rise to the most basic of patterns faced by life on Earth. Earth's rotation is responsible for the cycle of night and day. Earth's axial tilt and its passage around the Sun bring the change of the seasons. As life evolved on Earth, it had to adapt to these patterns.

The range of climate on Earth based on distance from the equator likely has contributed to the broad diversity of life of our planet. Earth's biodiversity includes life that adapted to the long, cold polar nights and life in equatorial latitudes that adapted to much higher temperatures. Earth's life adapted to seasonal patterns in rain and drought, leading to acquired seasonal patterns of migration and reproduction. If Earth had no axial tilt, the poles would continually be in winter and probably too cold for humans. Midlatitudes would not have the cool winters that are needed for many food crops. Latitudes near the equator would be even consistently warmer than they are now.

Life might have been affected by periodic changes in Earth's axial tilt. If Earth's tilt were larger than 23.5°, the seasonal variation would be even stronger. If the tilt were smaller, the seasonal variation would be weaker. Chinese, Indian, Greek, and Arabic records going back 3,000 years indicate that the tilt was estimated in ancient times by measuring the length of the shadow from a vertical pole on the day of the solstice. We now know that for the past few million years, Earth's axial tilt actually varied from 22.1° to 24.5° over a 41,000-year cycle. The Moon's gravity is responsible for maintaining the tilt within this small range over the past half-billion years—about the time since animal life greatly diversified on Earth. Currently, the tilt is about midway between the two extremes and getting smaller. It will reach its minimum value of 22.1° in about 10,000 years. Scientists are studying whether this variation in tilt correlates with periods of temperature change on Earth, especially the times of ice ages.

Nebraska Simulation: Obliquity Simulator

The first total solar eclipse in the continental United States in decades will take place in August 2017. In this story, one town claims that it will be the best place to see the eclipse.

ARTICLES QUESTIONS

Thousands Expected in Hopkinsville for 2017 Solar Eclipse

By **ADAM GHASSEMI**

HOPKINSVILLE, Kentucky—Hopkinsville has a population of a little more than 30,000 but in 2017 it's expected to more than double for just a few days.

"It's going to be a really big deal," said Cheryl Cook with the Hopkinsville-Christian County Convention and Visitors Bureau who started planning seven years ago for the biggest event they've ever seen. "It could cause traffic jams from here to Nashville," she said.

Visitors are coming from places as far away as Germany, Australia, and Japan to see a total eclipse for 2:40 of darkness.

It's so rare, a map of the projected path has been hanging in the office of Austin Peay Astronomy Professor Spencer Buckner for 15 years.

"The best place on Earth that will have the longest period of totality is actually just north and west of Hopkinsville," Buckner said Friday. "I don't know of another one that will happen in the next few hundred years."

City leaders want to make sure they don't miss any details, like visitors have protective eyewear to see the eclipse, or cutting electricity off in certain parts of the city. That way when things do go dark, lights won't automatically come on and disrupt the view.

"We're hoping for a bright, sunny, warm day. No clouds in the sky," Cook said.

Scientists are planning how they'll capture and study the eclipse along its cross-country path from Oregon to South Carolina, while "eclipse chasers" have their trips to Hopkinsville already confirmed.

"Over 400 rooms booked," said Chairman of the Hopkinsville-Christian County Convention and Visitors Bureau Board Jeff Smith. "I've never seen anything like this."

When the Moon perfectly aligns with the Sun there won't be any better place in the world to see it on August 21, 2017.

"The world's coming to Hopkinsville," Cook went on to say.

Spectators will be able to see the eclipse from a number of places across Southern Kentucky and Middle Tennessee, but people just 70 miles from Hopkinsville in Nashville will get 44 fewer seconds to witness it.

ARTICLES QUESTIONS

1. Why are people excited about this solar eclipse?
2. How long is this eclipse as seen from Hopkinsville? Explain why people in Nashville observe a much shorter eclipse.
3. Would you predict that there will be a lunar eclipse in summer 2017? If so, what are the possible dates?
4. Look at the map on the NASA eclipse page: http://eclipse.gsfc.nasa.gov/SEgoogle/SEgoogle2001/SE2017Aug21Tgoogle.html. Will you be able to see the eclipse from your school?
5. The claim in this story was challenged by people who argued that Hopkinsville may have the shadow of the Moon passing closest to Earth's center, but a town in Illinois will have 0.1 seconds more of totality. Will most people care about this 0.1-second difference in totality? What other factors will likely affect where people go to see this eclipse?

Summary

The motions of Earth and the Moon are responsible for many of the repeating patterns that can be observed in the sky. Calendars keep track of time using these patterns. Earth's rotation about its axis causes daily patterns of rising and setting. Earth's revolution around the Sun causes yearly patterns of the stars in the sky and the passage of the seasons. The tilt of Earth on its axis changes both the length of daytime and the intensity of sunlight, causing the seasons. The Moon's revolution around Earth causes the month-long pattern of the phases of the Moon. Occasionally, alignments of Earth, the Moon, and the Sun cause eclipses. The tilt of Earth's axis causes the variation in climate. This tilt varies slightly over tens of thousands of years. Life on Earth adapted to these seasonal variations.

LG 1 **Describe how Earth's rotation about its axis and revolution around the Sun affect our perception of celestial motions as seen from different places on Earth.** The daily rotation of Earth on its axis causes the apparent daily motion of the Sun, Moon, and stars. Our location on Earth and Earth's location in its orbit around the Sun determine which stars we see at night. You can determine your latitude from the altitude of the pole star. When observing objects in our sky, we need to consider the relative motion of Earth and other objects. The ecliptic is the path that the Sun appears to take through the stars.

LG 2 **Explain why there are different seasons throughout the year.** A year is the time it takes for Earth to complete one revolution around the Sun. Constellations are patterns of stars that reappear in the same place in the sky at the same time of night each year. The tilt of Earth's axis determines the seasons by changing the angle at which sunlight strikes the surface of Earth in different locations. The changing angle of sunlight and the differing length of the day cause the seasonal variations on Earth. The changing seasons are marked by equinoxes and solstices.

LG 3 **Describe the factors that create the phases of the Moon.** The relative locations of the Sun, Earth, and Moon determine the phases of the Moon. The Moon takes one sidereal month to complete one revolution around Earth and one synodic month to go through a cycle of phases. The Moon's motion around Earth causes it to be illuminated differently at different times. When the Moon is farther from the Sun than Earth is, it is in gibbous phases. When the Moon is closer to the Sun than Earth is, it is in crescent phases.

LG 4 **Sketch the alignment of Earth, the Moon, and the Sun during eclipses of the Sun and the Moon.** A solar eclipse occurs when the new Moon is in the plane of Earth and the Sun and the shadow of the Moon falls on Earth. A lunar eclipse occurs when the full Moon is in the plane of Earth and the Sun and the shadow of Earth falls on the Moon. Twice a year, at new or at full Moon, the Moon is exactly in line between Earth and the Sun. At these times, eclipses occur.

? UNANSWERED QUESTION

- How long will Earth continue to have total solar eclipses? These occur because the Moon and the Sun are coincidentally the same size in our sky, but will that always be the case? The observed size of an object in the sky depends on its actual diameter and its distance from us. One or both of these can change. The Moon is slowly moving away from Earth by about 4 meters per century. Over time, the Moon will appear smaller in the sky, and it won't be able to cover the full disk of the Sun. While we can measure the current rate of the Moon's movement away from Earth, we are less certain of how this rate may change with time. A lesser and more uncertain effect comes from the Sun—which will continue to brighten slowly, as it has throughout its history. With this brightening, the actual diameter of the Sun may slightly increase, and it will appear larger in our sky. A more distant Moon and a larger Sun will eventually result in an end to total eclipses on Earth.

Questions and Problems

Test Your Understanding

1. Constellations are groups of stars that
   a. are close to each other in space.
   b. are bound to each other by gravity.
   c. are close to each other in Earth's sky.
   d. all have the same composition.

2. Where on Earth can you stand and, over the course of a year, see the entire sky?
   a. only at the North Pole
   b. at either pole
   c. at the equator
   d. anywhere

3. Day and night are caused by
   a. the tilt of Earth on its axis.
   b. the rotation of Earth on its axis.
   c. the revolution of Earth around the Sun.
   d. the revolution of the Sun around Earth.

4. Polaris, the North Star, is unique because
   a. it is the brightest star in the night sky.
   b. it is the only star in the sky that doesn't move throughout the night.
   c. it is always located at the zenith, for any observer.
   d. it has a longer path above the horizon than any other star.

5. There is an angle between the ecliptic and the celestial equator because
   a. Earth's axis is tilted with respect to its orbit.
   b. Earth's orbit is tilted with respect to the orbits of other planets.
   c. the Sun follows a rising and falling path through space.
   d. the Sun's orbit is tilted with respect to Earth's.

6. The tilt of Earth's axis causes the seasons because
   a. one hemisphere of Earth is closer to the Sun in summer.
   b. the days are longer in summer.
   c. the rays of light strike the ground more directly in summer.
   d. both a and b
   e. both b and c

7. Which is *not* true on the vernal and autumnal equinoxes?
   a. Every place on Earth has 12 hours of daylight and 12 hours of darkness.
   b. The Sun rises due east and sets due west.
   c. The Sun is located on the celestial equator.
   d. The motion of the stars in the sky is different than on other days.

8. We always see the same side of the Moon because
   a. the Moon does not rotate on its axis.
   b. the Moon rotates on its axis once for each revolution around Earth.
   c. when the other side of the Moon is facing Earth, it is unlit.
   d. when the other side of the Moon is facing Earth, it is on the opposite side of Earth.

9. You see the Moon on the meridian at sunrise. The phase of the Moon is
   a. waxing gibbous.
   b. full.
   c. first quarter.
   d. third quarter.

10. A lunar eclipse occurs when __________ shadow falls on __________.
    a. Earth's; the Moon
    b. the Moon's; Earth
    c. the Sun's; the Moon
    d. the Sun's; Earth

11. Different cultures created different calendars because
    a. they had measured different lengths of the day, month, and year.
    b. they used different definitions of the day, month, and year.
    c. the number of days in a month and the number of days and months in a year are not integers.
    d. calendars are completely arbitrary.

12. Which stars we see at night depends on
    a. our location on Earth.
    b. Earth's location in its orbit.
    c. the time of the observation.
    d. all of the above

13. On the summer solstice in June, the Sun will be directly above __________ and all locations north of __________ will experience daylight all day.
    a. the Tropic of Cancer; the Antarctic Circle
    b. the Tropic of Capricorn; the Arctic Circle
    c. the Tropic of Cancer; the Arctic Circle
    d. the Tropic of Capricorn; the Antarctic Circle

14. The Sun, Moon, and stars
    a. appear to move each day because the celestial sphere rotates about Earth.
    b. change their relative positions over time.
    c. rise north or south of west and set north or south of east, depending on their location on the celestial sphere.
    d. always remain in the same position relative to each other.

15. You see the first quarter Moon on the meridian. Where is the Sun?
    a. on the western horizon
    b. on the eastern horizon
    c. below the horizon
    d. on the meridian.

Thinking about the Concepts

16. Polaris was used for navigation by seafarers such as Columbus as they sailed from Europe to North America. When Magellan sailed the South Seas, he could not use Polaris for navigation. Explain why.
17. If you were standing at Earth's North Pole, where would you see the north celestial pole relative to your zenith?
18. Observers in the Northern Hemisphere see the zodiacal constellation Gemini in the winter. Why do they not see it in the summer?
19. Imagine that you are flying along in a jetliner.
    a. Describe ways to tell that you are moving.
    b. If you look down at a building, which way is it moving relative to you?
20. Astronomers are sometimes asked to serve as expert witnesses in court cases. Suppose you are called in as an expert witness, and the defendant states that he could not see the pedestrian because the full Moon was casting long shadows across the street at midnight. Is this claim credible? Why or why not?
21. Imagine that one person was developing a theory of seasons as described in the three "takes" in the Process of Science Figure in this chapter. Compare this process with the flowchart of the Process of Science Figure in Chapter 1. Describe what the development of this theory would look like on that flowchart.
22. Why is the winter solstice *not* the coldest time of year?
23. Earth spins on its axis and wobbles like a top.
    a. How long does it take to complete one spin?
    b. How long does it take to complete one wobble?
24. What is the approximate time of day when you see the full Moon near the meridian? At what time is the first quarter (waxing) Moon on the eastern horizon? Use a sketch to help explain your answers.
25. Assume that the Moon's orbit is circular. Imagine that you are standing on the side of the Moon that faces Earth.
    a. How would Earth appear to move in the sky as the Moon made one revolution around Earth?
    b. How would the "phases of Earth" appear to you compared to the phases of the Moon as seen from Earth?
26. If people on Earth were observing a lunar eclipse, what would you see from the Moon?
27. From any given location, why are you more likely to witness a partial eclipse of the Sun than a total eclipse?
28. Why do we not see a lunar eclipse each time the Moon is full or witness a solar eclipse each time the Moon is new?
29. How would Earth's temperature variation be different if it was tilted 90° on its axis (like the planet Uranus)?
30. Explain how a cyclic change in Earth's tilt could affect its seasonal temperatures.

Applying the Concepts

31. Earth is spinning along at 1,674 km/h at the equator. Use this fact, along with the length of the day, to calculate Earth's equatorial diameter.
32. Determine the latitude where you live. Draw and label a diagram showing that your latitude is the same as (a) the altitude of the north celestial pole and (b) the angle (along the meridian) between the celestial equator and your local zenith. What is the altitude of the Sun at noon as seen from your home at the times of the winter solstice and the summer solstice?
33. Using a protractor, you estimate an angle of 40° between your zenith and Polaris. What is the altitude of Polaris? What is your latitude? Are you in the continental United States or Canada?
34. The southernmost star in a group of stars known as the Southern Cross lies approximately 65° south of the celestial equator. What is the farthest-north latitude for which the entire Southern Cross is visible? Can it be seen in any U.S. states? If so, which ones?
35. Imagine that you are standing on the South Pole at the time of the southern summer solstice.
    a. How far above the horizon will the Sun be at noon?
    b. How far above (or below) the horizon will the Sun be at midnight?
36. Suppose the tilt of Earth's equator relative to its orbit were 10° instead of 23.5°. At what latitudes would the Arctic and Antarctic circles and the Tropics of Cancer and Capricorn be located?
37. The Moon's orbit is tilted by about 5° relative to Earth's orbit around the Sun. What is the highest altitude in the sky that the Moon can reach, as seen in Philadelphia (latitude 40° north)?

38. Suppose you would like to witness the midnight Sun (when the Sun appears just above the northern horizon at midnight), but you don't want to travel any farther north than necessary.
    a. How far north (that is, to which latitude) would you have to go?
    b. At what time of year would you make this trip?

39. If, as some historians believe, the Egyptian stadion was about 157.5 meters, then what would Eratosthenes have computed for the size of Earth? How close is this to the modern value?

40. a. The vernal equinox is now in the zodiacal constellation Pisces. The precession of Earth's axis will eventually cause the vernal equinox to move into Aquarius. How long, on average, does the vernal equinox spend in each of the 12 zodiacal constellations?
    b. Stonehenge was erected roughly 4,000 years ago. Referring to the zodiacal constellations shown in Figure 2.14, identify the constellation in which these ancient builders saw the vernal equinox.

41. Referring to Figure 2.19, estimate when Vega, the fifth-brightest star in our sky (excluding the Sun), will once again be the northern pole star.

42. The apparent diameter of the Moon in the sky is approximately ½°. How long does it take the Moon to move 360°? About how long does it take the Moon to move a distance equal to its own diameter across the sky?

43. The apparent size of an object in the sky is proportional to its actual diameter divided by its distance. The Moon has a radius of 1,737 km, with an average distance of 3.780×10^5 km from Earth. The Sun has a radius of 696,000 km, with an average distance of 1.496×10^8 km from Earth. Show that the apparent sizes of the Moon and Sun in our sky are approximately the same.

44. Earth has an average radius of 6,371 km. If you were standing on the Moon, how much larger would Earth appear in the lunar sky than the Moon appears in our sky?

45. How would the length of the eclipse season change if the plane of the Moon's orbit were inclined less than its current 5.2° to the plane of Earth's orbit? Explain your answer.

USING THE WEB

46. Go to the U.S. Naval Observatory website (USNO "Data Services," at http://aa.usno.navy.mil/data). Look up the times for sunrise and sunset for your location for the current week. (You can change the dates one at a time or bring up a table for the entire month.) How are the times changing from one day to the next? Bring up the "Duration of Days/Darkness Table for One Year" page for your location. Are the days getting longer or shorter? When do the shortest and the longest days occur? Look up a location in the opposite hemisphere (Northern or Southern). When are the days shortest and longest?

47. Go to the "Earth and Moon Viewer" website (http://fourmilab.ch/earthview). Under "Viewing the Earth," click on "latitude, longitude and altitude" and enter your approximate latitude and longitude, and 40,000 for altitude; then select "View Earth." Are you in daytime or nighttime? Now play with the locations; keep the same latitude but change to the opposite hemisphere (Northern or Southern). Is it still night or day? Go back to your latitude, and this time enter 180° minus your longitude, and change from west to east, or from east to west, so that you are looking at the opposite side of Earth. Is it night or day there? What do you see at the North Pole (latitude 90° north) and the South Pole (latitude 90° south)? At the bottom of your screen you can play with the time. Move back 12 hours. What do you observe at your location and at the poles?

48. Go to the U.S. Naval Observatory website (USNO "Data Services," at http://aa.usno.navy.mil/data). Look up the Moon data for the current day. When will it rise and set? What is the phase? How will it change over the next 4 weeks. Enter one day at a time or look at the yearlong tables for moonrise and moonset and for the dates of primary phases. What time of day does a third quarter Moon rise? When (and in what phases) can you see the Moon in the daytime?

49. Using the times of moonrise and moonset that you located in question 48, make a plan to observe the Moon directly at least once a day for a week. Take a picture of the Moon (or make a sketch) every day. How is the brightness of the Moon changing? If it's daytime, how far is the Moon from the Sun in the sky? If it's nighttime, are the stars that are near the Moon in the sky the same every night?

50. Go to the "NASA Eclipse" website (http://eclipse.gsfc.nasa.gov/eclipse.html). When is the next lunar eclipse? Will it be visible at your location if the skies are clear? Is it a total or partial eclipse? When is the next solar eclipse? Will it be visible at your location? Compare the fraction of Earth that the solar eclipse will affect with the fraction for the lunar eclipse. Why are lunar eclipses visible in so many more locations?

smartwork5

If your instructor assigns homework in Smartwork5, access your assignments at digital.wwnorton.com/astro5.

digital.wwnorton.com/astro5

Visit the Student Site at the Digital Landing Page, and open the Lunar Phase Simulator applet in Chapter 2.

Study the diagrams shown in the simulator. The largest window shows a view of the Earth-Moon system as seen from above Earth's North Pole. The Sun is far off the screen to the left. An observer stands on Earth. The small window at upper right shows the appearance of the Moon as seen from the Northern Hemisphere. The small window at lower right shows the observer's location, with the Sun and Moon pictured as flat disks in the sky.

1 Given the relative positions of the observer and the Sun, approximately what time is it for this observer: 6:00 A.M., noon, 6:00 P.M., or midnight?

---

2 Where is the Moon in the observer's sky: on the eastern horizon, on the western horizon, below the horizon, or crossing the meridian?

---

3 What is the phase of the Moon?

---

4 Imagine yourself on the Moon in the image shown in the larger window. If you looked toward Earth, what phase of Earth would you see?

Now select "start animation." Allow the animation to run until the Moon is 20 percent illuminated (as shown in the upper small window on the right).

5 In which direction does the Moon orbit Earth: clockwise or counterclockwise?

---

6 For observers in the Northern Hemisphere, which side of the Moon is illuminated first after a new Moon: right or left?

---

7 If you observe a crescent Moon with the horns of the crescent pointing right, is the Moon waxing or waning?

Grab the Moon with your mouse, and drag it to first quarter. Drag the observer so that her local time is approximately midnight.

8 Where is the first quarter Moon in the observer's sky: on the eastern horizon, on the western horizon, below the horizon, or crossing the meridian?

These three things are related: the time, the phase of the Moon, and the Moon's location in the sky.

9 Arrange the observer and the Moon so that the Moon is full and crossing the meridian. What time is it for the observer: 6:00 A.M., noon, 6:00 P.M., or midnight?

---

10 Arrange the observer and the Moon so that the Moon is in third quarter and the time for the observer is approximately noon (the Sun is on the meridian). Where is the Moon in the observer's sky: on the eastern horizon, on the western horizon, below the horizon, or crossing the meridian?

---

11 Arrange the observer and the Moon so that it is approximately 6:00 P.M. (sunset) for the observer, and the Moon is just rising on the eastern horizon. What is the phase of the Moon?

There are many other combinations of the time, phase of the Moon, and Moon's location to play with. Challenge yourself to be able to set up any two of the three and find the third. When you can do this without the simulator, just by making the picture in your head, you will really understand the phases of the Moon.

3 Motion of Astronomical Bodies

The birth of modern astronomy dates back to the time when astronomers and mathematicians discovered regular patterns in the motions of the planets. A successful theory of how Earth moved and how it fit in with its neighbors in the Solar System was the first step toward understanding Earth's place in the universe.

LEARNING GOALS

In this chapter, we will examine how astronomers came to understand that Earth and other planets orbit the Sun. By the conclusion of this chapter, you should be able to:

LG 1 Describe and contrast the geocentric and heliocentric models of the Solar System.

LG 2 Use Kepler's laws to describe the motion of objects in the Solar System.

LG 3 Explain how Galileo's astronomical discoveries provided empirical evidence for the heliocentric model.

LG 4 Describe the work of Galileo and Newton, which led them to discover the physical laws that govern the motion of all objects.

The shadows of a few of the Galilean moons of Jupiter fall on the planet. ▶▶▶

Why doesn't Jupiter orbit Earth?

3.1 The Motions of Planets in the Sky

Nebraska Simulation: Ptolemaic Orbit of Mars

When people in ancient times looked up at the sky, they saw that the Sun, Moon, and stars rose in the east and set in the west and appeared to be moving around Earth. The ancient peoples were aware of five planets (*planet* means "wandering star") because they moved in a generally eastward direction from one night to the next among the stars, whose positions were fixed on the celestial sphere. But they did not know that Earth was similar to these planets. A successful theory of how Earth and the planets move and how Earth fits in with its neighbors in the Solar System was the first step to understanding Earth's place in the universe. The history of the progression of ideas—from Earth at the center of all things to Earth as a tiny, insignificant rock—is a prime example of the self-correcting nature of science.

Figure 3.1 In the Ptolemaic view of the heavens, Earth is at the center, orbited by the Moon, Mercury, Venus, the Sun, Mars, Jupiter, and Saturn.

The Geocentric Model

As you saw in the previous chapter, hard evidence of the motions of Earth was remarkably difficult to come by. Largely because the motion of Earth through space cannot be felt, early astronomers developed a **geocentric** (Earth-centered) model of the Solar System to explain what they observed in the sky. When people looked up at the sky, the Sun, Moon, planets, and stars appeared to be moving around Earth. Before the 17th century, most educated people believed that the Sun, the Moon, and the known planets all moved in circles around a stationary Earth. **Figure 3.1** illustrates Ptolemy's geocentric model.

However, the geocentric model did not account for all observations. Ancient astronomers knew that the planets would occasionally do something unusual. Most of the time, the planets have an eastward **prograde motion**, in which each night they move a little eastward compared to the background stars. But sometimes the ancients observed apparent **retrograde motion**, in which the planets appear to move westward for a period of time before resuming their normal eastward travel. This retrograde motion is shown for Mars in **Figure 3.2**.

This odd behavior of the five "naked eye" planets—Mercury, Venus, Mars, Jupiter, and Saturn—created a puzzling problem for the geocentric model as it was summarized in 150 CE by the Alexandrian astronomer Ptolemy (Claudius Ptolemaeus, 90–168 CE). Some astronomers and philosophers in ancient times, for example Aristarchus of Samos (310–230 BCE), hypothesized that the Sun might be the center of the Solar System, but they did not have the tools to test the hypothesis or the mathematical insight to formulate a more complete and testable model. But most other astronomers of the time were skeptical, because they thought that if Earth moved around the Sun, they should feel Earth's motion. Therefore they preferred the geocentric model, in which the Sun, Moon, and planets all moved in perfect circles around a stationary Earth, with the "fixed stars" being located somewhere way out beyond the planets.

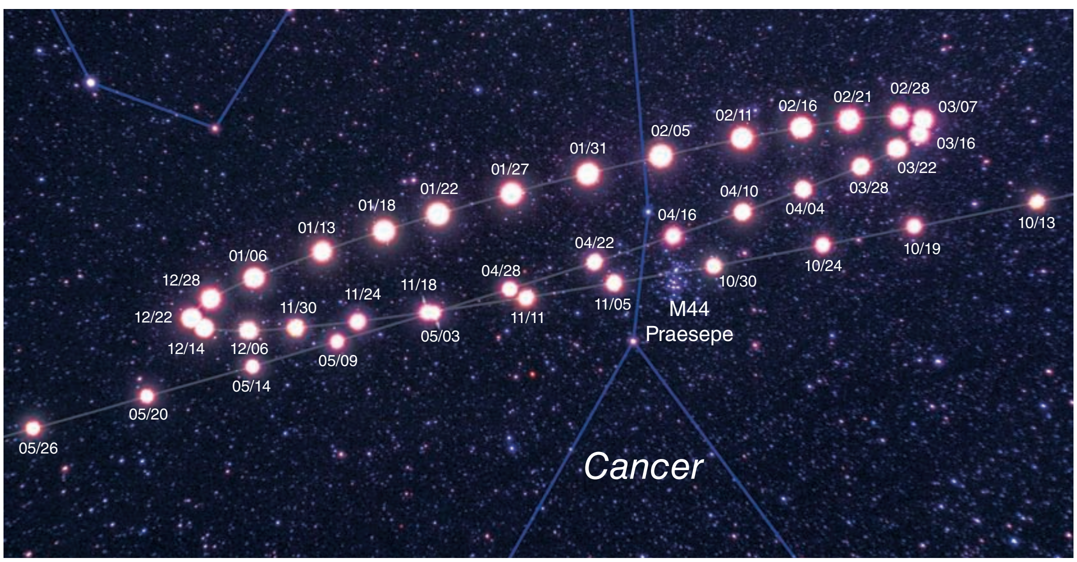


Figure 3.2 This time-lapse photographic series shows Mars as it moves in apparent retrograde motion.

Because the geocentric model in its simplest form failed to explain retrograde motion of the planets, Ptolemy added an embellishment called an *epicycle*, a small circle superimposed on each planet's larger circle, as illustrated in **Figure 3.3**. In this model, as the planet travels along its larger circle around Earth, it is also moving along a smaller circle. When its motion along the smaller circle was in a direction opposite to that of the forward motion of the larger circle, its forward motion would be reversed. Ptolemy's model had many of these epicycles, but they made the model *work*, in the sense that this model was reasonably successful at predicting the positions of planets in the sky. For nearly 1,500 years, Ptolemy's model of the heavens was the accepted paradigm in the Western world.

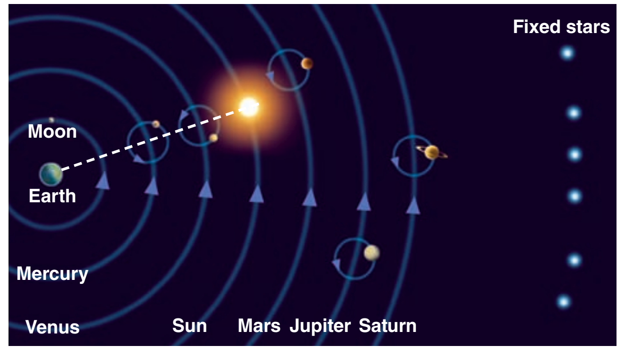


Figure 3.3 To reconcile retrograde motion with the geocentric model of the Solar System, additional loops called epicycles were added to each planet's circular orbit around Earth.

CHECK YOUR UNDERSTANDING 3.1

How did the ancients know the planets were different from the stars?

Copernicus Proposes a Heliocentric Model

Nicolaus Copernicus (1473–1543—**Figure 3.4**) is famous for placing the Sun rather than Earth at the center of the Solar System. He was not the first person to consider the idea that Earth orbited the Sun, and probably he had read the ideas of ancient Greek and medieval Arab astronomers who considered putting the Sun at the center of the Solar System. However, he was the first to develop a comprehensive mathematical model that could be tested by later astronomers. This work was the beginning of the Copernican Revolution. Through the work of 16th- and 17th-century scientists such as Tycho Brahe, Galileo Galilei, Johannes Kepler, and Isaac Newton, the **heliocentric** (Sun-centered) theory of the Solar System became one of the best-corroborated theories in all of science.

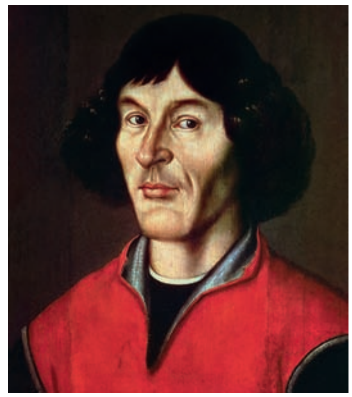


Figure 3.4 Nicolaus Copernicus rejected the ancient Greek model of an Earth-centered universe and replaced it with a model that centered on the Sun.

Nebraska Simulation: Retrograde Motion

Copernicus was multilingual and highly educated: he studied philosophy, canon (Catholic) law, medicine, economics, mathematics, and astronomy in his native Poland and in Italy. Copernicus conducted astronomical observations from a small tower, and sometime around 1514 he started writing about heliocentricity. Eighteen years later, he completed his manuscript. He did not publish the book because he knew his ideas would be controversial: philosophical and religious views of the time held that humanity and thus Earth must be the center of the universe. Late in his life, Copernicus was finally persuaded to publish his ideas, and his great work *De revolutionibus orbium coelestium* ("On the Revolutions of the Heavenly Spheres") appeared in 1543, the year of his death. This work pointed the way toward the modern cosmological principle introduced in Chapter 1—the idea that our location in the universe is not special.

Figure 3.5 shows Copernicus's model with the planets orbiting around the Sun. This model explained the observed motions of Earth, the Moon, and the planets, including retrograde motion, much more simply than the geocentric model did. Think about when you were in a car or train and you passed a slower-moving car or train, and it seemed as if the other vehicle was moving backward. It can be hard to tell which vehicle is moving and in which direction without an external frame of reference. Copernicus provided that frame of reference for the Sun and its planets.

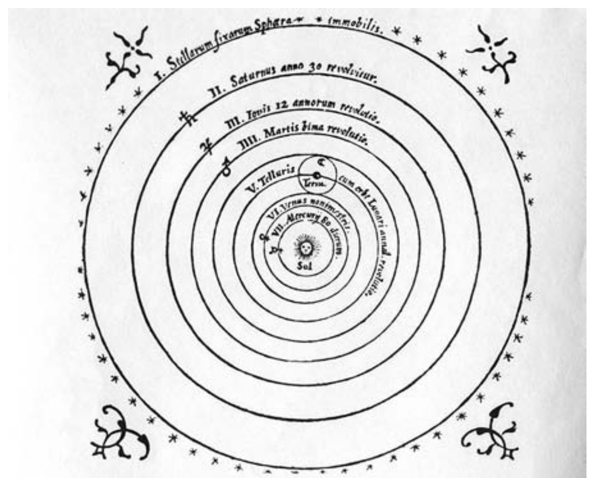


Figure 3.5 This illustration shows the Copernican heliocentric view of the Solar System (II–VII) and the fixed stars (I). The Sun is at the center and is orbited by Mercury, Venus, Earth, Mars, Jupiter, and Saturn. The Moon orbits Earth.

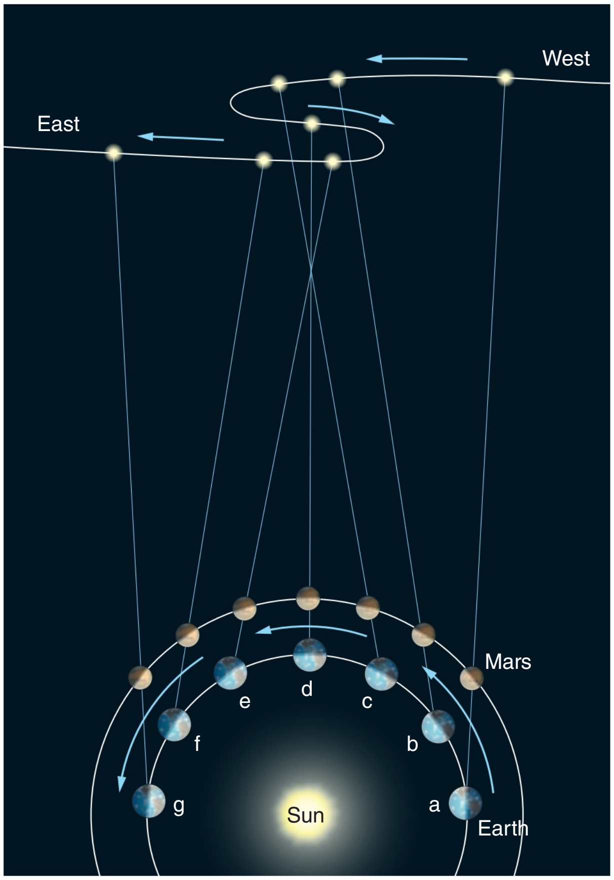


Figure 3.6 The Copernican model explains the apparent retrograde motion of Mars (see Figure 3.1) as seen in Earth's sky when Earth passes Mars in its orbit. The figure is not to scale.

In the Copernican model, the planets farther from the Sun undergo apparent retrograde motion when Earth overtakes them in their orbits. **Figure 3.6** illustrates this for Mars. Conversely, the planets closer to the Sun than Earth is—Mercury and Venus—move in apparent retrograde motion when overtaking Earth. Except for the Sun, all Solar System objects exhibit apparent retrograde motion. The magnitude of the effect diminishes with increasing distance from Earth. Retrograde motion is an illusion caused by the relative motion between Earth and the other planets.

Copernicus still conceived of the planets as moving in perfectly circular orbits, and as a result he needed to use some epicycles to match the observations. His model made testable predictions of the location of each planet on a given night, which were at least as accurate, but not more accurate, than those of the geocentric model. But this heliocentric model was, overall, simpler than the geocentric model and became the basis for further refinements in understanding how Earth moved. As copies of *De Revolutionibus* and Copernicus's ideas slowly spread across Europe, other scientists were excited by the heliocentric model, and a scientific revolution began.

Scaling the Solar System

Copernicus's model assumed that the planets traveled around the Sun in circular orbits with constant speeds. From his observations he deduced the correct order of the planets and concluded that planets closer to the Sun traveled faster than planets farther from the Sun. He also realized he needed to consider two categories of planets: **inferior** planets are closer to the Sun than Earth is; and **superior** planets are farther from the Sun than Earth is.

In Copernicus's model, periodically Earth, another planet, and the Sun line up in space to form either a straight line or a right triangle. As shown in **Figure 3.7a**, when a superior planet is in line with the Sun and Earth but on the other side of the Sun from Earth, we call the configuration a *conjunction*. A superior planet in conjunction will rise and set in the sky with the Sun. Note that when a superior planet is in conjunction, it is the farthest away from Earth that it gets and

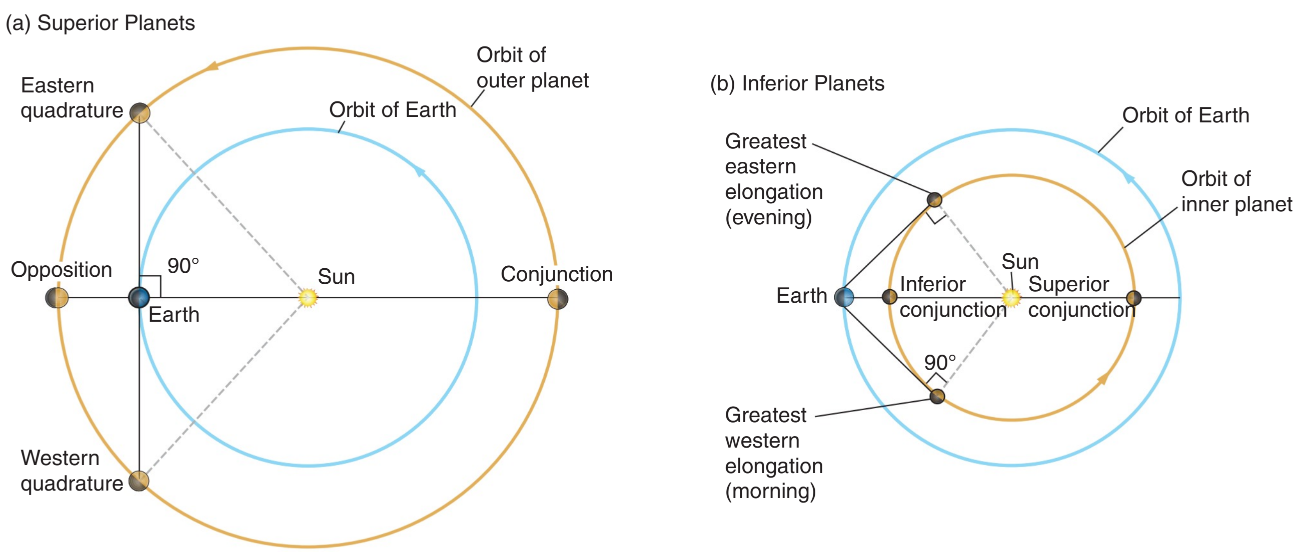


Figure 3.7 The diagrams show planetary configurations for (a) superior (outer) planets and (b) inferior (inner) planets.

therefore is at its faintest. You won't see the planet at all exactly at conjunction, because it's on the far side of the Sun.

In contrast, when a superior planet is in line with the Sun and Earth on the same side of the Sun as Earth, we call the configuration an *opposition*. At opposition, the superior planet is "opposite" the Sun in the sky: like a full Moon, it rises when the Sun sets and sets when the Sun rises. When the superior planet is in opposition, it is the closest it gets to Earth and thus is at its brightest; therefore, opposition is the best time to observe the planet in the sky. Opposition is also the time when the planet exhibits retrograde motion, because that is exactly when Earth is overtaking the planet in its orbit. *Quadrature* is when Earth, the Sun, and a superior planet form a right triangle in space.

For an inferior planet, the configurations are slightly different (Figure 3.7b). If the inferior planet is between Earth and the Sun, we call the configuration an *inferior conjunction*: this is when the planet is closest to Earth. If the inferior planet is on the other side of the Sun from Earth, we call the configuration a *superior conjunction*: this is when the planet is farthest from Earth. When the inferior planet forms a right triangle with Earth and the Sun—and thus is the farthest it gets from the Sun in the sky—we call the configuration the *greatest elongation*. When you are standing on Earth and looking toward the inner planets, you always see them close to the Sun in the sky, so you see Mercury and Venus only within a few hours of sunrise or sunset. The best time to observe these planets is at greatest elongation because they will have the greatest separation from the Sun in the sky.

Copernicus used the geometry of these alignments along with his observations of the positions of the planets in the sky, including their altitudes and the times they rose and set, to estimate the planet–Sun distances in terms of the Earth–Sun distance. He realized there were two types of orbital periods. Similar to the terms used for lunar orbits, a planet's *sidereal period* is how long it takes the planet to make one orbit around the Sun with respect to the stars and return to the same point in space. A planet's *synodic period* is how long it takes the planet to return to the same configuration with the Sun and Earth, such as inferior conjunction to inferior conjunction or opposition to opposition. The synodic period is what can be observed from Earth; for example, from opposition to opposition.

As shown in **Figure 3.8a**, Earth and the superior planet are in opposition at point A. Superior planets move around the Sun more slowly than Earth does, so Earth will complete one orbit around the Sun and then catch up to the superior planet to form the next opposition at point B. In Figure 3.8b, Earth and the inferior planet are in inferior conjunction at point A. An inferior planet moves around the Sun faster than Earth does, so it completes one sidereal period and then must continue in its orbit to catch up to Earth for the next inferior conjunction at point B. The numerical details are shown in **Working It Out 3.1**. **Table 3.1** shows that these relative distances calculated by Copernicus are remarkably close to distances obtained by modern methods. Copernicus's model not only predicted planetary positions in the sky but also could be used to compare the distances between the planets and the Sun accurately and thus to set the scale of the Solar System.

CHECK YOUR UNDERSTANDING 3.2

The planet Uranus will be observed in retrograde motion when: (a) Uranus is closest to the Sun; (b) Uranus is farthest from the Sun; (c) Earth overtakes Uranus in its orbit; (d) Uranus overtakes Earth in its orbit.

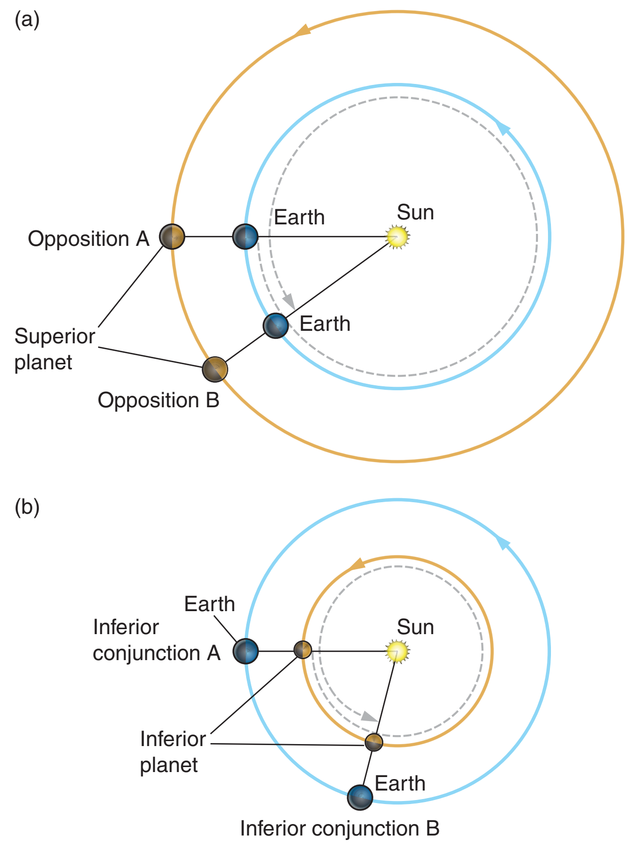


Figure 3.8 The synodic periods of planets indicate how long it takes them to return to the same configuration with Earth and the Sun. (a) Earth completes one orbit around the Sun first and then catches up to the superior planet. (b) Inferior planets complete a full orbit around the Sun first and then catch up to Earth.

Nebraska Simulation: Planetary Configurations Simulator

TABLE 3.1 Copernicus's Scale of the Solar System

Planet	Copernicus's Value (AU)	Modern Value (AU)
Mercury	0.38	0.39
Venus	0.72	0.72
Earth	1.00	1.00
Mars	1.52	1.52
Jupiter	5.22	5.20
Saturn	9.17	9.58

AU = astronomical unit.

3.1 Working It Out How Copernicus Computed Orbital Periods and Scaled the Solar System

Orbital Periods

Copernicus was able to calculate the sidereal period from observations of the synodic period. He didn't know the actual Earth–Sun distance in miles or kilometers, so he let the Earth–Sun distance equal 1. We call this distance 1 astronomical unit (AU). Let P be the sidereal period and S the synodic period of a planet. E is the sidereal period of Earth, which equals 1 year, or 365.25 days. By thinking about the distance that Earth and the planet move in one synodic period, and noting that an inferior planet orbits the Sun in less time than Earth does, it can be shown that

$$\frac{1}{P} = \frac{1}{E} + \frac{1}{S}$$

for an inferior planet, with P, E, and S all in the same units of days or years. Similarly, Earth orbits the Sun in less time than a superior planet does, so the planet has traveled only part of its orbit around the Sun after 1 Earth year. The equation for a superior planet is

$$\frac{1}{P} = \frac{1}{E} - \frac{1}{S}$$

Let's consider Saturn as an example. The time that passes between one opposition—the date of maximum brightness—and the next shows that Saturn's synodic period is 378 days, or $378 \div 365.25 = 1.035$ years. Then to compute its sidereal period, P of Saturn in years, we use $S = 1.035$ and $E = 1$:

$$\frac{1}{P} = \frac{1}{1\,\text{yr}} - \frac{1}{1.035\,\text{yr}}$$
$$= 1 - 0.966 = 0.034\,\text{yr}^{-1}$$

and thus

$$P = \frac{1}{0.034\,\text{yr}^{-1}} = 29.4\,\text{yr}$$

The sidereal period of Saturn is 29.4 years, meaning that it takes Saturn 29.4 years to travel around the Sun and return to where it started in space.

Nebraska Simulation: Synodic Period Calculator

Scaling the Solar System

Copernicus used the configurations of the planets shown in Figure 3.7 along with the sidereal periods of the planets to compute the relative distances of the planets. For the superior planets, he measured the fraction of the circular orbit that the planet completed in the time between opposition and quadrature, and then used trigonometry to solve for the planet–Sun distance in astronomical units (see Figure 3.7a). For the inferior planets, he had a right triangle at the point of greatest elongation, and then he used right-triangle trigonometry to solve for the planet–Sun distance in astronomical units (see Figure 3.7b). Copernicus's values are impressively similar to modern values (see Table 3.1). Copernicus still did not know the actual value of the astronomical unit in miles, but he was able to compute accurately the relative distances of the planets from the Sun for the first time.

Figure 3.9 Tycho Brahe, known commonly as Tycho, was one of the greatest astronomical observers before the invention of the telescope.

3.2 Kepler's Laws Describe Planetary Motion

Copernicus did not understand *why* the planets move about the Sun, but he realized that his heliocentric picture provided a way to compute the relative distances of the planets. His theory is an example of **empirical science**, which seeks to describe patterns in nature with as much accuracy as possible. Copernicus's work was revolutionary because he was able to challenge the accepted geocentric model and propose that Earth is one planet among many. His conclusions paved the way for other great empiricists, including Tycho Brahe and Johannes Kepler.

Tycho Brahe's Observations

Tycho Brahe (1546–1601—**Figure 3.9**) was a Danish astronomer of noble birth who entered university at age 13 to study philosophy and law. After seeing a partial solar eclipse in 1560, Tycho (conventionally referred to by his first name) became interested in astronomy. A few years later, he observed Jupiter and Saturn near each other in the sky, but not in the exact positions predicted by the astronomical tables based on Ptolemy's model. Tycho gave up studying law and devoted himself to making better tables of the positions of the planets in the sky.

The king of Denmark granted Tycho the island of Hven, located between Sweden and Denmark, to build an observatory. Tycho designed and built new instruments, operated a printing press, and taught students and others how to conduct observations. With the assistance of his sister Sophie, Tycho carefully measured the precise positions of planets in the sky over several decades, developing the most comprehensive set of planetary data available at that time. He created his own geo-heliocentric model, shown in **Figure 3.10**. In Tycho's model, the planets orbit the Sun, and the Sun and planets orbit Earth. This model gained limited acceptance among people who preferred to keep Earth at the center for philosophical or religious reasons. Tycho lost his financial support when the king died, and in 1600 he relocated to Prague.

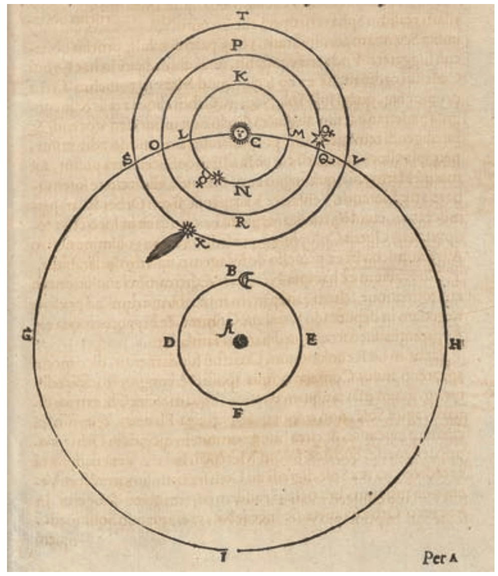


Figure 3.10 This reproduction shows Tycho's geo-heliocentric model with the Moon and Sun orbiting Earth, and the other planets orbiting the Sun.

Kepler's Laws

In 1600, Tycho hired a more mathematically inclined astronomer, Johannes Kepler (1571–1630—**Figure 3.11**), as his assistant. Kepler, who had studied the ideas of Copernicus, was responsible for the next major step toward understanding the motions of the planets. Upon Tycho's death, Kepler inherited the records of his observations. Working first with Tycho's observations of Mars, Kepler deduced three empirical rules, now generally referred to as **Kepler's laws**, which accurately describe the motions of the planets. These laws are empirical: they use prior data to make predictions about future behavior but do not include an underlying theory of why the objects behave as they do.

Figure 3.11 Johannes Kepler explained the motions of the planets with three empirically based laws.

Kepler's First Law When Kepler compared Tycho's extensive planetary observations with predictions from Copernicus's heliocentric model, he expected the data to confirm circular orbits for planets orbiting the Sun. Instead he found disagreements between his predictions and Tycho's observations. He was not the first to notice such discrepancies. Rather than discarding Copernicus's model, Kepler made some revisions.

Kepler discovered that if he replaced Copernicus's circular orbits with *elliptical* orbits, he could predict the positions of planets for any day, and found that his predictions fit Tycho's observations almost perfectly. An **ellipse** is a shape that looks like an elongated circle. It is symmetric from right to left and from top to bottom. As shown in **Figure 3.12a**, you can draw an ellipse by attaching the two

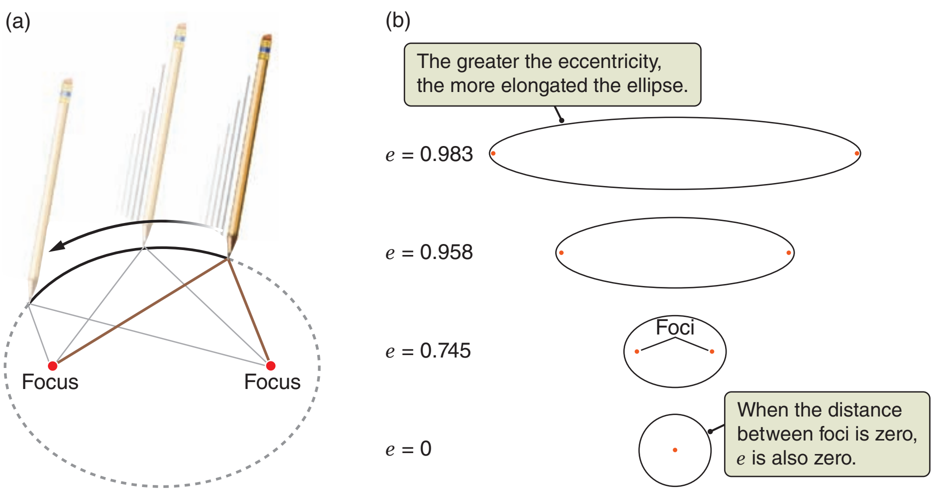


Figure 3.12 (a) We can draw an ellipse by attaching a length of string to a piece of paper at two points (called foci) and then pulling the string around as shown. (b) Ellipses range from circles to elongated eccentric shapes. e = eccentricity.

AstroTour: Kepler's Laws

Nebraska Simulation: Eccentricity Demonstrator

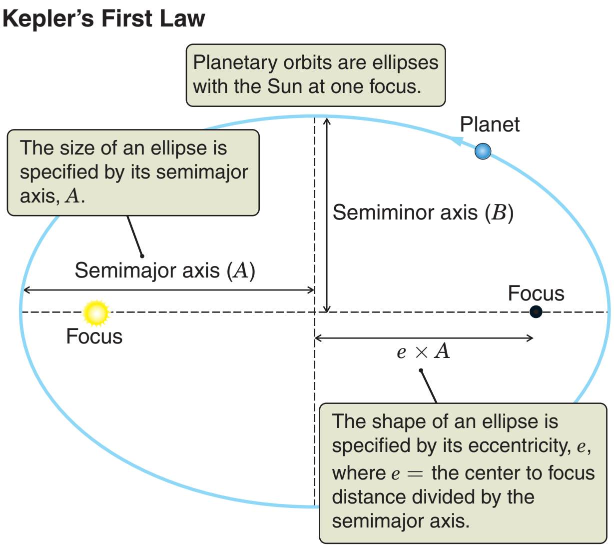


Figure 3.13 Planets move on elliptical orbits with the Sun at one focus. The eccentricity is given by the center-to-focus distance divided by the semimajor axis.

ends of a piece of string to a piece of paper, stretching the string tight with the tip of a pencil, and then drawing around those two points while keeping the string tight. Each of the points at which the string is attached is a **focus** (plural: *foci*) of the ellipse. In Figure 3.12b, you can see that as the two foci become closer together, the ellipse becomes more circular. As the two foci move farther apart, the ellipse becomes more and more elongated. The **eccentricity (*e*)** of an ellipse measures this elongation; it is determined by the separation between the two foci divided by the length of the long axis. A circle has an eccentricity of 0 because the two foci coincide at the center of the circle. The more elongated the ellipse becomes, the closer its eccentricity gets to 1.

Kepler's first law of planetary motion states that the orbit of each planet is an ellipse with the Sun located at one focus (see the **Process of Science Figure**). There is nothing but empty space at the other focus. **Figure 3.13** illustrates Kepler's first law and shows how the features of an ellipse match observed planetary motions. The dashed lines in Figure 3.13 represent the two main axes of the ellipse. Half of the length of the long axis (the major axis) of the ellipse is called the **semimajor axis**, often denoted by the letter *A*. The semimajor axis of an orbit is the average distance between one focus and the ellipse itself. The average distance between the Sun and a planet equals the semimajor axis of the planet's orbit.

The eccentricities of planetary orbits vary widely, but most planetary objects in our Solar System have nearly circular orbits. As shown in **Figure 3.14a**, Earth's orbit is very nearly a circle centered on the Sun; with an eccentricity of 0.017, the distance variation is small. In contrast, dwarf planet Pluto's orbit, as shown in Figure 3.14b, has an eccentricity of 0.249. The orbit is noticeably elongated, with the Sun offset from center.

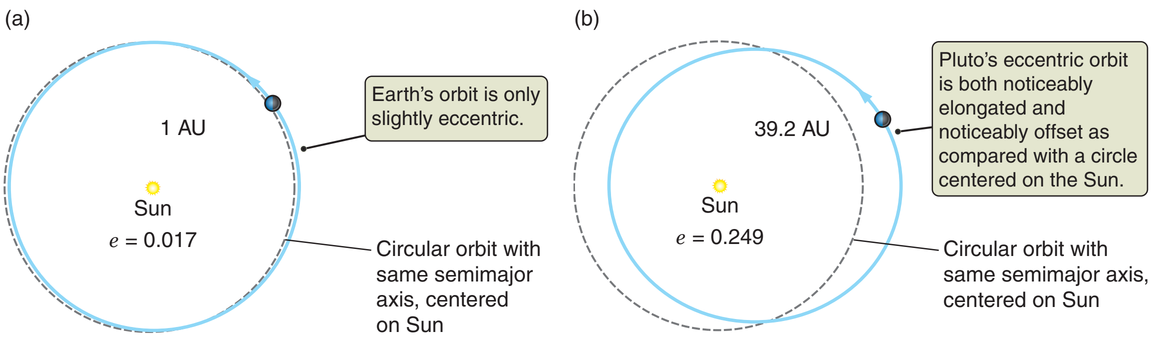


Figure 3.14 The orbits of (a) Earth and (b) Pluto compared with circles around the Sun. e = eccentricity.

Kepler's Second Law

From a close analysis of Tycho's observational data of changes in the positions of the planets, Kepler found that a planet moves fastest when it is closest to the Sun and slowest when it is farthest from the Sun. For example, we now measure Earth's average speed in its orbit around the Sun at 29.8 kilometers per second (km/s). When Earth is closest to the Sun, it travels at 30.3 km/s. When it is farthest from the Sun, it travels at 29.3 km/s.

Kepler found an elegant way to describe the changing speed of a planet in its orbit around the Sun. **Figure 3.15** shows a planet at six different points in its orbit (t_1 to t_6). Imagine a straight line connecting the Sun with this planet. We can think of this line as "sweeping out" an area as it moves with the planet from one point to another. Area A (in orange) is swept out between times t_1 and t_2, area B (in blue) is swept out between times t_3 and t_4, and area C (in green) is swept out between times t_5 and t_6. When the planet is closest to the Sun (area A), it is moving the fastest, but the distance between the planet and the Sun is small. Kepler realized that changes in the distance between the Sun and a planet and changes in the speed of a planet work together so that the area swept out by a planet in the same amount of time is always the same, regardless of the location of the planet in its orbit. This means that if the three time intervals in the figure are equal (that is, $t_1 \to t_2 = t_3 \to t_4 = t_5 \to t_6$), then the three areas A, B, and C will be equal as well.

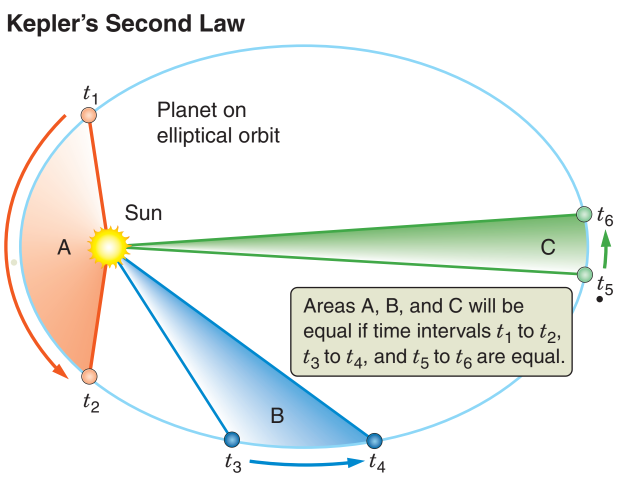
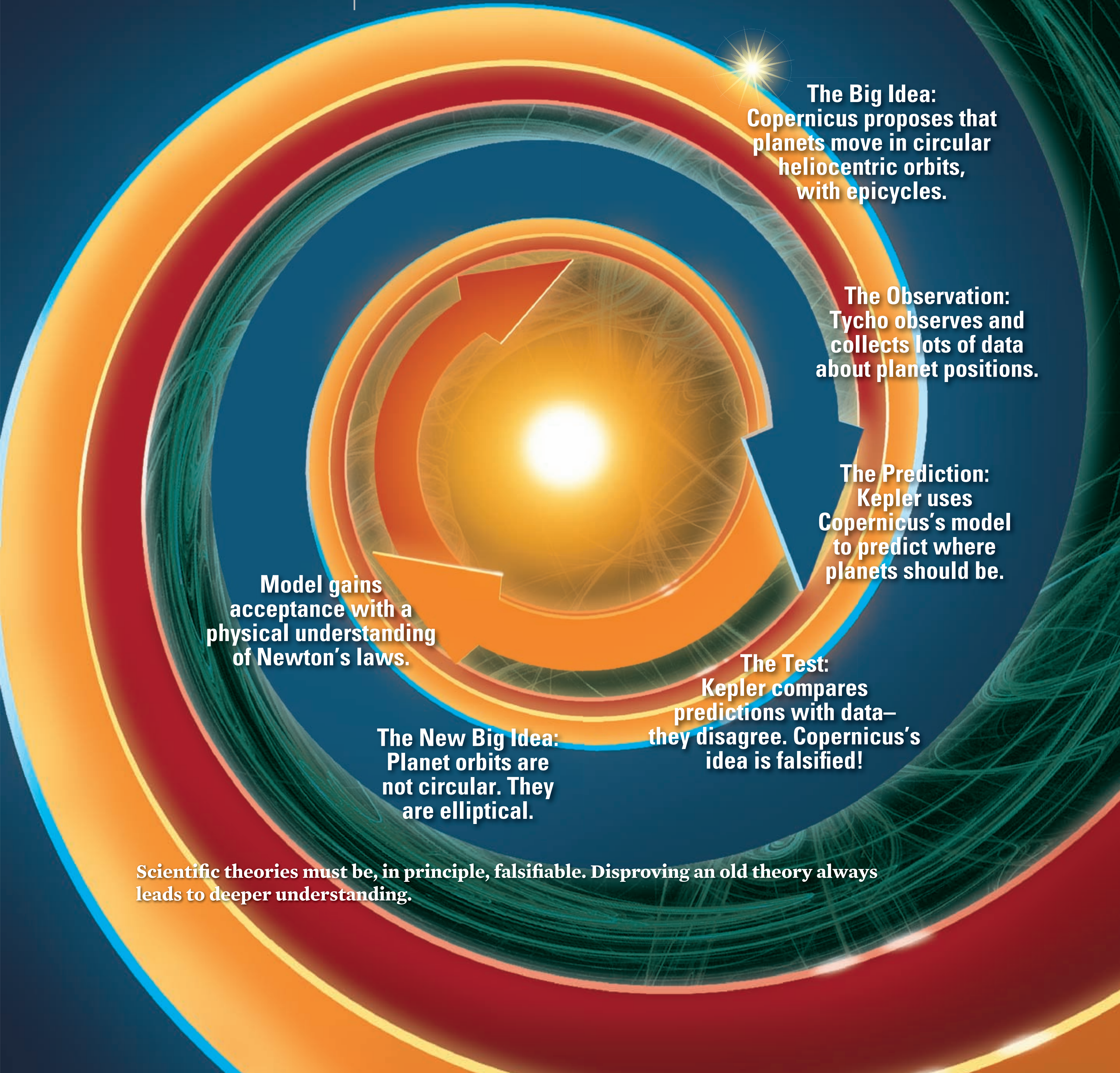


Figure 3.15 An imaginary line between a planet and the Sun sweeps out an area as the planet orbits. If the three intervals of time shown are equal, then the three areas A, B, and C will be the same.

Process of Science

THEORIES ARE FALSIFIABLE

Early astronomers studied the motions of the planets but did not understand why they behave as they do.



Scientific theories must be, in principle, falsifiable. Disproving an old theory always leads to deeper understanding.

Kepler's second law, also called Kepler's **law of equal areas**, states that the imaginary line connecting a planet to the Sun sweeps out equal areas in equal times, regardless of where the planet is in its orbit. This law applies to only one planet at a time. The area swept out by Earth in a given time is always the same. Likewise, the area swept out by Mars in a given time is always the same. But the area swept out by Earth and the area swept out by Mars in a given time are *not* the same. This law can be used to find the speed of a planet anywhere in its orbit.

CHECK YOUR UNDERSTANDING 3.3

Kepler's second law says that if a planet is in an elliptical orbit around a star, then the planet moves fastest when the planet is: (a) farthest from the star; (b) closest to the star; (c) located at one of the foci; (d) closest to another planet.

Kepler's Third Law Kepler looked for patterns in the orbital periods of the planets. He found that compared to planets closer to the Sun, planets farther from the Sun travel on longer orbits and they move more slowly in their orbits around the Sun. Kepler discovered a mathematical relationship between the sidereal period of a planet's orbit—how many years it takes to go around the Sun and return to the same position in space—and its average distance from the Sun in astronomical units. **Kepler's third law** states that in these units, the square of the sidereal period (P) of a planet's orbit is equal to the cube of the semimajor axis (A) of the planet's orbit.

Table 3.2 shows the periods and semimajor axes of the orbits of the eight classical planets and three of the dwarf planets, along with the values of the ratio P^2 divided by A^3. These data are also plotted in **Figure 3.16**. Kepler referred to this relationship as his **harmonic law** or, more poetically, as the "Harmony of the Worlds." Kepler's third law is explored further in **Working It Out 3.2**. Kepler's laws enhanced the heliocentric mathematical model of Copernicus and led to its greater acceptance.

Nebraska Simulation: Planetary Orbit Simulator

3.2 Working It Out Kepler's Third Law

Kepler's third law states that the square of the period of a planet's orbit, measured in years P_{years}, is equal to the cube of the semimajor axis of the planet's orbit, measured in astronomical units A_{AU}. Translated into math, the law says

$$(P_{\text{years}})^2 = (A_{\text{AU}})^3$$

Kepler used units based on Earth—astronomical units and years—as a matter of convenience. If other units were used, then P^2 would still be proportional to A^3, but the constant of proportionality would not be 1.

As an example of using this law, suppose that you want to know the average radius of Neptune's orbit in astronomical units. First you need to find out how long Neptune's period is in Earth years, which you can determine by observing the synodic period and then computing its sidereal period from that (using Working It Out 3.1). Neptune's sidereal period is 165 years. Plugging this number into Kepler's third law gives this result:

$$(P_{\text{years}})^2 = (165)^2 = 27{,}225 = (A_{\text{AU}})^3$$

To solve this equation, you must first square 165 to get 27,225 and then take its cube root (see Appendix 1 for calculator hints). Then

$$A_{\text{AU}} = \sqrt[3]{27{,}225} = 30.1$$

The semimajor axis of Neptune's orbit, that is, the average distance between Neptune and the Sun, is 30.1 AU.

TABLE 3.2 Kepler's Third Law: $P^2 = A^3$

Planet	Period P (years)	Semimajor Axis A (AU)	$\frac{P^2}{A^3}$
Mercury	0.241	0.387	$\frac{0.241^2}{0.387^3} = 1.00$
Venus	0.615	0.723	$\frac{0.615^2}{0.723^3} = 1.00$
Earth	1.000	1.000	$\frac{1.000^2}{1.000^3} = 1.00$
Mars	1.881	1.524	$\frac{1.881^2}{1.524^3} = 1.00$
Ceres	4.599	2.765	$\frac{4.559^2}{2.765^3} = 1.00$
Jupiter	11.86	5.204	$\frac{11.86^2}{5.204^3} = 1.00$
Saturn	29.46	9.582	$\frac{29.46^2}{9.582^3} = 0.99$*
Uranus	84.01	19.201	$\frac{84.01^2}{19.201^3} = 1.00$
Neptune	164.79	30.047	$\frac{164.79^2}{30.047^3} = 1.00$
Pluto	247.68	39.236	$\frac{247.68^2}{39.236^3} = 1.02$*
Eris	557.00	67.696	$\frac{557.00^2}{67.696^3} = 1.00$

*Slight perturbations from the gravity of other planets are the reason that these ratios are not exactly 1.00.

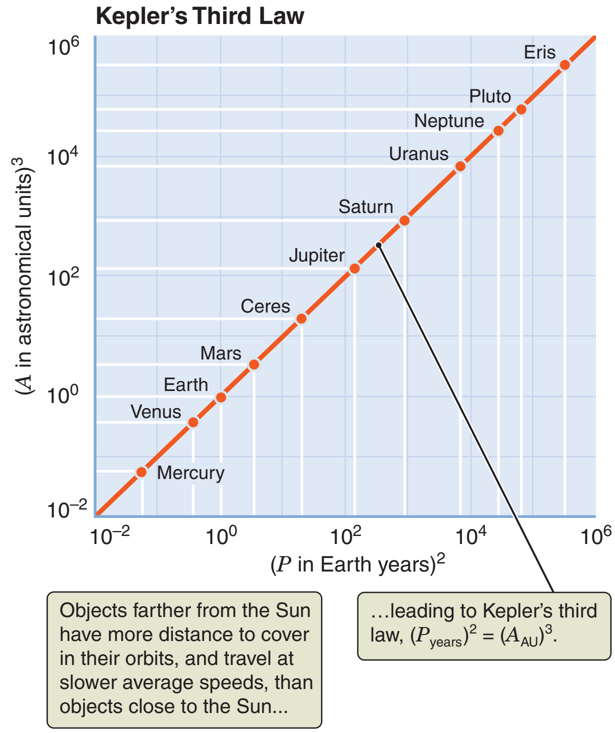


Figure 3.16 A plot of A^3 versus P^2 for objects in our Solar System shows that they obey Kepler's third law. (Note that by plotting powers of 10 on each axis, we are able to fit both large and small values on the same plot. We will do this frequently.)

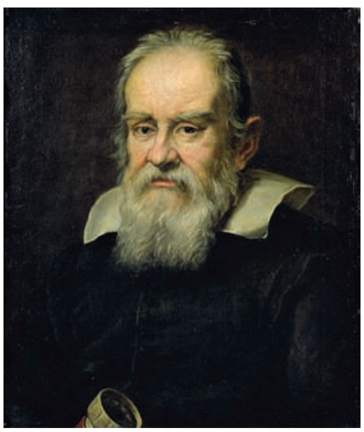
CHECK YOUR UNDERSTANDING 3.4

Place the following in order from largest to smallest semimajor axis: (a) a planet with a period of 84 Earth days; (b) a planet with a period of 1 Earth year; (c) a planet with a period of 2 Earth years; (d) a planet with a period of 0.5 Earth year.

3.3 Galileo's Observations Supported the Heliocentric Model

Galileo Galilei (1564–1642—**Figure 3.17**)—one of the heroes of astronomy—was the first to use a telescope to conduct and report on significant discoveries about astronomical objects. Galileo's telescopes were relatively small, yet sufficient for him to observe spots on the Sun, the uneven surface and craters of the Moon, and the large number of stars in the band of light in the sky called the Milky Way.

Figure 3.17 Galileo Galilei laid the physical framework for Newton's laws.



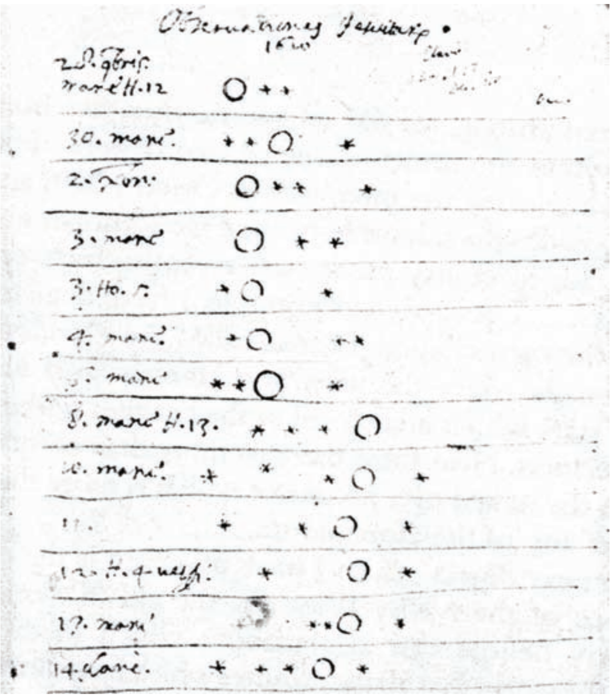


Figure 3.18 This page from Galileo's notebook shows his observations of the four largest moons of Jupiter.

Nebraska Simulations: Phases of Venus; Ptolemaic Phases of Venus

AstroTour: Velocity, Acceleration, Inertia

Figure 3.19 Modern photographs of the phases of Venus show that when we see Venus more illuminated, it also appears smaller, implying that Venus is farther away at that time.

Galileo's Observations

Galileo provided the first observational evidence that some objects in the sky do not orbit Earth. When Galileo turned his telescope to the planet Jupiter, he observed four "stars" in a line near the planet. Over time he observed that the objects changed position from night to night (**Figure 3.18**). Galileo hypothesized that these objects were moons in orbit around Jupiter. These four moons are the largest of Jupiter's many moons and are still called the Galilean moons. Galileo also estimated the relative distance of each moon from Jupiter and the periods of their orbits, and he was able to show that they followed Kepler's third law.

Galileo also observed that the planet Venus went through phases like the Moon. He noticed that the phases of Venus were correlated with the size of the image of Venus in his telescope. In a geocentric model in which Venus orbits Earth like the Moon does, the apparent size of Venus would be constant, like we see for the Moon. In the heliocentric model, the Earth–Venus distance varies, and the size of Venus changes accordingly. When Venus is in its gibbous to full phases, it is farther away, on the other side of the Sun than the side Earth is on, and it is smaller in the sky. When Venus is in its crescent to new phases, it is closer, on the same side of the Sun as the side Earth is on, and it is larger in the sky (**Figure 3.19**). The observations of Jupiter's moons and the phases of Venus in particular convinced Galileo that Copernicus was correct in placing the Sun at the center of the Solar System.

In addition to his astronomical observations, Galileo did important work on the motion of objects. Unlike natural philosophers, who thought about objects in motion but did not actually experiment with them, Galileo conducted experiments with falling and rolling objects. As with his telescopes, Galileo improved or developed new technology to enable him to conduct these experiments. For example, by carefully rolling balls down an inclined plane and by dropping various objects from a height, he found that the distance traveled by a falling object is proportional to the square of the time it has been falling. If he simultaneously dropped two objects of different masses, they reached the ground at the same time, demonstrating that all objects falling to Earth accelerate at the same rate, independent of their mass.

Galileo's observations and experiments with many types of moving objects, such as carts and balls, led him to disagree with the Greek philosophers about when and why objects continue to move or come to rest. Prior to Galileo, it was thought that the natural state of an object was to be at rest. But Galileo found that the natural state of an object is to keep doing what it was doing until a force acts on it. That is, an object in motion continues moving along a straight line with a constant speed until a force acts on it to change its state of motion. This idea of *inertia*, which was later adopted by Newton as his first law of motion, has implications for not only the motion of carts and balls but also the orbits of planets.

Dialogue Concerning the Two Chief World Systems

Much has been written about the considerable danger Galileo faced because of his work. His later life was consumed by conflict with the Catholic Church over his support of the Copernican system. In 1632, Galileo published his best-selling book, *Dialogo sopra i due massimi sistemi del mondo* ("Dialogue Concerning the

Two Chief World Systems"). The *Dialogo* presents a brilliant philosopher named Salviati as the champion of the Copernican heliocentric view of the universe. The defender of an Earth-centered universe, Simplicio—who uses arguments made by the classical Greek philosophers and the pope—sounds silly and ignorant.

Galileo, a religious man who had two daughters in a convent, thought he had the tacit approval of the Catholic Church for his book. But when he placed a number of the pope's geocentric arguments in the unflattering mouth of Simplicio, the perceived attack on the pope attracted the attention of the church. Galileo was put on trial for heresy, sentenced to prison, and eventually placed under house arrest. To escape a harsher sentence, Galileo was forced publicly to recant his belief in the Copernican theory that Earth moves around the Sun. According to one story, as he left the courtroom, Galileo stamped his foot on the ground and muttered, "And yet it moves!"

The *Dialogo* was placed on the pope's Index of Prohibited Works, along with Copernicus's *De Revolutionibus*, but it traveled across Europe, was translated into other languages, and was read by other scientists. (Two centuries later, in 1835, the church finally removed the uncensored version of the *Dialogo* from its prohibited list.) Galileo spent his final years compiling his research on inertia and other ideas into the book *Discourses and Mathematical Demonstrations Relating to Two New Sciences*, which was published in 1638 in Holland, outside the jurisdiction of the Catholic Church.

CHECK YOUR UNDERSTANDING 3.5

Which of Galileo's astronomical observations were best explained by a heliocentric model? (a) sunspots; (b) craters on the Moon; (c) moons of Jupiter; (d) phases of Venus

3.4 Newton's Three Laws Help to Explain the Motion of Celestial Bodies

Empirical laws, like Kepler's laws, describe what happens, but they do not explain why. Kepler described the orbits of planets as ellipses, but he did not explain why they should be so. To take that next step in the scientific process, scientists use basic physical principles and the tools of mathematics to derive the empirically determined laws. Alternatively, a scientist might start with physical laws and predict relationships, which are then verified or falsified by experiment and observation. If these predictions are verified by experiment and observation, the scientist may have determined something fundamental about how the universe works.

Sir Isaac Newton (1642–1727—**Figure 3.20**) took this next step in explaining the nature of motion. Newton was a student of mathematics at Cambridge University when it closed down because of the Great Plague and students were sent home to the safer countryside. Over the next 2 years, he continued to study on his own, and at the age of 23 he invented calculus, which would become crucial to his development of the physics of motion. The German mathematician Gottfried Leibniz independently developed calculus around the same time.

Building on the work of Kepler, Galileo, and others, Newton proposed three physical laws that govern the motions of all objects in the sky and on Earth. In this section, we will examine these three laws, which are essential to an understanding of the motions of the planets and all other celestial bodies.

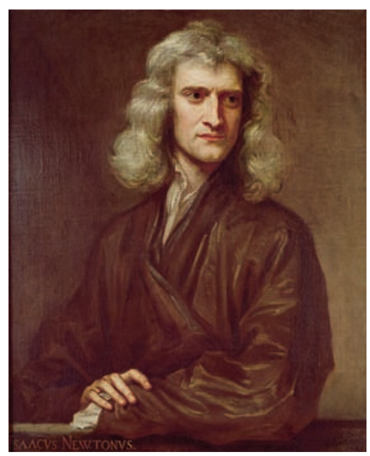


Figure 3.20 Sir Isaac Newton formulated three laws of motion.

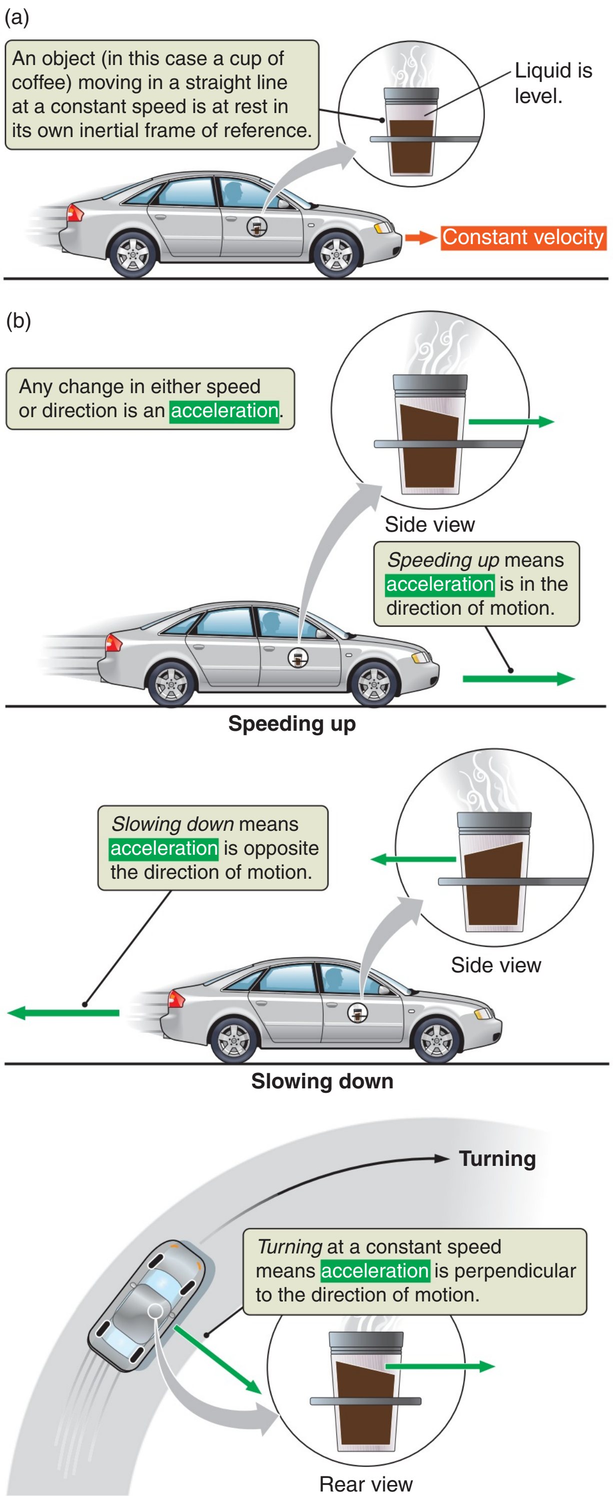


Figure 3.21 (a) An object moving in a straight line at a constant speed is at rest in its own inertial frame of reference. (b) Any change in the velocity of an object is an acceleration. When you are driving, for example, any time your speed changes or you follow a curve in the road, you are experiencing an acceleration. (Throughout the text, velocity arrows will be shown as red, and acceleration arrows will be shown as green.)

Newton's First Law: Objects at Rest Stay at Rest; Objects in Motion Stay in Motion

A **force** is a push or a pull on an object. It is possible for two or more forces to oppose one another in such a way that they are perfectly balanced and cancel out. For example, gravity pulls down on you as you sit in your chair. But the chair pushes up on you with an exactly equal and opposite force. So you remain motionless. Forces that cancel out have no effect on an object's motion. When forces add together to produce an effect, we often use the term *net force*, or sometimes just *force*.

Imagine that you are driving a car, and your phone is on the seat next to you. A rabbit runs across the road in front of you, and you press the brakes hard. You feel the seat belt tighten to restrain you. At the same time, your phone flies off the seat and hits the dashboard. You have just experienced what Newton describes in his first law of motion. **Inertia** is the tendency of an object to maintain its state—either of motion or of rest—until it is pushed or pulled by a net force. In the case of the stopping car, you did not hit the dashboard because the force of the seat belt slowed you down. The phone did hit the dashboard because no such force acted upon it.

Newton's first law of motion describes inertia and states that an object in motion tends to stay in motion, in the same direction, until a net force acts upon it; and an object at rest tends to stay at rest until a net force acts upon it. Galileo's law of inertia became the cornerstone of physics as Newton's first law.

Recall from Section 2.1 of Chapter 2 the concept of a frame of reference. Within a frame of reference, only the relative motions between objects have any meaning. Without external clues, you cannot tell the difference between sitting still and traveling at constant speed in a straight line. For example, if you close your eyes while riding in the passenger seat of a quiet car on a smooth road, you would feel as though you were sitting still. Returning to the earlier example, your phone was "at rest" beside you on the front seat of your car, but a person standing by the side of the road would see the phone moving past at the same speed as the car. People in a car approaching you would see the phone moving quite fast—at the speed they are traveling plus the speed you are traveling! All of these perspectives are equally valid, and all of these speeds of the phone are correct when measured in the appropriate reference frame.

A reference frame moving in a straight line at a constant speed is an **inertial frame of reference**. Any inertial frame of reference is as good as another. As illustrated in **Figure 3.21a**, in the inertial frame of reference of a cup of coffee, the cup is at rest in its own frame even if the car is moving quickly down the road.

Newton's Second Law: Motion Is Changed by Forces

What if a net force does act? In the earlier example, you were traveling in the car, and your motion was slowed when the force of the seat belt acted upon you. Forces change an object's motion—by changing either the speed or the direction. This reflects **Newton's second law of motion**: if a net force acts on an object, then the object's motion changes.

As an example of changes in an object's motion, think about a car. When you are in the driver's seat of a car, you have a number of controls, including a gas pedal and a brake pedal. You use these to make the car speed up or slow down. A *change in speed* is one way the car's motion can change. But you also have the steering wheel in your hands. When you are moving down the road and you turn the wheel, your speed does not necessarily change, but the direction of your motion does. A *change in direction* is also a kind of change in motion.

Together, the combined speed and direction of an object's motion are called the object's **velocity**. "Traveling at 50 kilometers per hour (km/h)" indicates speed; "traveling north at 50 km/h" indicates velocity. The rate at which the velocity of an object changes is called **acceleration**. Acceleration tells you how rapidly a change in velocity happens. For example, if you go from 0 to 100 km/h in 4 seconds, you feel a strong push from the seat back as it shoves your body forward, causing you to accelerate along with the car. However, if you take 2 minutes to go from 0 to 100 km/h, the acceleration is so slight that you hardly notice it.

Partly because the gas pedal on a car is often called the accelerator, some people think *acceleration* always means that an object is speeding up. But we need to stress that, as used in physics, any change in speed or direction is an acceleration. Figure 3.21b illustrates the point by showing what happens to the coffee in a coffee cup as the car speeds up, slows down, or turns. Slamming on your brakes and going from 100 to 0 km/h in 4 seconds is just as much acceleration as going from 0 to 100 km/h in 4 seconds. Similarly, the acceleration you experience as you go through a fast, tight turn at a constant speed is every bit as real as the acceleration you feel when you slam your foot on the gas pedal or the brake pedal. Speeding up, slowing down, turning left, turning right—if you are not moving in a straight line at a constant speed, you are experiencing an acceleration.

Newton's second law of motion says that a net force causes acceleration. The acceleration an object experiences depends on two things. First, as shown in **Figure 3.22**, the acceleration depends on the strength of the net force acting on the object to change its motion. If the forces acting on the object do *not* add up to zero, then there is a net force and the object accelerates (Figure 3.22a). The stronger the net force, the greater the acceleration. Push on something twice as hard and it experiences twice as much acceleration (Figure 3.22b). Push on something 3 times as hard and its acceleration is 3 times as great. The resulting change in motion occurs in the direction the net force points. Push an object away from you, and it will accelerate away from you.

The acceleration that an object experiences also depends on its inertia. You can push some objects easily, for example, an empty box from a refrigerator delivery. However, the actual refrigerator, even though it is about the same size, is not easily shoved around. The greater the mass, the greater the inertia, and the *less* acceleration will occur in response to the same net force, as shown in Figure 3.22c. This relationship among acceleration, force, and mass is expressed mathematically in **Working It Out 3.3**.

Newton's Second Law: $\text{Acceleration } (a) = \dfrac{\text{Force } (F)}{\text{Mass } (m)}$

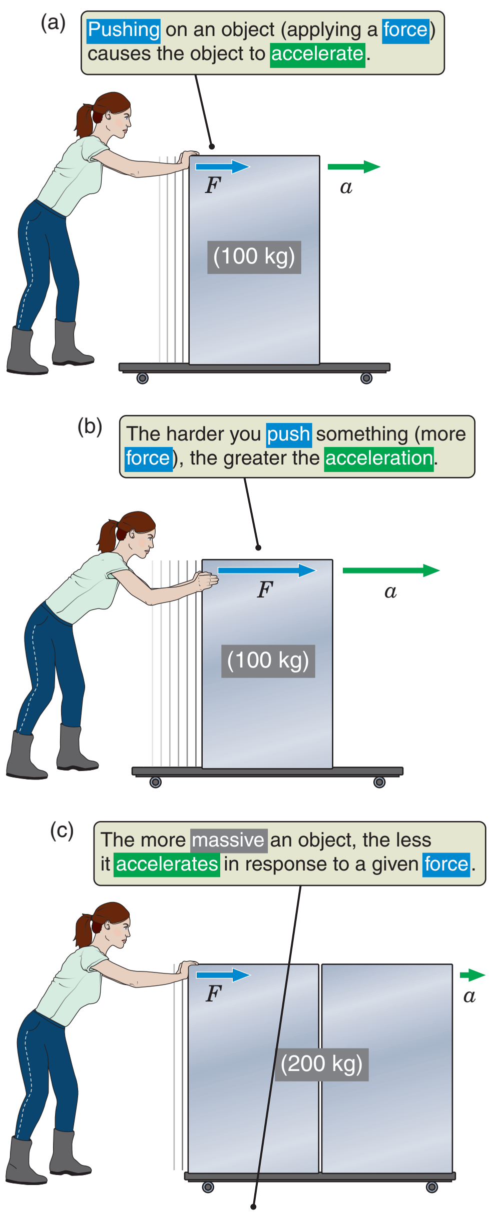


Figure 3.22 Newton's second law of motion says that the acceleration experienced by an object is determined by the force acting on the object divided by the object's mass. (Throughout the text, force arrows will be shown as blue.)

Astronomy in Action: Velocity, Force, and Acceleration

AstroTour: Velocity, Acceleration, Inertia

Newton's Third Law: Whatever Is Pushed, Pushes Back

Imagine that you are standing on a skateboard and pushing yourself along with your foot. Each shove of your foot against the ground sends you faster along your way. But why does this happen? Your muscles flex, and your foot exerts a force on the ground. (Earth itself does not noticeably accelerate, because its great mass gives it great inertia.) Yet this does not explain why *you* experience an acceleration. The fact that you accelerate means that as you push on the ground, the ground must be pushing back on you.

Part of Newton's genius was his ability to see patterns in such everyday events. Newton realized that *every* time one object exerts a force on another, the second

3.3 Working It Out Using Newton's Laws

Your acceleration is determined by how much your velocity changes, divided by how long it takes for that change to happen:

$$\text{Acceleration} = \frac{\text{How much velocity changes}}{\text{How long the change takes to happen}}$$

For example, if an object's speed goes from 5 to 15 meters per second (m/s), then the change in velocity is 10 m/s. If that change happens over the course of 2 seconds, then the acceleration is given by

$$a = \frac{15\,\text{m/s} - 5\,\text{m/s}}{2\,\text{s}} = 5\,\text{m/s}^2$$

If we want to know how an object's motion is changing, we need to know two things: what net force is acting on the object, and what is the resistance of the object to that force? We can put the idea into equation form as follows:

$$\begin{pmatrix}\text{The}\\ \text{acceleration}\\ \text{experienced}\\ \text{by an object}\end{pmatrix} = \frac{\begin{matrix}\text{The force acting to change}\\ \text{the object's motion}\end{matrix}}{\begin{matrix}\text{The object's resistance}\\ \text{to that change}\end{matrix}} = \frac{\text{Force}}{\text{Mass}}$$

Newton's second law above is often written as Force = mass × acceleration, or $F = ma$. The units of force are called **newtons (N)**, so that $1\,\text{N} = 1\,\text{kg m/s}^2$.

As a simple example, suppose you are holding two blocks of the same size. The block in your right hand has twice the mass of the block in your left hand. When you drop the blocks, they both fall with the same acceleration, as shown by Galileo, and they hit your two feet at the same time. Which will hit with more force: the block falling onto your right foot or the one falling onto your left foot? The block in your right hand, with twice the mass, will hit your right foot with twice the force that the other block hits your left foot.

To see how Newton's three laws of motion work together, study **Figure 3.23**. An astronaut is adrift in space, motionless with respect to the nearby space shuttle. With no tether to pull on, how can the astronaut get back to the ship? Suppose the 100-kg astronaut throws a 1-kg wrench directly away from the shuttle at a speed of 10 m/s. Newton's second law says that in order to cause the motion of the wrench to change, the astronaut has to apply a force to it in the direction away from the shuttle. Newton's third law says that the wrench must therefore push back on the astronaut with as much force but in the opposite direction. The force of the wrench on the astronaut causes the astronaut to begin drifting toward the shuttle. How fast will the astronaut move? Turn to Newton's second law again. Because the astronaut has more mass, she will accelerate less than the wrench will. A force that causes the 1-kg wrench to accelerate to 10 m/s will have much less effect on the 100-kg astronaut. Because acceleration equals force divided by mass, the 100-kg astronaut will experience only 1/100 as much acceleration as the 1-kg wrench. The astronaut will drift toward the shuttle, but only at the leisurely rate of 1/100 × 10 m/s, or 0.1 m/s.

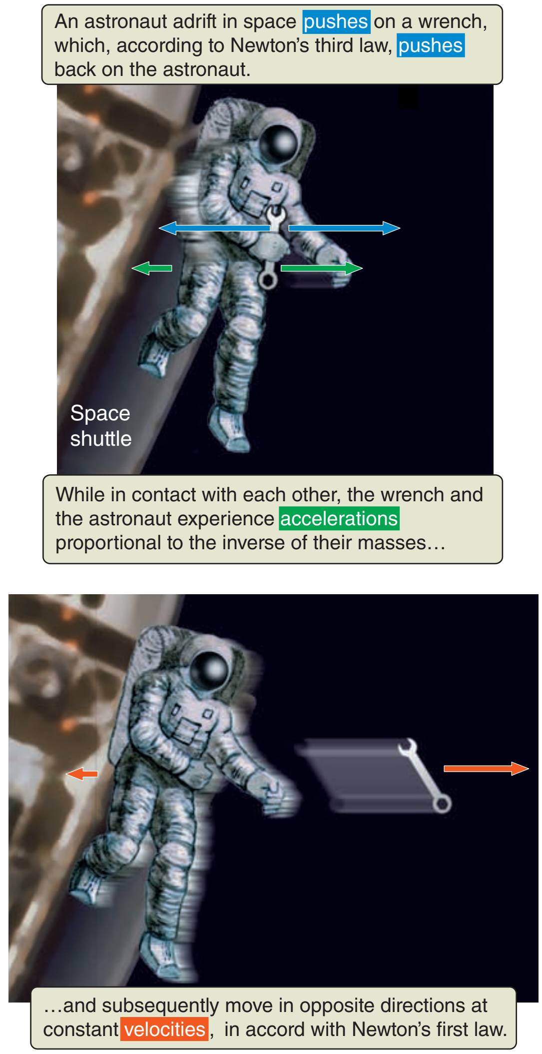


Figure 3.23 According to Newton's laws, if an astronaut adrift in space throws a wrench, the two will move in opposite directions. Their speeds will depend on their masses: the same force will produce a smaller acceleration of a more massive object than of a less massive object. (Acceleration and velocity arrows are not drawn to scale.)

object exerts a matching force on the first. That second force is exactly as strong as the first force but is in exactly the opposite direction. When you are accelerating yourself on the skateboard, you push backward on Earth, and Earth pushes you forward. As shown in **Figure 3.24**, a woman pulling a load on a cart pulls on the rope, and the rope pulls back. A car tire pushes back on the road, and the road pushes forward on the tire. Earth pulls on the Moon, and the Moon pulls on Earth. A rocket engine pushes hot gases out of its nozzle, and those hot gases push back on the rocket, propelling it into space.

All of these force pairs are examples of **Newton's third law of motion**, which says that forces always come in pairs, and the forces of a pair are always equal in strength but opposite in direction. The forces in these pairs always act on two different objects. Your weight pushes down on the floor, and the floor pushes back up on your feet with the same amount of force. For every force there is *always* an equal force in the opposite direction.

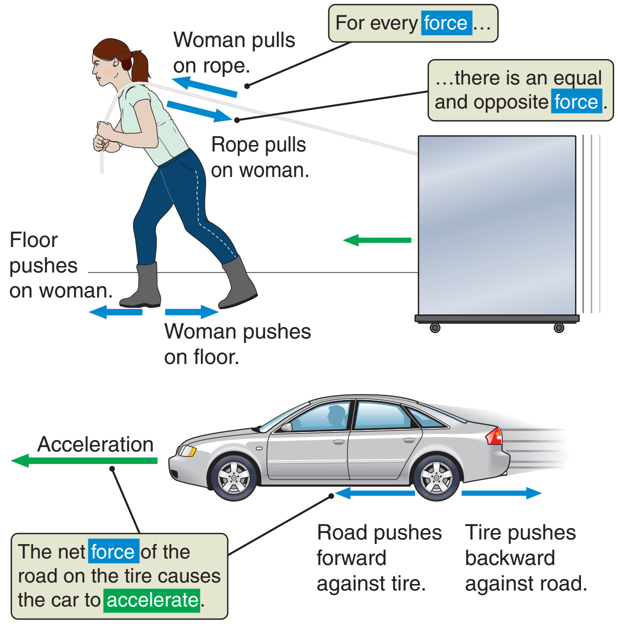


Figure 3.24 Newton's third law states that for every force there is always an equal and opposite force. These opposing forces always act on the two different objects in the same pair.

CHECK YOUR UNDERSTANDING 3.6

Imagine a planet moving in a perfectly circular orbit around the Sun. Is this planet experiencing acceleration? (a) Yes, because it is changing its speed all the time. (b) Yes, because it is changing its direction of motion all the time. (c) No, because its speed is not changing all the time. (d) No, because planets do not experience accelerations.

Origins

Planets and Orbits

In addition to the planets in our own Solar System, several thousand planets have been detected orbiting stars other than our own. Their orbits can be calculated and understood by applying the same three Kepler's laws that we have discussed here. Astrobiologists think that the orbit of a planet around its star affects its chances of developing life.

Consider the average distance of the planet from its star. You might intuitively guess that a planet close to its star will receive more energy from its star than that received by a planet far from its star. If Earth were closer to the Sun, it would be hotter throughout the year—perhaps so hot that water would evaporate and not exist as a liquid. If Earth were farther from the Sun, it would be colder and perhaps all water would freeze. We know that liquid water was a crucial element for the formation of life on Earth. So some astronomers look for planets at a distance from their star such that liquid water can exist (this distance will vary depending on the temperature and size of the star).

We might also think about the eccentricity of a planet's orbit: recall from Figure 3.14a that Earth's orbit differs from a circle by less than 2 percent. Thus, Earth's distance from the Sun does not vary much throughout the year; and as we saw in Chapter 2, seasonal variation on Earth is caused by the tilt of Earth's axis, not by the slight changes in its distance from the Sun. However, if we look at our neighboring planet Mars, which has about the same axial tilt as Earth, we see a greater seasonal variation because of its more eccentric orbit. The distance between Mars and the Sun varies from 1.38 AU (207 million km) to 1.67 AU (249 million km)—an eccentricity of 9 percent. As a result, the seasons on Mars are not equal. They are shorter when Mars is closer to the Sun and moving faster and longer when Mars is farther from the Sun and moving slower. The inequality of the seasons on Mars has an effect on the overall stability of its temperature and climate. When we look at planets orbiting other stars, we see that many have orbital eccentricities even higher than that of Mars and therefore large variations in temperature.

Earth is at the right distance from the Sun to have temperatures that permit water to be liquid, and its orbital eccentricity is low enough that the average planetary temperature does not change much over the course of its orbit. These orbital characteristics have contributed to making the conditions on Earth suitable for the development of life.

ARTICLES QUESTIONS

In this article we see that there are practical implications to planetary alignments. A spacecraft on the other side of the Sun will lose radio contact with the Earth.

NASA Spacecraft Take Spring Break at Mars

By **MIKE WALL, Space.com**

NASA's robotic Mars explorers are taking a cosmic break for the next few weeks, thanks to an unfavorable planetary alignment of Mars, the Earth, and the Sun.

Mission controllers won't send any commands to the agency's *Opportunity* rover, *Mars Reconnaissance Orbiter* (*MRO*), or *Mars Odyssey* orbiter from today (April 9) through April 26. The blackout is even longer for NASA's car-size *Curiosity* rover, which is slated to go solo from April 4 through May 1.

The cause of the communications moratorium is a phenomenon called a Mars solar conjunction, during which the Sun comes between Earth and the Red Planet (**Figure 3.25**). Our star can disrupt and degrade interplanetary signals in this formation, so mission teams won't be taking any chances.

"Receiving a partial command could confuse the spacecraft, putting them in grave danger," NASA officials explain in a video posted last month by the agency's Jet Propulsion Laboratory (JPL) in Pasadena, California.

Opportunity and *Curiosity* will continue performing stationary science work, using commands already beamed to the rovers. *Curiosity* will focus on gathering weather data, assessing the martian radiation environment, and searching for signs of subsurface water and hydrated minerals, officials said Monday (April 8).

MRO and *Odyssey* will also keep studying the Red Planet from above, and they'll continue to serve as communications links between the rovers and Earth. The conjunction will also affect the European Space Agency's *Mars Express* orbiter, officials have said.

Odyssey will send rover data home as usual during conjunction, though the orbiter may have to relay information multiple times due to dropouts. *MRO*, on the other hand, entered record-only mode on April 4. The spacecraft will probably have about 52 gigabits of data to relay when it's ready to start transmitting again on May 1, *MRO* officials have said.

Mars solar conjunctions occur every 26 months, so NASA's Red Planet veterans have dealt with them before. This is the fifth conjunction for *Opportunity*, in fact, and the sixth for *Odyssey*, which began orbiting Mars in 2001.

But it'll be the first for *Curiosity*, which touched down on August 5, kicking off a two-year surface mission to determine if the Red Planet has ever been capable of supporting microbial life.

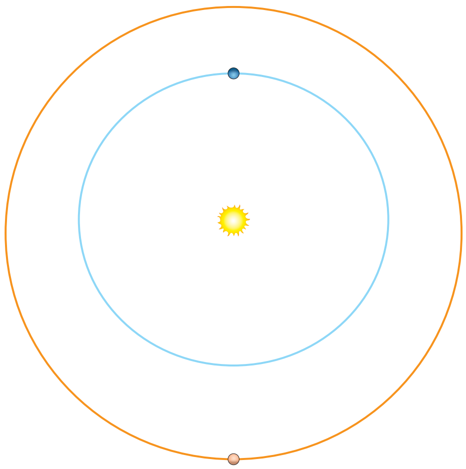


Figure 3.25 Every 26 months, Mars and Earth are on opposite sides of the Sun, making communication between the two planets impossible.

"The biggest difference for this 2013 conjunction is having *Curiosity* on Mars," *Odyssey* mission manager Chris Potts, of NASA's Jet Propulsion Laboratory in Pasadena, California, said in a statement last month.

ARTICLES QUESTIONS

1. How often do these Mars solar conjunctions occur? Does this interval correspond to the sidereal period or the synodic period of Mars?
2. Give two reasons that conjunction is a bad time to view Mars in the sky.
3. Make a sketch of the Mars solar conjunction, showing Mars, Earth, and the Sun. Using the orbital periods in Table 3.2, add in the positions of Mars and Earth at the next Mars conjunction. Will it take place at the same location in space?
4. View this short video from NASA: http://www.jpl.nasa.gov/video/?id=1204. Do you think it explains the concepts well to someone who is not reading an astronomy textbook?
5. If people were on a mission on Mars, a loss of contact would be very troubling. How might NASA plan to avoid losing contact with astronauts on Mars during conjunctions?

Summary

Early astronomers hypothesized that Earth was stationary at the center of the Solar System. Later astronomers realized that a Sun-centered Solar System was much simpler and could explain the observations. Planets, like Jupiter, orbit the Sun, not Earth. Kepler's laws describe the elliptical orbits of planets around the Sun, including details about how fast a planet travels at various points in its orbit. These laws helped Newton to advance science by developing his laws of motion, which govern the motion of all objects (not just orbiting ones). Orbital semimajor axis, eccentricity, and stability may affect a planet's suitability to foster life.

LG 1 **Describe and contrast the geocentric and heliocentric models of the Solar System.** Earth's motion is hard to detect, so prior to the Copernican Revolution, most people accepted a geocentric model of the Solar System, in which all objects orbit around Earth. In particular, apparent retrograde motion of the planets was difficult to understand in this model. Copernicus created the first comprehensive mathematical model of the Solar System with the Sun at the center, called a heliocentric model. His model explained apparent retrograde motion as a visual illusion seen when an inner planet passes an outer planet in their orbits.

LG 2 **Use Kepler's laws to describe the motion of objects in the Solar System.** Using Tycho's observational data, Kepler developed empirical rules to describe the motions of the planets. Kepler's three laws state that (1) planets move in elliptical orbits around the Sun, (2) planets move fastest when closest to the Sun and slowest when farthest from the Sun, so that the planets sweep out equal areas in equal times, and (3) the orbital period of a planet squared equals the semimajor axis of its orbit cubed, or $P^2 = A^3$.

LG 3 **Explain how Galileo's astronomical discoveries provided empirical evidence for the heliocentric model.** Galileo invented astronomical telescopes and used them to observe moons in orbit around Jupiter. He also saw Venus going through phases like the Moon, but changing its apparent size in each phase. These astronomical observations were difficult to explain with a geocentric model.

LG 4 **Describe the work of Galileo and Newton, which led them to discover the physical laws that govern the motion of all objects.** Galileo studied the physics of falling objects and discovered the principle of inertia. Newton's laws state that (1) objects do not change their motion unless they experience a net force, (2) Force = mass × acceleration, and (3) "every force has an equal and opposite force." Net forces cause accelerations; that is, changes in motion. Inertia resists changes in motion.

? UNANSWERED QUESTIONS

- Would the history of scientific discoveries in physics and astronomy have been different if the Catholic Church had not prosecuted Galileo? Galileo wrote the *Dialogo* after being ordered by the Catholic Church in 1616 not to "hold or defend" the idea that Earth moves and the Sun is still. And he wrote his equally famous *Discorsi e Dimostrazioni Matematiche* (often shortened in English to "Two New Sciences") while under house arrest after his trial. However undeterred Galileo appeared to be, the effects of the decrees, prohibitions, and prosecutions might have dissuaded other scientists in Catholic countries from pursuing this type of work. Indeed, after Galileo's experiences, the center of the scientific revolution moved north to Protestant Europe.
- What percentage of planets are in unstable orbits? In younger planetary systems, planets might migrate in their orbits because of the presence of other massive planets nearby. We will see in Chapter 7 that Uranus and Neptune might have migrated in this way. Some planets have been discovered moving through the galaxy without any obvious orbit around a star—and therefore are not in the stable orbits we see in our own Solar System.

Questions and Problems

Test Your Understanding

1. An *empirical science* is one that is based on
   a. hypothesis.
   b. calculus.
   c. computer models.
   d. observed data.
2. When Earth catches up to a slower-moving outer planet and passes it in its orbit, the planet
   a. exhibits retrograde motion.
   b. slows down because it feels Earth's gravitational pull.
   c. decreases in brightness as it passes through Earth's shadow.
   d. moves into a more elliptical orbit.

3. Copernicus's model of the Solar System was superior to Ptolemy's because
   a. it had a mathematical basis that could be used to predict the positions of planets.
   b. it was much more accurate.
   c. it did not require any epicycles.
   d. it fit the telescopic data better.

4. An inferior planet is one that is
   a. smaller than Earth.
   b. larger than Earth.
   c. closer to the Sun than Earth is.
   d. farther from the Sun than Earth is.

5. The time it takes for a planet to come back to the same position relative to the Sun is called its __________ period.
   a. synodic
   b. sidereal
   c. heliocentric
   d. geocentric

6. Suppose a planet is discovered orbiting a star in a highly elliptical orbit. While the planet is close to the star it moves __________, but while it is far away it moves __________.
   a. faster; slower
   b. slower; faster
   c. retrograde; prograde
   d. prograde; retrograde

7. If a superior planet is observed from Earth to have a synodic period of 1.2 years, what is its sidereal period?
   a. 0.54 years
   b. 1.8 years
   c. 4.0 years
   d. 6.0 years

8. A net force must be acting when an object
   a. accelerates.
   b. changes direction but not speed.
   c. changes speed but not direction.
   d. all of the above

9. For Earth, $P^2/A^3 = 1.0$ (in appropriate units). Suppose a new dwarf planet is discovered that is 14 times as far from the Sun as Earth is. For this planet,
   a. $P^2/A^3 = 1.0$.
   b. $P^2/A^3 > 1.0$.
   c. $P^2/A^3 < 1.0$.
   d. one can't know the value of P^2/A^3 without more information.

10. Galileo observed that Venus had phases that correlated with its size in his telescope. From this information, you may conclude that Venus
    a. is the center of the Solar System.
    b. orbits the Sun.
    c. orbits Earth.
    d. orbits the Moon.

11. Kepler's second law says that
    a. planetary orbits are ellipses with the Sun at one focus.
    b. the square of a planet's orbital period equals the cube of its semimajor axis.
    c. net forces cause changes in motion.
    d. planets move fastest when they are closest to the Sun.

12. Suppose you read in the newspaper that a new planet has been found. Its average speed in orbit is 33 km/s. When it is closest to its star it moves at 31 km/s, and when it is farthest from its star it moves at 35 km/s. This story is in error because
    a. the average speed is far too fast.
    b. Kepler's third law says the planet has to sweep out equal areas in equal times, so the speed of the planet cannot change.
    c. Kepler's second law says the planet must move fastest when it is closest, not when it is farthest away.
    d. using these numbers, the square of the orbital period will not be equal to the cube of the semimajor axis.

13. Galileo observed that Jupiter has moons. From this information, you may conclude that
    a. Jupiter is the center of the Solar System.
    b. Jupiter orbits the Sun.
    c. Jupiter orbits Earth.
    d. some things do not orbit Earth.

14. If you start from rest and accelerate at 10 mph/s and end up traveling at 60 mph, how long did it take?
    a. 1 second
    b. 6 seconds
    c. 60 seconds
    d. 0.6 seconds

15. Planets with high eccentricity may be unlikely candidates for life because
    a. the speed varies too much.
    b. the period varies too much.
    c. the temperature varies too much.
    d. the orbit varies too much.

Thinking about the Concepts

16. Study Figure 3.1. During normal motion, does Mars move toward the east or west? Which direction does it travel when moving retrogradely? For how many days did Mars move retrogradely? If one of the martian missions were photographing *Earth* in the sky during these days, what would it have observed?

17. Copernicus and Kepler engaged in what is called empirical science. What do we mean by *empirical*?

18. Explain why the synodic period of Saturn is very close to 1 Earth year (a sketch may help).

19. Make a sketch of Earth, Venus, and the Sun in a geocentric model and in a heliocentric model. Label the Sun and Earth, and then show the changing phases of Venus over the course of one orbit of Venus. What would we observe in each model? Why was the invention of the telescope necessary to distinguish between these models?

20. Experiment with falling objects as Galileo did. Drop pairs of objects of different masses—do they reach the ground at the same time? Do they hit the ground with the same force? Does this work with a sheet of paper or a tissue—why or why not?

21. The speed of a planet in its orbit varies in its journey around the Sun. At what point in its orbit is the planet moving the fastest? At what point is it moving the slowest?

22. The orbit of the Moon around Earth also is elliptical, with an eccentricity of 0.05. How does this compare with the eccentricity of Earth's orbit? How do these elliptical orbits explain the types of solar eclipses discussed in Chapter 2?

23. Galileo came up with the concept of inertia. What do we mean by *inertia*?

24. If Kepler had lived on Mars, would he have deduced the same empirical laws for the motion of the planets? Explain.

25. What is the difference between speed and velocity? between velocity and acceleration?

26. When involved in an automobile collision, a person not wearing a seat belt will move through the car and often strike the windshield directly. Which of Newton's laws explains why the person continues forward, even though the car stopped?

27. When riding in a car, we can sense changes in speed or direction through the forces that the car applies on us. Do we wear seat belts in cars and airplanes to protect us from speed or from acceleration? Explain your answer.

28. An astronaut standing on Earth can easily lift a wrench having a mass of 1 kg, but not a scientific instrument with a mass of 100 kg. In the International Space Station, she is quite capable of manipulating both, although the scientific instrument responds much more slowly than the wrench. Explain why.

29. The Process of Science Figure illustrates that scientific ideas are always open to challenge. Construct an argument that this constant process of challenging and falsifying ideas is a strength of science, rather than a weakness.

30. How might you expect conditions on Earth to be different if the eccentricity of its orbit was 0.17 instead of 0.017?

Applying the Concepts

31. Study the graph in Figure 3.16. Is this graph linear or logarithmic? From the data on the graph, find the approximate semimajor axis and period of Saturn. Show your work.

32. Study Figure 3.19, which shows that the apparent size of Venus changes as it goes through phases. Approximately how many times larger is Venus in the sky at the tiniest crescent than at the gibbous phase shown? Therefore, approximately how many times closer is Venus to us at the phase of that tiniest crescent than at the gibbous phase?

33. Suppose a new dwarf planet is discovered orbiting the Sun with a semimajor axis of 50 AU. What would be the orbital period of this new dwarf planet?

34. Planet Neptune's orbital period is 164.8 years. What is the semimajor axis of its orbit? How much time passes between oppositions of Neptune?

35. Dwarf planet Ceres is located at 2.77 AU from the Sun. Its synodic period is 1.278 years.
    a. Use Working It Out 3.1 to find the sidereal period in years.
    b. Use Kepler's law to find the sidereal period in years.
    c. Compare your results for (a) and (b).

36. Suppose you read online that "experts have discovered a new planet with a distance from the Sun of 2 AU and a period of 3 years." Use Kepler's third law to argue that this is impossible.

37. Show, as Galileo did, that Kepler's third law applies to the four moons of Jupiter that he discovered by calculating P^2 divided by A^3 for each moon. (Data on the moons can be found in Appendix 4.)

38. In a period of 3 months, a planet travels 30,000 km with an average speed of 3.8 m/s. Some time later, the same planet travels 65,000 km in 3 months. How fast is the planet traveling at this later time? During which period is the planet closer to the Sun?

39. If you were on Mars, how often would you see retrograde motion of *Earth* in the martian night sky? (You can view a simulation at http://mars.jpl.nasa.gov/allaboutmars/nightsky/retrograde/.)

40. The elliptical orbit of a comet recently visited by a spacecraft is 1.24 AU from the Sun at its closest approach and 5.68 AU from the Sun at its farthest.
    a. Sketch the orbit of the comet. When is it moving fastest? When is it moving slowest?
    b. What is the semimajor axis of its orbit? How long does it take to go around the Sun?
    c. What is the distance from the Sun to the "center" of the ellipse? What is the eccentricity of the comet's orbit?

41. You are driving down a straight road at a speed of 90 km/h, and you see another car approaching you at a speed of 110 km/h along the road.
    a. Relative to your own frame of reference, how fast is the other car approaching you?
    b. Relative to the other driver's frame of reference, how fast are you approaching the other driver's car?

42. During the latter half of the 19th century, a few astronomers thought there might be a planet circling the Sun inside Mercury's orbit. They even gave it a name: Vulcan. We now know that Vulcan does not exist. If a planet with an orbit one-fourth the size of Mercury's actually existed, what would be its orbital period relative to that of Mercury?

43. Suppose you are pushing a small refrigerator of mass 50 kg on wheels. You push with a force of 100 N.
    a. What is the refrigerator's acceleration?
    b. Assume the refrigerator starts at rest. How long will the refrigerator accelerate at this rate before it gets away from you (that is, before it is moving faster than you can run—of the order 10 m/s)?

44. If a 100-kg astronaut pushes on a 5,000-kg satellite and the satellite experiences an acceleration of 0.1 m/s^2, what is the acceleration experienced by the astronaut in the opposite direction?

45. Sketch the orbit of Mars using the information provided in the "Origins: Planets and Orbits" section of the chapter for the closest and farthest distances of Mars from the Sun.
    a. What is its major axis? What is its semimajor axis?
    b. What is the distance from the "center" of the orbit to the Sun? Compute the eccentricity of the orbit. Compare this with the eccentricity of Earth's orbit.

USING THE WEB

46. Go to the Web page "This Week's Sky at a Glance" (http://skyandtelescope.com/observing/ataglance) at the *Sky & Telescope* magazine website. Which planets are visible in your sky this week? Why are Mercury and Venus visible only in the morning before sunrise or in the evening just after sunset? Before telescopes, how did people know the planets were different from the stars?

47. Look up the dates for the next opposition of Mars, Jupiter, or Saturn. One source is the NASA "Sky Events Calendar" at http://eclipse.gsfc.nasa.gov/SKYCAL/SKYCAL.html. Check only the "Planet Events" box in "Section 2: Sky Events"; and in Section 3, generate a Sky Events Calendar for the year. If you are coming up on an opposition, take pictures of the planet over the next few weeks. Can you see its position move in retrograde motion with respect to the background stars?

48. Refer to the Web page from question 47 to find the current observational positions of all the planets.
    a. Which ones are in or near to conjunction, opposition, or greatest elongation?
    b. Which are visible in the morning sky? in the evening sky?
    c. To connect when we see the planets on Earth with the physical alignments of the planets with Earth and the Sun in space, sketch the Solar System with Earth, Sun, and planets as it looks today from "above." Check your result using NASA's "Solar System Simulator" (http://space.jpl.nasa.gov): set it for "Show Me Solar System" as seen from above, and look at the field of view of 2°, 20°, and 45° to see the inner and then the outer planets. Does the simulator agree with your sketch?

49. Go to the Museo Galileo website and view the exhibit on Galileo's telescope (http://www.museogalileo.it/en/explore/exhibitions/pastexhibitions/galileostelescope.html). What did his telescope look like? What other instruments did he use? From the museum page you can link to short videos (in English) on his science and his trial (http://catalogue.museogalileo.it/index/VideoIndexByThematicArea.html#s7). For example, click on "Galileo's micrometer": How did he measure the separation of the moons from Jupiter? How did this measurement allow him to show that the moons obeyed Kepler's law? Why is Galileo often considered the first modern scientist? Why is his middle finger on display in the museum?

50. Go to the online "Extrasolar Planets Encyclopedia" (http://exoplanet.eu/catalog).
    a. Find a planet with an orbital period similar to that of Earth. What is the semimajor axis of its orbit? If it is very different from 1 AU, then the mass of the star is different from that of the Sun. Click on the star name in the first column to see the star's mass. What is the orbital eccentricity?
    b. Click on "Planet" to sort by name, and select a star with multiple planets. Verify that Kepler's third law applies by showing that the value of P^2/A^3 is about the same for each of the planets of this star. How eccentric are the orbits of the multiple planets?

smartwork5

If your instructor assigns homework in Smartwork5, access your assignments at digital.wwnorton.com/astro5.

EXPLORATION

Kepler's Laws

digital.wwnorton.com/astro5

In this Exploration, we will examine how Kepler's laws apply to the orbit of Mercury. Visit the Student Site at the Digital Landing page, and open the Planetary Orbit Simulator applet. This simulator animates the orbits of the planets, enabling you to control the simulation speed, as well as a number of other parameters. Here we focus on exploring the orbit of Mercury, but you may wish to spend some time examining the orbits of other planets as well.

Kepler's First Law

To begin exploring the simulation, in the "Orbit Settings" panel, use the drop-down menu next to "set parameters for" to select "Mercury" and then click "OK." Click the "Kepler's 1st Law" tab at the bottom of the control panel. Use the radio buttons to select "show empty focus" and "show center."

1 How would you describe the shape of Mercury's orbit?

Deselect "show empty focus" and "show center," and select "show semiminor axis" and "show semimajor axis." Under "Visualization Options," select "show grid."

2 Use the grid markings to estimate the ratio of the semiminor axis to the semimajor axis.

3 Calculate the eccentricity of Mercury's orbit from this ratio using $e = [1 - (\text{Ratio})^2]^{1/2}$.

Kepler's Second Law

Click on "reset" near the top of the control panel, set parameters for Mercury, and click "OK." Then click on the "Kepler's 2nd Law" tab at the bottom of the control panel. Slide the "adjust size" slider to the right, until the fractional sweep size is $\frac{1}{8}$.

Click on "start sweeping." The planet moves around its orbit, and the simulation fills in area until one-eighth of the ellipse is filled. Click on "start sweeping" again as the planet arrives at the rightmost point in its orbit (that is, at the point in its orbit farthest from the Sun). You may need to slow the animation rate using the slider under "Animation Controls." Click on "show grid" under the visualization options. (If the moving planet annoys you, you can pause the animation.) One easy way to estimate an area is to count the number of squares.

4 Count the number of squares in the yellow area and in the red area. You will need to decide what to do with fractional squares. Are the areas the same? Should they be?

Kepler's Third Law

Click on "reset" near the top of the control panel, set parameters for Mercury, and then click on the "Kepler's 3rd Law" tab at the bottom of the control panel. Select "show solar system orbits" in the "Visualization Options" panel. Study the graph. Use the eccentricity slider to change the eccentricity of the simulated planet. Make the eccentricity first smaller and then larger.

5 Did anything in the graph change?

6 What do your observations of the graph tell you about the dependence of the period on the eccentricity?

Set parameters back to those for Mercury. Now use the semimajor axis slider to change the semimajor axis of the simulated planet.

7 What happens to the period when you make the semimajor axis smaller?

8 What happens when you make it larger?

9 What do these results tell you about the dependence of the period on the semimajor axis?

4 Gravity and Orbits

In this chapter, we explore the physical laws that explain the regular patterns in the motions of the planets. Because the Sun is far more massive than all the other parts of the Solar System combined, its gravity shapes the motions of every object in its vicinity, from the almost circular orbits of some planets to the extremely elongated orbits of comets.

LEARNING GOALS

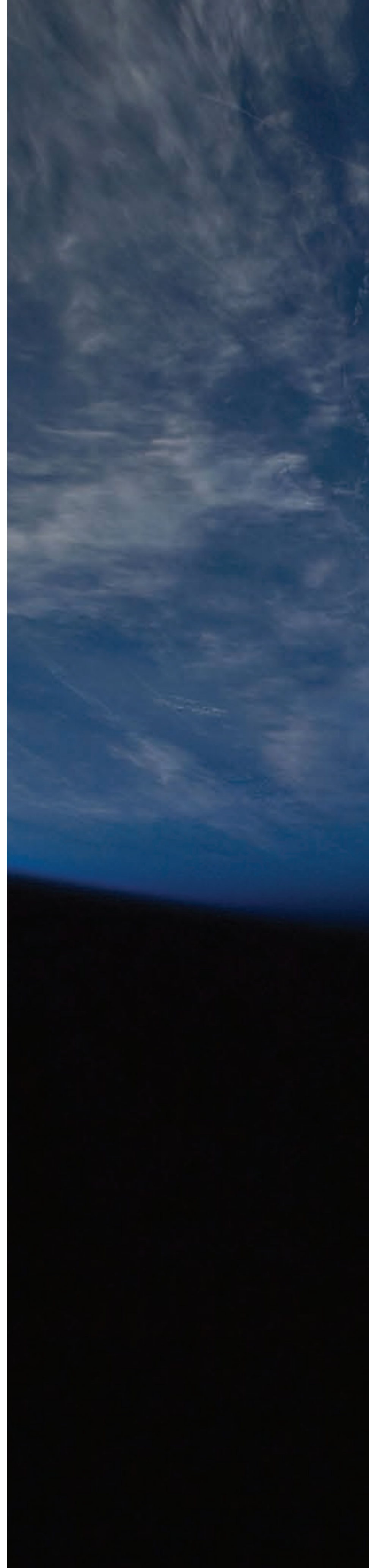
By the conclusion of this chapter, you should be able to:

LG 1 Explain the elements of Newton's universal law of gravitation.

LG 2 Use the laws of motion and gravitation to explain planetary orbits.

LG 3 Explain how tidal forces from the Sun and Moon create Earth's tides.

LG 4 Describe the effects of tidal forces on solid bodies.



The International Space Station in orbit around Earth. ▶▶▶

What keeps a space station in orbit?

4.1 Gravity Is a Force between Any Two Objects Due to Their Masses

In Chapter 3, we explored Kepler's work on the movement of the planets around the Sun and Newton's laws of motion. In this chapter, we build on those concepts to look at Newton's universal law of gravitation. Although some of the properties of gravity were observed before Newton, his work connected the everyday phenomenon of falling objects to the motion of the planets around the Sun. Newton's theory of gravity combined Kepler's empirical laws and Newton's own laws of motion.

Gravity, Mass, and Weight

Many forces that we see in everyday life involve direct contact between objects. The cue ball on a pool table slams into the eight ball, knocking it into the pocket. The shoe of the child pushing a scooter presses directly against the surface of the pavement. When there is physical contact between two objects, the source of the forces between them is easy to see.

If you drop a ball, it falls toward the ground. The ball picks up speed as it falls, accelerating downward toward Earth. Newton's second law says that where there is acceleration, there is force. But where is the force that causes the ball to accelerate? The ball falling toward Earth is an example of a different kind of force, one that acts at a distance across the intervening void of space. The ball falling toward Earth is accelerating in response to the force of gravity. **Gravity**, one of the fundamental forces of nature, is the mutually attractive force between objects with mass.

Recall from Chapter 3 that Galileo discovered that all freely falling objects accelerate toward Earth at the same rate, regardless of their mass. Drop a marble and a book at the same time and from the same height, and they will hit the ground together. Note that air resistance becomes a factor at higher speeds, but it is negligible for dense, slow objects. The acceleration of falling objects due to gravity near the surface of Earth, also measured experimentally by Galileo, is usually written as g (lowercase) and has an average value across the surface of Earth of 9.8 meters per second squared (m/s^2). The value of g varies slightly across Earth's surface, ranging from 9.78 m/s^2 at the equator to 9.83 m/s^2 at the poles. This variation exists because Earth is not a perfect sphere: its rotation makes it flatter at the poles, so the radius of Earth is smaller at the poles.

After working out the laws governing the motion of objects, Newton realized that if all objects, no matter what their mass, fall with the same acceleration, then the gravitational *force* on an object must be determined by the object's *mass*.

Recall Newton's second law from Chapter 3: acceleration equals force divided by mass, or $a = F/m$. The acceleration due to gravity can be the same for all objects only if the value of the force divided by the mass is the same for all objects. In other words, an object twice as massive has double the gravitational force acting on it; an object 3 times as massive has triple the gravitational force acting on it, and so on.

The gravitational force acting on an object attracted by a planet is called the object's **weight**. On the surface of Earth, weight equals mass multiplied by the acceleration of gravity at Earth's surface, g. In common language, we often use weight and mass interchangeably. To be more scientifically precise, astronomers use *mass* to refer to the amount of stuff in an object and *weight* to refer to the force exerted on that object by the planet's gravitational pull. Your mass is the same no matter what planet or moon you are on, but your weight will be different:

$$F_{\text{weight}} = m \times g$$

where F_{weight} is an object's weight in newtons (N), the metric unit of force; m is the object's mass in kilograms (kg); and g is Earth's constant for acceleration due to gravity, 9.8 m/s^2. On Earth, an object with a *mass* of 1 kg has a *weight* of 9.8 N. As illustrated in **Figure 4.1**, on the Moon the acceleration due to gravity is about 6 times lower at 1.6 m/s^2, so the 1-kg mass would have a weight of 1.6 N. On the Moon, your weight would be about one-sixth of your weight on Earth.

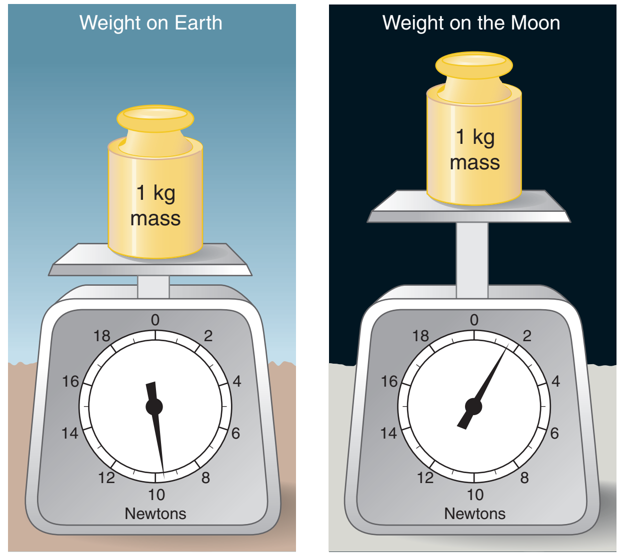


Figure 4.1 On the Moon, a mass of 1 kg has $\frac{1}{6}$ the weight (displayed in newtons) that it has on Earth.

Newton's Law of Gravity

As Newton told the story, he saw an apple fall from a tree to the ground, and he reasoned that if gravity is a force that depends on mass, then there should be a gravitational force between *any* two masses, including between a falling apple and Earth. This great insight came from applying his third law of motion to gravity. Recall that Newton's third law states that for every force there is an equal and opposite force. Therefore, if Earth exerts a force of 9.8 N on a 1-kg mass sitting on its surface, then that 1-kg mass must also exert a force of 9.8 N on Earth. Drop a 7-kg bowling ball and it falls toward Earth, but at the same time Earth falls toward the 7-kg bowling ball. The reason we do not notice the motion of Earth is that Earth is very massive, so it has a lot of resistance to changes in its motion. In the time it takes a 7-kg bowling ball to fall to the ground from a height of 1 kilometer (km), Earth has "fallen" toward the bowling ball by only a tiny fraction of the size of an atom.

Newton reasoned that if doubling the mass of any object doubles the gravitational force between the object and Earth, then doubling the mass of Earth ought to do the same thing. In short, the gravitational force between Earth and an object must be equal to the product of the two masses multiplied by *something*:

$$\text{Gravitational force} = \text{Something} \times \text{Mass of Earth} \times \text{Mass of object}$$

If the mass of the object is 2 times greater, then the force of gravity will be 2 times greater. Likewise, if the mass of Earth happened to be 3 times what it is, the force of gravity would also have to be 3 times greater. If both the mass of Earth and the mass of the object were greater by these amounts, the gravitational force would increase by a factor of 2×3, or 6 times. Because objects fall toward the center of Earth, we know that gravity is an attractive force acting along a line between the two masses.

If gravity is a force that depends on mass, then there should be a gravitational force between *any* two masses. Suppose we have two masses—call them mass 1 and mass 2, or m_1 and m_2 for short. The gravitational force between them is *something* multiplied by the product of the masses:

$$\text{Gravitational force between two objects} = \text{Something} \times m_1 \times m_2$$

We have gotten this far just by combining Galileo's observations of falling objects with (1) Newton's laws of motion and (2) Newton's belief that Earth is a mass just like any other mass. But what about that "something" in the previous expression?

Kepler had already thought about this question. He reasoned that because the Sun is the focal point for planetary orbits, the Sun must exert an influence over the motions of the planets. Kepler speculated that this influence must grow weaker with distance from the Sun, because the planets closer to the Sun moved much faster than the farther ones. Kepler did not know about forces or inertia or gravity as the cause of celestial motion, but he thought that geometry alone suggested how this solar "influence" might change for planets progressively farther from the Sun.

To see why the influence must become weaker, imagine you have a certain amount of paint to spread over the surface of a sphere. If the sphere is small, you will get a thick coat of paint. But if the sphere is larger, the paint has to spread farther, and you will get a thinner coat. The surface area of a sphere depends on the square of the sphere's radius. Double the radius of a sphere, and the sphere's surface area becomes 4 times what it was. If you paint this new, larger sphere, the paint must cover 4 times as much area, and the thickness of the paint will be only a fourth of what it was on the smaller sphere. Triple the radius of the sphere: the sphere's surface will be 9 times larger and the coat of paint will be only one-ninth as thick.

Kepler reasoned that as the influence of the Sun extended farther and farther into space, it would have to spread out to cover the surface of a larger and larger imaginary sphere centered on the Sun. The influence of the Sun should diminish with the square of the distance from the Sun—a relationship known as an **inverse square law**.

Kepler had an interesting idea, but not a scientific hypothesis with testable predictions. He lacked an explanation for how the Sun influences the planets and the mathematical tools to calculate how an object would move under such an influence. Newton had both. If gravity is a force between *any* two objects, then there should be a gravitational force between the Sun and each of the planets. If this gravitational force were the same as Kepler's "influence," then gravity might behave according to an inverse square law.

Newton's expression for gravity came to look like this:

$$\text{Gravitational force between two objects} = \text{Something} \times \frac{m_1 \times m_2}{(\text{Distance between objects})^2}$$

There is still a "something" left in this expression, and that something is a constant of proportionality. This constant determines the strength of gravity between objects, and it is the same for all pairs of objects. Newton named it the **universal gravitational constant**, written as G (uppercase). Newton estimated this gravitational constant G by using Galileo's measurement of g, estimates of Earth's radius, and a guess at the mass of Earth by assuming it had about the same density as typical rocks. It was not until many years later that the actual value of G was first measured. Today the value of G is accepted as 6.67×10^{-11} N m^2/kg^2 or its equivalents: 6.67×10^{-11} m^3/(kg s^2) or 6.67×10^{-20} km^3/(kg s^2).

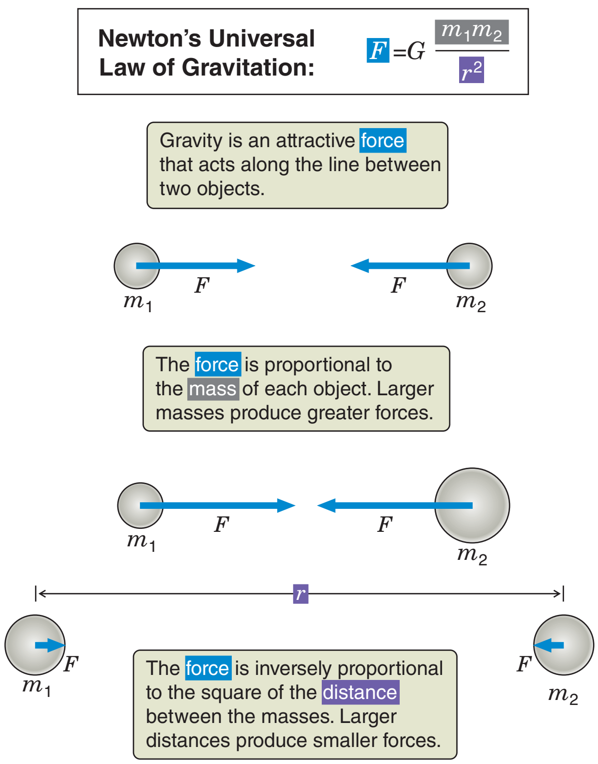


Figure 4.2 Gravity is an attractive force between two objects. The force of gravity depends on the masses of the objects, m_1 and m_2, and the distance, r, between them.

A Universal Law of Gravitation

Newton's **universal law of gravitation**, illustrated in **Figure 4.2**, states that gravity is a force between any two objects having mass and has the following properties:

1. It is an attractive force acting along a straight line between the two objects.

2. It is proportional to the mass of one object (m_1) multiplied by the mass of the other object (m_2). If we double m_1, then the force (F) increases by a factor of 2. Likewise, if we double m_2, F increases by a factor of 2.
3. It is inversely proportional to the square of the distance r between the centers of the two objects: As seen in **Figure 4.3**, if we double r, F decreases by a factor of 4. If we triple r, F falls by a factor of 9.

Written as a mathematical formula, the universal law of gravitation states

$$F_{\text{grav}} = G \times \frac{m_1 \times m_2}{r^2}$$

where F_{grav} is the force of gravity between two objects, m_1 and m_2 are the masses of objects 1 and 2, r is the distance between the centers of mass of the two objects, and G is the universal gravitational constant. The relationship between the force of gravity and the masses and separation distance between two objects is further explored in **Working It Out 4.1**.

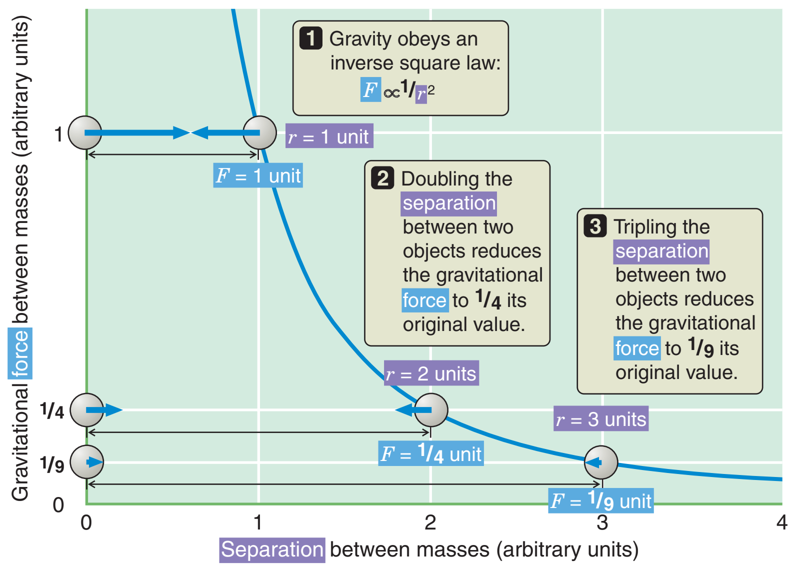


Figure 4.3 As two objects move apart, the gravitational force between them decreases by the inverse square of the distance between them.

4.1 Working It Out Playing with Newton's Laws of Motion and Gravitation

For any two objects, the force of gravity is directly proportional to the masses and inversely proportional to the *square* of the distance between them. Let's look at a few examples of how to use this equation:

Changing the Distance

How would the gravitational force between Earth and the Moon change if the distance between them were doubled? In this example, the masses of the Sun and Moon stay the same, and r becomes $2r$. We can calculate how the force changes by writing the equation for distance r and again for distance $2r$, and then taking a ratio to compare them:

$$\frac{F_{\text{grav at distance } 2r}}{F_{\text{grav at distance } r}} = \frac{G \times \dfrac{M_{\text{Earth}} M_{\text{Moon}}}{(2r)^2}}{G \times \dfrac{M_{\text{Earth}} M_{\text{Moon}}}{r^2}}$$

We can cancel out the constant G and the masses of Earth and the Moon, which do not change. Then you need to multiply both the numerator and denominator of the fraction by r^2, and remember that both the 2 and the r get squared in $(2r)^2 = 4r^2$. The equation becomes

$$\frac{F_{\text{grav at distance } 2r}}{F_{\text{grav at distance } r}} = \frac{\cancel{G} \times \cancel{M_{\text{Earth}}} \times \cancel{M_{\text{Moon}}}}{\cancel{G} \times \cancel{M_{\text{Earth}}} \times \cancel{M_{\text{Moon}}}} \times \frac{r^2}{(2r)^2}$$

$$= \frac{\cancel{r^2}}{4\cancel{r^2}} = \frac{1}{4}$$

Doubling the distance reduced the force by a factor of 4; that is, the force is $\frac{1}{4}$ as strong.

Nebraska Simulation: Gravity Algebra

Gravitational Acceleration

There are two ways to think about the gravitational force that Earth exerts on an object with mass m located on the surface of Earth. Recall Newton's second law of motion: $F = m \times a$. Here we are considering the gravitational force and the acceleration due to gravity, or $F_{\text{grav}} = m \times g$. The other way to think about the force is from the perspective of the universal law of gravitation, which says

$$F_{\text{grav}} = G \times \frac{M_{\text{Earth}} \times m}{R_{\text{Earth}}^2}$$

Here, M_{Earth} is the mass of Earth, and R_{Earth} is the radius of Earth. The two expressions describing this force must be equal to each other. Therefore,

$$\cancel{m} \times g = G \times \frac{M_{\text{Earth}} \times \cancel{m}}{R_{\text{Earth}}^2}$$

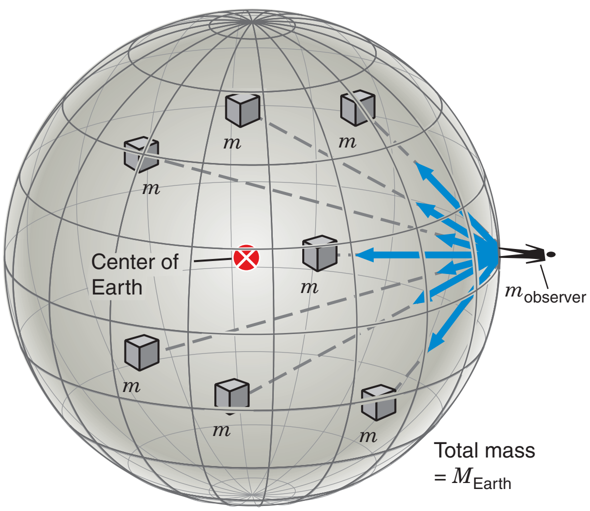
The mass m is on both sides of the equation, so we can cancel it out. The equation then becomes

$$g = G \times \frac{M_{\text{Earth}}}{R_{\text{Earth}}^2}$$

The expression shows that the gravitational acceleration (g) experienced by an object of mass m on the surface of Earth is determined by the mass of Earth and by the radius of Earth. The mass of the object itself (m) appears nowhere in this expression, so changing m has no effect on the gravitational acceleration of an object on Earth.

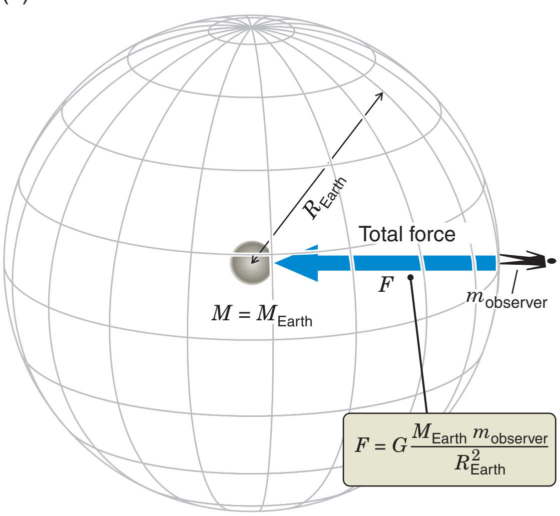
Gravity pulls you toward the center of Earth. Gravity holds the planets and stars together and keeps the thin blanket of air we breathe close to Earth's surface. The planets, including Earth, orbit around the Sun, and gravity holds them in orbit. Gravity caused a vast interstellar cloud of gas and dust to collapse 4.5 billion years ago to form the Sun, Earth, and the rest of the Solar System. Gravity binds colossal groups of stars into galaxies. Gravity shapes space and time, and it can affect the ultimate fate of the universe. We will return often to the concept of gravity and find it central to an understanding of the universe.

(a)



An object on the surface of a spherical mass (such as Earth) feels a gravitational attraction toward each small part of the sphere.

(b)



The net force is the same as if we scooped up the mass of the entire sphere and concentrated it at a point at the center.

Figure 4.4 Outside a sphere, the net gravitational force due to a spherical mass is the same as the gravitational force from the same mass concentrated at a point at the center of the sphere.

CHECK YOUR UNDERSTANDING 4.1

If the distance between Earth and the Sun were cut in half, the gravitational force between these two objects would: (a) decrease by a factor of 4; (b) decrease by a factor of 2; (c) increase by a factor of 2; (d) increase by a factor of 4.

Gravity Differs from Place to Place within an Object

You can think of Earth as a collection of small masses, each of which feels a gravitational attraction toward every other small part of Earth. The mutual gravitational attraction that occurs among all parts of the same object is called self-gravity.

As you sit reading this book, you are exerting a gravitational attraction on every other fragment of Earth, and every other fragment of Earth is exerting a gravitational attraction on you. Your gravitational interaction is strongest with the parts of Earth closest to you. The parts of Earth that are on the other side of our planet are much farther from you, so their pull on you is correspondingly less.

The net effect of all these forces is to pull you (or any other object) toward the center of Earth. If you drop a hammer, it falls directly toward the ground. Because Earth is nearly spherical, for every piece of Earth pulling you toward your right, a corresponding piece of Earth is pulling you toward your left with just as much force. For every piece of Earth pulling you forward, a corresponding piece of Earth is pulling you backward. As you can see in **Figure 4.4a**, because Earth is almost spherically symmetric, all of these "sideways" forces cancel out, leaving behind an overall force that points toward Earth's center.

Some parts of Earth are closer to you and others are farther away, but there is an average distance between you and all of the small fragments of Earth that are pulling on you. This average distance is the distance between you and the center of Earth. As illustrated in Figure 4.4b, the overall pull that you feel is the same as it would be if all the mass of Earth was concentrated at a single point located at the very center of the planet.

This relationship is true for any spherically symmetric object. Outside the object, the gravity from such an object behaves as if all the mass of that object were concentrated at a point at its center. This relationship will be important in many applications. For example, when you estimate your weight on another planet, you are calculating the force of gravity between you and the planet. The "distance" in the gravitational equation will be the distance between you and the center of the planet, which is just the radius of the planet.

CHECK YOUR UNDERSTANDING 4.2

If Earth shrank to a smaller radius but kept the same mass, would the gravitational force between Earth and the Moon become: (a) smaller; (b) larger; or (c) stay the same? Would everyone's weight on Earth: (a) increase; (b) decrease; or (c) stay the same?

4.2 An Orbit Is One Body "Falling around" Another

Kepler's laws on the motions of planets enabled astronomers to predict the positions of the planets accurately, but these laws did not explain why the planets behave as they do. Newton's work explained why planets orbit the Sun.

Newton used his laws of motion and his proposed law of gravity to predict the paths of planetary orbits. His calculations showed that these orbits should be ellipses with the Sun at one focus, that planets should move faster when closer to the Sun, and that the square of the period of a planet's orbit should vary as the cube of the semimajor axis of that elliptical orbit. Newton's universal law of gravitation *predicted* that planets should orbit the Sun in just the way that Kepler's empirical laws described. By explaining Kepler's laws, Newton found important corroboration for his law of gravitation.

Gravity and Orbits

Newton's laws tell us how forces change an object's motion and how objects interact with each other through gravity. To know where an object will be at any given time, we carefully have to "add up" the object's motion over time. Newton invented calculus to do this, but we will aim just for a conceptual understanding.

In Newton's time, the closest thing to making a heavy object fly was shooting cannonballs out of a cannon, so he used cannonballs in "thought experiments" about planetary motions. If one drops a cannonball, it falls directly to the ground, like any other mass does. However, as you can see in **Figure 4.5a**, a cannonball fired out of a cannon that is level with the ground behaves differently. The cannonball still falls to the ground in the same amount of time as it does when it is dropped, but while falling it also travels over the ground, following a curved path that carries it a horizontal distance before it finally lands. As shown in Figure 4.5b, the faster the cannonball moves when it is fired from the cannon, the farther it will go before it hits the ground.

In the real world this experiment reaches a natural limit. To travel through air, the cannonball must push the air out of its way—an effect normally referred to as *air resistance*—which slows it down. But because this is only a thought experiment, we can ignore such real-world complications. Instead imagine that, having inertia, the cannonball continues along its course until it runs into something. The faster the cannonball moves when it is fired, the farther it goes before hitting the ground. If the cannonball flies far enough, Earth's surface curves out from under it, as shown in Figure 4.5c. As illustrated in Figure 4.5d, eventually a point is reached where the cannonball is flying so fast that the surface of Earth curves away from the cannonball at exactly the same rate at which the cannonball is falling toward Earth. When this occurs, the cannonball, which always falls

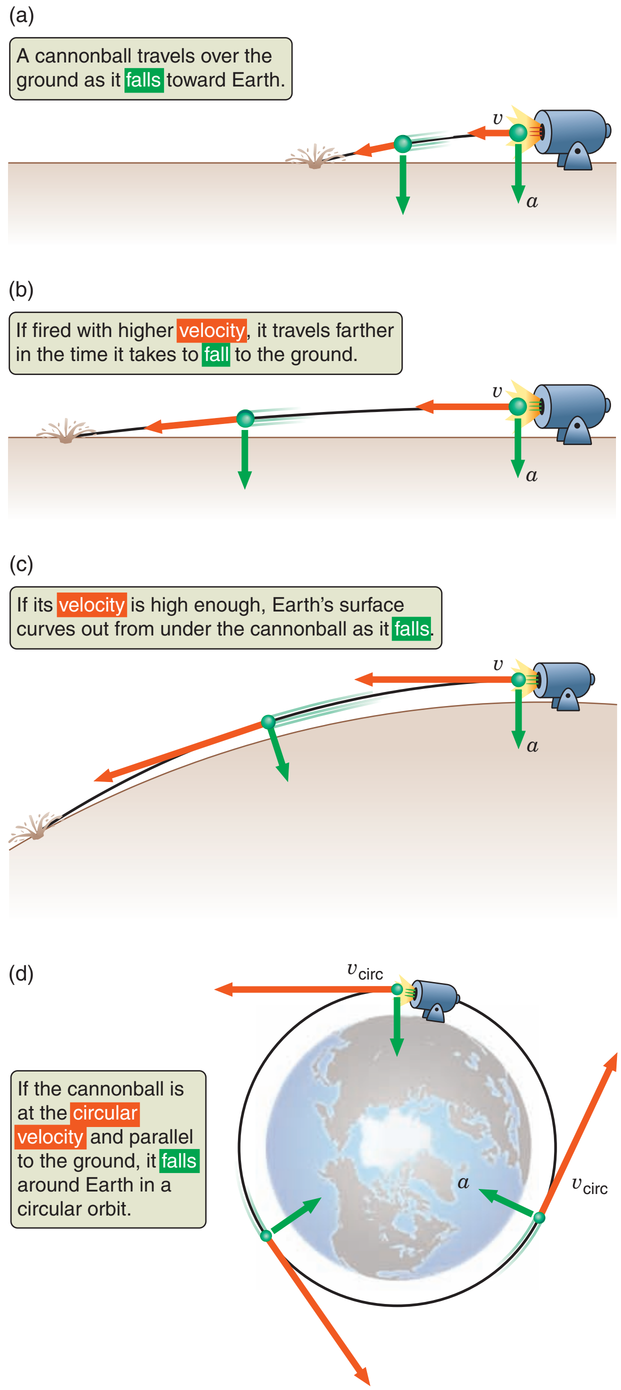


Figure 4.5 Newton realized that a cannonball fired at the right speed would fall around Earth in a circle. Velocity (*v*) is indicated by a red arrow and acceleration (*a*) by a green arrow.

AstroTour: Newton's Laws and Universal Gravitation

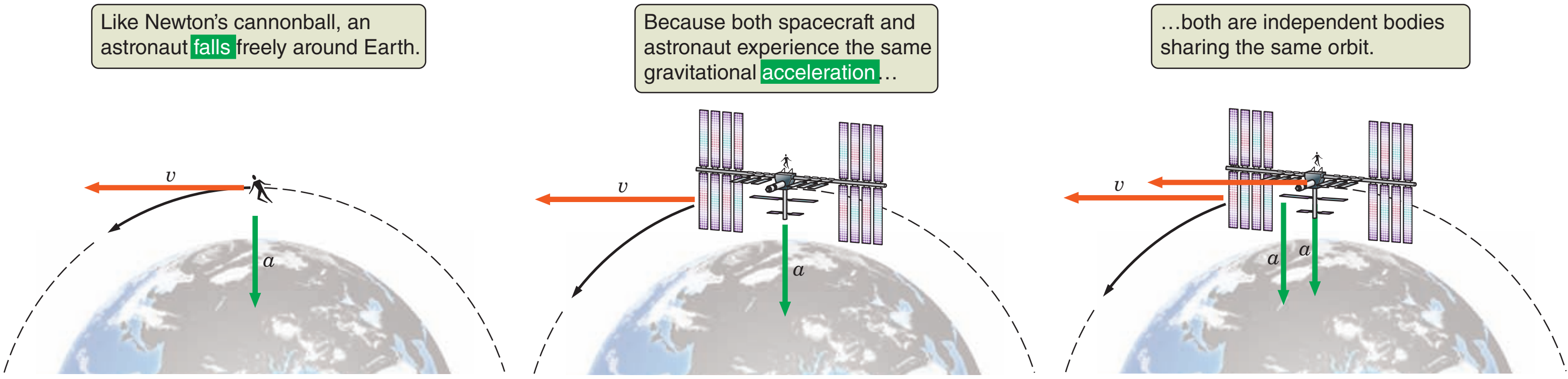


Figure 4.6 A "weightless" astronaut has not escaped Earth's gravity. Rather, an astronaut and a spacecraft share the same orbit as they fall around Earth together.

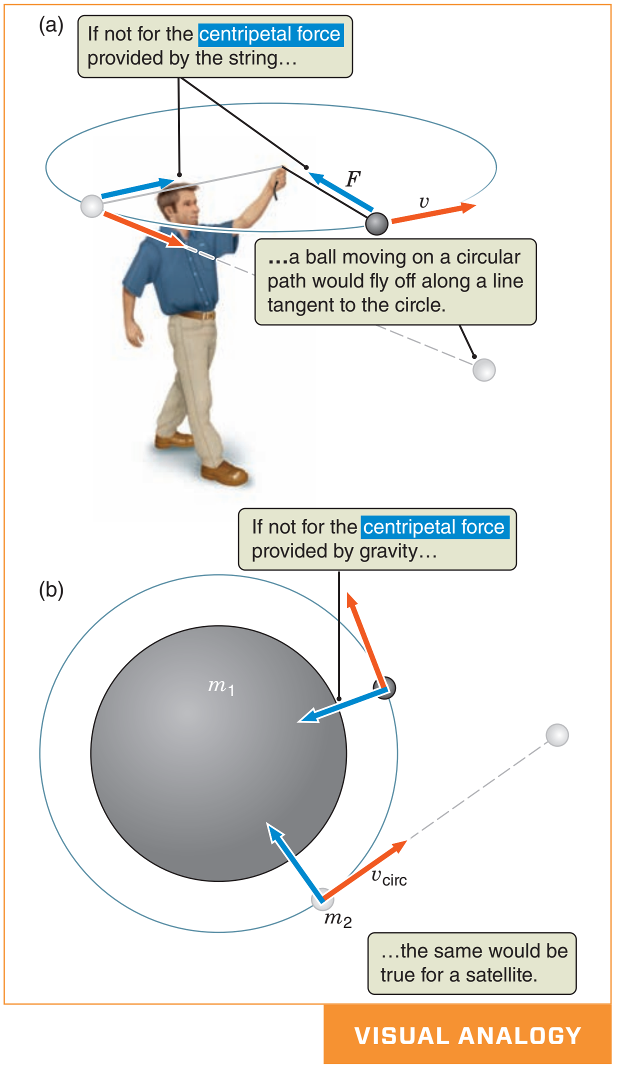


Figure 4.7 (a) A string provides the centripetal force that keeps a ball moving in a circle. (We are ignoring the smaller force of gravity that also acts on the ball.) (b) Similarly, gravity provides the centripetal force that holds a satellite in a circular orbit.

toward the center of Earth, is, in a sense, falling around the world. An **orbit** is the path of one object that freely falls around another.

Why do astronauts appear to float freely about the cabin of a spacecraft? It is not because they have escaped Earth's gravity; it is Earth's gravity that holds them in their orbit. Instead the answer lies in Galileo's early observation that all objects fall with the same acceleration, regardless of their mass. The astronauts and the spacecraft are both in orbit around Earth, moving in the same direction, at the same speed, and experiencing the same gravitational acceleration, so they fall around Earth together. **Figure 4.6** demonstrates this point. The astronaut is orbiting Earth just as the spacecraft is orbiting Earth. On the surface of Earth, your body tries to fall toward the center of Earth, but the ground gets in the way. You experience your weight when you are standing on Earth because the ground pushes on you to oppose the force of gravity, which pulls you downward. In the spacecraft, however, nothing interrupts the astronaut's fall, because the spacecraft is falling around Earth in just the same orbit. The astronaut is in **free fall**, falling freely in Earth's gravity. The **Process of Science Figure** illustrates the universality of Newton's law of gravitation.

What Velocity Is Needed to Reach Orbit?

How fast must Newton's cannonball be fired for it to fall around the world? The cannonball would be in **uniform circular motion**, which means it moves along a circular path at constant speed. This type of motion is discussed in more depth in Appendix 8. Another example of uniform circular motion is a ball whirling around your head on a string, illustrated in **Figure 4.7a**. If you let go of the string, the ball will fly off in a straight line in whatever direction it is traveling at the time, just as Newton's first law predicts for an object in motion. The string prevents the ball from flying off by constantly changing the direction the ball is traveling. The central force of the string on the ball is called a **centripetal force**: a force toward the center of the circle. Using a more massive ball, speeding up its motion, or making the string shorter so that the turn is tighter all increase the force needed to keep a ball moving in a circle.

In the case of Newton's cannonball (or a satellite), there is no string to hold the ball in its circular motion. Instead, the force is provided by gravity, as illustrated in Figure 4.7b. The force of gravity must be just enough to keep the satellite moving on its circular path. Because this force has a specific strength, it follows that

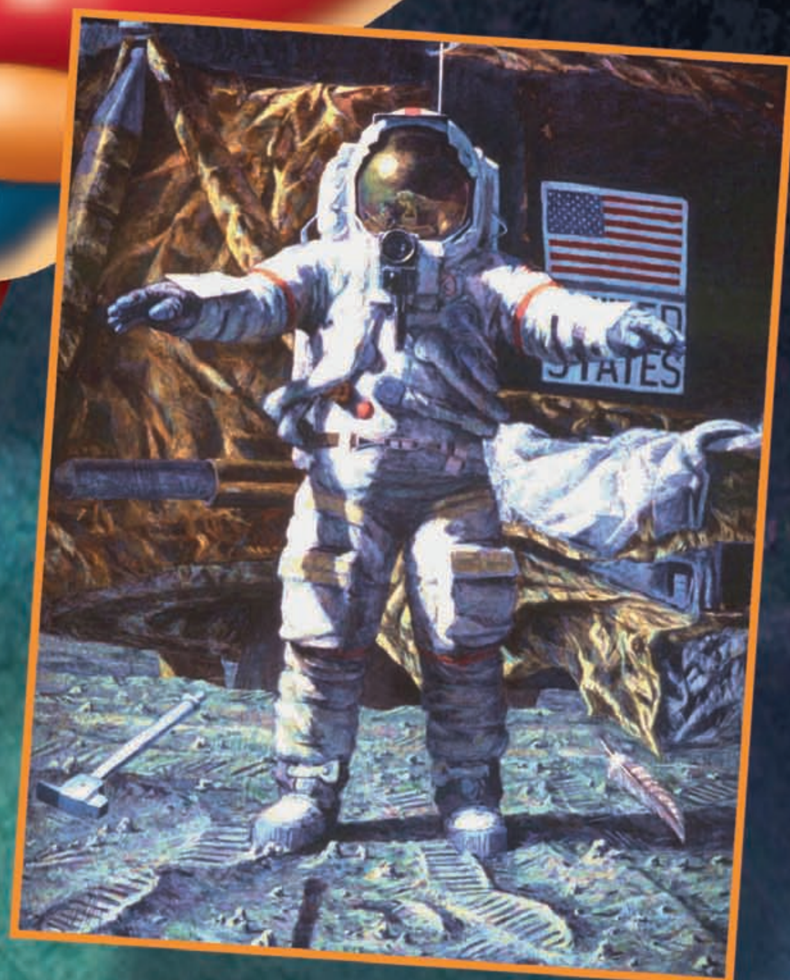
Process of Science

UNIVERSALITY

The laws of physics are the same everywhere and at all times. The principle underlies our understanding of the natural world.

Galileo determined that all objects have the same gravitational acceleration.

Newton's law of universal gravitation extended this observation to the Solar System.



Apollo 15 **commander David Scott tested the law with a feather and a hammer on the Moon. With no air resistance, the feather and the hammer fell at the same rate.**

The same physical laws apply to falling objects, to planets orbiting the Sun, to stars orbiting within the galaxy, and to galaxies orbiting each other.

the satellite must be moving at a particular speed around the circle, which we call its **circular velocity** (v_{circ}). If the satellite were moving at any other velocity, it would not be moving in a circular orbit. Remember the cannonball: if it is moving too slowly, it will drop below the circular path and hit the ground. Similarly, if the cannonball is moving too fast, its motion will carry it above the circular orbit. Only a cannonball moving at just the right velocity—the circular velocity—will fall around Earth on a circular path (see Figure 4.5d).

Nebraska Simulation: Earth Orbit Plot

Newton's thought experiment became a reality in 1957, when the Soviet Union launched the first human-made object to orbit Earth. They used a rocket to lift Sputnik 1, an object about the size of a basketball, high enough above Earth's upper atmosphere that air resistance wasn't an issue. Sputnik 1 was given a high enough speed that it fell around Earth, just as Newton's imaginary cannonball.

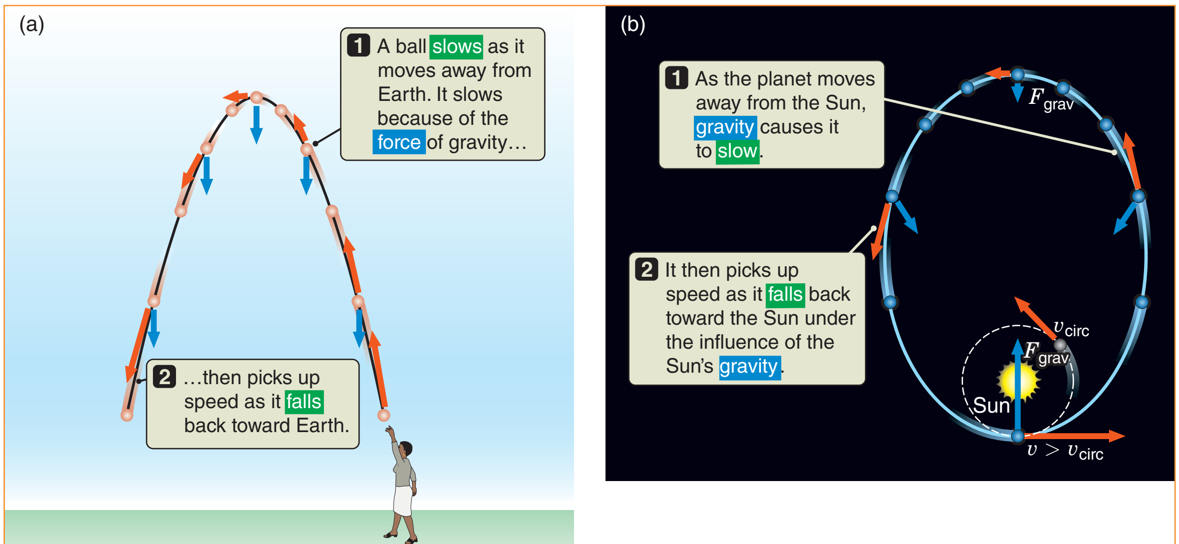
When one object is falling around a much more massive object, we say that the less massive object is a **satellite** of the more massive object. Planets are satellites of the Sun, and moons are natural satellites of planets. Newton's imaginary cannonball and Sputnik 1 were satellites (*sputnik* means "satellite" in Russian). A spacecraft orbiting Earth and the astronauts inside of it are independent satellites of Earth that conveniently happen to share the same orbit.

The Shape of Orbits

AstroTour: Elliptical Orbit

Some Earth satellites travel a circular path at constant speed. Just like the ball on the string, satellites traveling at the circular velocity remain the same distance from Earth at all times, neither speeding up nor slowing down in orbit. But what if the satellite then fired its rockets and started traveling *faster* than the circular velocity? The pull of Earth is as strong as ever, but because the satellite has greater speed, its path is not bent by Earth's gravity sharply enough to hold it in a circle. So the satellite begins to climb above a circular orbit.

As the distance between the satellite and Earth increases, the satellite slows down. Think about a ball thrown upwards into the air, illustrated in **Figure 4.8a**. As the ball climbs higher, the pull of Earth's gravity opposes its motion, slowing the ball down. The ball climbs more and more slowly until its vertical motion



VISUAL ANALOGY

Figure 4.8 (a) A ball thrown into the air slows as it climbs away from Earth and then speeds up as it heads back toward Earth. (b) A planet on an elliptical orbit around the Sun does the same thing. (Although no planet has an orbit as eccentric as the one shown here, the orbits of comets can be far more eccentric.)

stops for an instant and then is reversed; the ball then begins to fall back toward Earth, speeding up along the way. A satellite does exactly the same thing. As the satellite climbs above a circular orbit and begins to move away from Earth, Earth's gravity opposes the satellite's outward motion, slowing the satellite down. The farther the satellite is from Earth, the more slowly the satellite moves—just like the ball thrown into the air. Also just like the ball, the satellite reaches a maximum height on its curving path and then begins falling back toward Earth, while Earth's gravity speeds it up as it gets closer and closer to Earth. The satellite's orbit has changed from circular to elliptical.

Any object in an elliptical orbit, including a planet orbiting the Sun, will therefore move faster when it is closer to the object it is orbiting due to gravity. Recall from Chapter 3 that Kepler's second law says that a planet moves fastest when it is closest to the Sun and slowest when it is farthest from the Sun. As shown in Figure 4.8b, planets lose speed as they pull away from the Sun and then gain that speed back as they fall inward toward the Sun.

Newton's laws do more than explain Kepler's laws: they predict different types of orbits beyond Kepler's empirical experience. **Figure 4.9a** shows a series of satellite orbits, each with the same point of closest approach to Earth but with different velocities at that point, as indicated in Figure 4.9b. The greater the speed a satellite has at its closest approach to Earth, the farther the satellite is able to pull away from Earth, and the more eccentric its orbit becomes. As long as it remains elliptical, no matter how eccentric, the orbit is called a **bound orbit** because the satellite is gravitationally bound to the object it is orbiting.

In this sequence of faster and faster satellites there comes a point at which the satellite is moving so fast that gravity is unable to reverse its outward motion, so the object travels away from Earth, never to return. The lowest speed at which an object can permanently leave the gravitational grasp of another mass is called the **escape velocity**, v_{esc}. Once a satellite's velocity at closest approach equals or exceeds v_{esc}, and it is no longer gravitationally bound to the object it was orbiting, we say it is in an **unbound orbit**.

As Figure 4.9 shows, an object with a velocity *less* than the escape velocity (v_{esc}) will be on an elliptically shaped orbit and will follow the same path over and over again. Unbound orbits do not close like an ellipse (see Figure 4.9a). An object such as a comet on an unbound orbit makes only a single pass around the Sun and then continues away from the Sun into deep space, never to return. Circular velocity and escape velocity are further explored in **Working It Out 4.2**.

Measuring Mass Using Newton's Version of Kepler's Law

Newton's calculations opened up an entirely new way of investigating the universe. He showed that the same physical laws that describe the flight of a cannonball on Earth—or the legendary apple falling from a tree—also describe the motions of the planets through the heavens. His laws of motion and gravitation predict all three of Kepler's empirical laws of planetary motion. Newton's version of Kepler's laws can be used to measure the mass of the Sun from the orbit of Earth, as seen in **Working It Out 4.3**.

When a much lower mass object such as Earth is orbiting a much more massive object such as the Sun, the Sun's gravity has a strong influence on Earth, but Earth's gravity has little effect on the Sun. Therefore, it is a good approximation to say that the Sun remains motionless as Earth orbits around it.

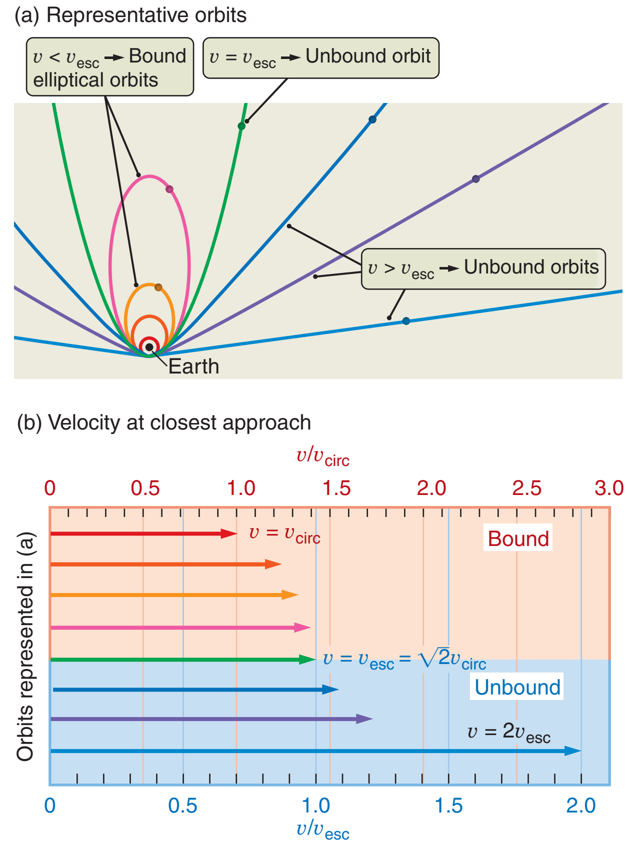


Figure 4.9 (a) A range of different orbits that share the same point of closest approach but differ in velocity at that point. (b) Closest-approach velocities for the orbits in (a). An object's velocity at closest approach determines the orbit shape and whether the orbit is bound or unbound. v_{circ} = circular velocity; v_{esc} = escape velocity.

4.2 Working It Out Circular Velocity and Escape Velocity

Circular Velocity

In Appendix 7, we show that the circular velocity is given by

$$v_{\text{circ}} = \sqrt{\frac{GM}{r}}$$

where M is the mass of the orbited object, and r is the radius of the circular orbit. A cannonball moving at just the right velocity—the circular velocity—will fall around Earth on a circular path.

We can use this equation to show how fast Newton's cannonball would have to travel to stay in its circular orbit. The average radius of Earth is 6,370 km, the mass of Earth is 5.97×10^{24} kg, and the gravitational constant is 6.67×10^{-20} km^3/(kg s^2). Inserting these values into the expression for v_{circ}, we get

$$v_{\text{circ}} = \sqrt{\frac{[6.67 \times 10^{-20}\,\text{km}^3/(\text{kg}\,\text{s}^2)] \times (5.97 \times 10^{24}\,\text{kg})}{6{,}370\,\text{km}}} = 7.9\,\text{km/s}$$

Newton's cannonball would have to be traveling about 8 kilometers per second (km/s)—more than 28,000 kilometers per hour (km/h)—to stay in its circular orbit. That's well beyond the reach of a typical cannon, but rockets routinely attain these speeds.

Now let's compare this speed with that needed to launch a satellite from the Moon into orbit just above the lunar surface. The radius of the Moon is 1,740 km, and its mass is 7.35×10^{22} kg. These values give the following circular velocity:

$$v_{\text{circ}} = \sqrt{\frac{[6.67 \times 10^{-20}\,\text{km}^3/(\text{kg}\,\text{s}^2)] \times (7.35 \times 10^{22}\,\text{kg})}{1{,}740\,\text{km}}} = 1.7\,\text{km/s}$$

The velocity needed to launch a satellite into a low circular orbit is considerably lower on the Moon than on Earth.

Escape Velocity

Sending a spacecraft to another planet requires launching it with a velocity greater than Earth's escape velocity. The escape velocity is a factor of $\sqrt{2}$, or approximately 1.41, times the circular velocity. This relation can be expressed as

$$v_{\text{esc}} = \sqrt{2} \times v_{\text{circ}} = \sqrt{\frac{2GM}{R}}$$

Using the numbers in the above example, we can calculate the escape velocity from the surface of Earth:

$$v_{\text{esc}} = \sqrt{2} \times v_{\text{circ}} = 1.41 \times 7.9\,\text{km/s} = 11.2\,\text{km/s}$$

To leave Earth, a rocket must have a speed of 11.2 km/s, or 40,300 km/h.

As with weight, the escape velocity from other astronomical objects will be different than the escape velocity from Earth. Ida is a small asteroid orbiting the Sun between the orbits of Mars and Jupiter. Ida has an average radius of 15.7 km and a mass of 4.2×10^{16} kg. Therefore,

$$v_{\text{esc}} = \sqrt{\frac{2 \times [6.67 \times 10^{-20}\,\text{km}^3/(\text{kg}\,\text{s}^2)] \times (4.2 \times 10^{16}\,\text{kg})}{15.7\,\text{km}}}$$

$$v_{\text{esc}} = 0.019\,\text{km/s} = 68\,\text{km/h}$$

A baseball thrown at about 130 km/h would easily escape from Ida's surface and fly off into interplanetary space.

However, later we will see that sometimes the two objects are closer to having the same mass; for example, dwarf planet Pluto and its moon Charon, or a large planet and a star, or two stars. In these examples, both objects experience significant accelerations in response to their mutual gravitational attraction. The two objects are both orbiting about a common point located between them, called the **center of mass**, so we now must think of them as falling around each other. Each mass is moving on its own elliptical orbit around the two objects' mutual center of mass. From measuring the size and period of any orbit, we can calculate the *sum* of the masses of the orbiting objects. Almost all knowledge about the masses of astronomical objects comes directly from the application of Newton's version of Kepler's third law.

Astronomy in Action: Center of Mass

CHECK YOUR UNDERSTANDING 4.3

If we wanted to increase the Hubble Space Telescope's altitude above Earth and keep it in a stable orbit, we also would need to: (a) increase its orbital speed; (b) increase its weight; (c) decrease its weight; (d) decrease its orbital speed.

4.3 Working It Out Calculating Mass from Orbital Periods

Newton's Version of Kepler's Third Law

The time it takes for a planet to complete one orbit around the Sun equals the distance traveled divided by the planet's speed. For simplicity, let's assume the orbit is circular. Thus, the time it takes an object to make one trip around the Sun is the circumference of the circle ($2\pi r$) divided by the object's speed (v). The speed of the planet must be equal to the circular velocity discussed in Working It Out 4.2. Putting these relationships together, we have

$$\text{Orbital period } (P) = \frac{\text{Circumference of orbit}}{\text{Circular velocity}} = \frac{2\pi r}{\sqrt{\dfrac{GM_{\text{Sun}}}{r}}}$$

Squaring both sides of the equation gives

$$P^2 = \frac{4\pi^2 r^2}{\dfrac{GM_{\text{Sun}}}{r}} = \frac{4\pi^2}{GM_{\text{Sun}}} \times r^3$$

The square of the period of an orbit is equal to a constant ($4\pi^2/GM_{\text{Sun}}$) multiplied by the cube of the radius of the orbit. This is Kepler's third law ($P^2 = \textit{constants} \times A^3$) applied to circular orbits. When Kepler used Earth units of years and astronomical units for the planets, he was taking a ratio of their periods and orbital radii with those for Earth, so the constants cancelled out. Using calculus, Newton was similarly able to derive Kepler's third law for elliptical orbits with semimajor axis A instead of radius r.

Mass of the Sun

If we can measure the size and period of any orbit, then we can use Newton's universal law of gravitation to calculate the mass of the object being orbited. To do so, we rearrange Newton's form of Kepler's third law above to read

$$M = \frac{4\pi^2}{G} \times \frac{A^3}{P^2}$$

Everything on the right side of this equation is either a constant (4, π, and G) or a quantity that we can measure (the semimajor axis A and period P of an orbit). The left side of the equation is the mass of the object at the focus of the ellipse. For example, we can find the mass of the Sun by noting the period and semimajor axis of the orbit of a planet around the Sun. Let's use the numbers for Earth. Whenever we have an equation with G, it is best to put everything else into the same units as G (km, kg, s). So first we must compute the number of seconds in 1 year: $P = 1 \text{ yr} = 365.24 \text{ days/yr} \times 24 \text{ h/day} \times 60 \text{ min/h} \times 60 \text{ s/min} = 3.16 \times 10^7 \text{ s}$. The semimajor axis $A = 1 \text{ AU} = 1.5 \times 10^8 \text{ km}$. Then the mass of the Sun can be computed:

$$M_{\text{Sun}} = \frac{4\pi^2}{G} \times \frac{A^3}{P^2} = \frac{4\pi^2}{6.67 \times 10^{-20} \text{ km}^3/(\text{kg s}^2)} \times \frac{(1.5 \times 10^8 \text{ km})^3}{(3.16 \times 10^7 \text{ s})^2}$$

$$M_{\text{Sun}} = 2.00 \times 10^{30} \text{ kg}$$

We could have used the period and semimajor axis of any Solar System planet to get the same result.

4.3 Tidal Forces Are Caused by Gravity

The rise and the fall of the oceans are called Earth's **tides**. Coastal dwellers long ago noted that the strength of the tides varies with the phase of the Moon. Tides are strongest during a new or a full Moon and are weakest during first quarter or third quarter Moon. In this section, we see how tides result from differences between the strength of the gravitational pull of the Moon and Sun on one part of Earth in comparison to their pull on other parts of Earth.

Astronomy in Action: Tides

Tides and the Moon

Figure 4.4 demonstrated that each small part of an object feels a gravitational attraction toward every other small part of the object, and this self-gravity differs from place to place. In addition, each small part of an object feels a gravitational attraction toward every other mass in the universe, and these external forces differ from place to place within the object as well.

AstroTour: Tides and the Moon

The Moon's gravity pulls on Earth as if the mass of the Moon is concentrated at the Moon's center. The side of Earth that faces the Moon is closer to the Moon than is the rest of Earth, so it feels a stronger-than-average gravitational

Nebraska Simulation: Tidal Bulge Simulation

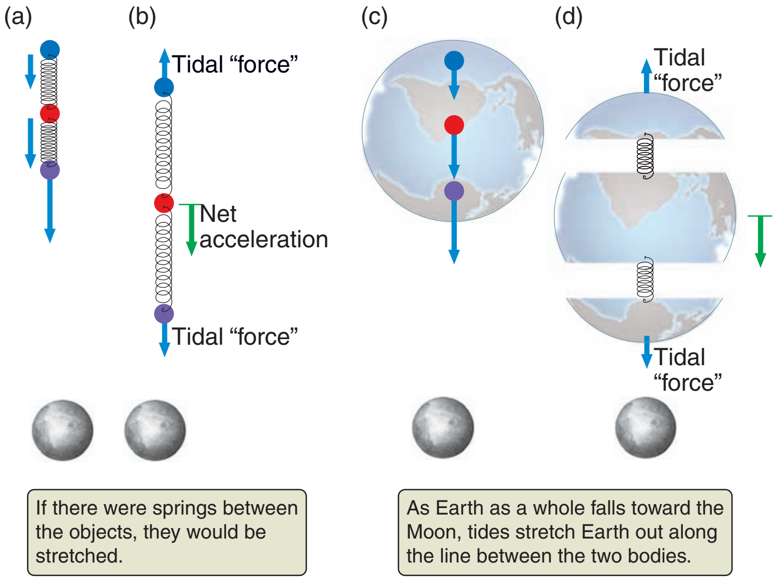


Figure 4.10 (a) Imagine three objects connected by springs. (b) The springs are stretched as if there were forces pulling outward on each end of the chain. (c) Similarly, three locations on Earth experience different gravitational attractions toward the Moon. (d) The difference in the Moon's gravitational attraction across Earth causes of Earth's tides.

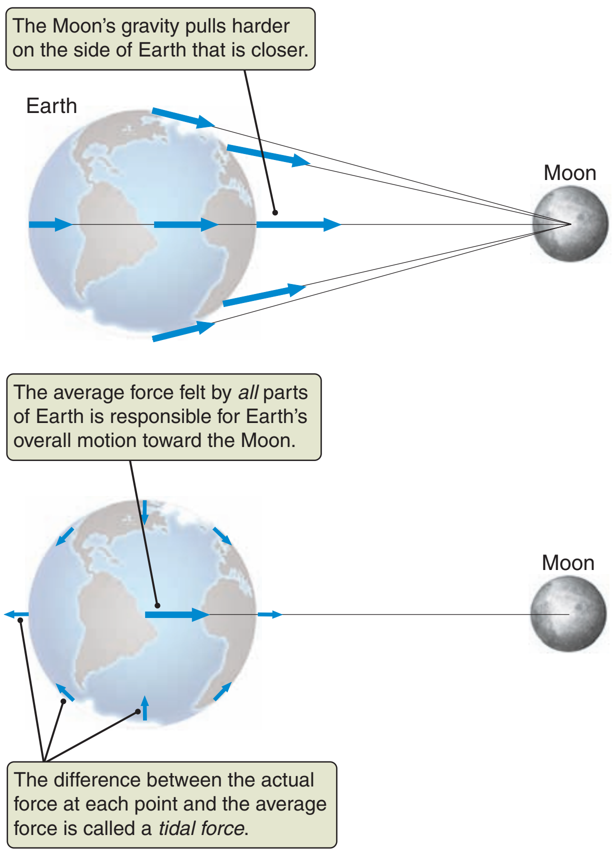


Figure 4.11 Tidal forces stretch Earth along the line between Earth and the Moon but compress Earth perpendicular to this line.

attraction toward the Moon. In contrast, the side of Earth facing away from the Moon is farther than average from the Moon, so it feels a weaker-than-average attraction toward the Moon. The pull of the Moon on the near side of Earth is about 7 percent greater than its pull on the far side of Earth.

To understand the consequence of this variation in the pull of the Moon, imagine three rocks being pulled by gravity toward the Moon. A rock closer to the Moon feels a stronger force than a rock farther from the Moon. Now suppose the three rocks are connected by springs (**Figure 4.10a**). As the rocks are pulled toward the Moon, the purple rock pulls away from the red rock, and the red rock pulls away from the blue rock. Therefore, the differences in the gravitational forces they feel will stretch *both* of the springs (Figure 4.10b). Now instead of springs, imagine that the rocks are at different places on Earth (Figure 4.10c). On the side of Earth away from the Moon, the force is smaller (as indicated by the shorter arrow), so that part gets left behind (Figure 4.10d). These differences in the Moon's gravitational attraction on different parts of Earth are called **tidal forces**.

Figure 4.11 shows how Earth is stretched, causing a tidal bulge. The Moon is not pushing the far side of Earth away; rather, it simply is not pulling on the far side of Earth as hard as it is pulling on the planet as a whole. The far side of Earth is "left behind" as the rest of the planet is pulled more strongly toward the Moon. Figure 4.11 shows that there is also a net force squeezing inward on Earth in the direction perpendicular to the line between Earth and the Moon. Together, the stretching by tidal forces along the line between Earth and the Moon and the squeezing by tidal forces perpendicular to this line distort the shape of Earth like a rubber ball caught in the middle of a tug-of-war.

If the surface of Earth was perfectly smooth and covered with a uniform ocean and Earth did not rotate, then the Moon would pull our oceans into an elongated **tidal bulge** like that shown in **Figure 4.12a**. The water would be at its deepest on the side toward the Moon and on the side away from the Moon and at its shallowest midway between. However, Earth is *not* covered with perfectly uniform oceans, and Earth does rotate. As any point on Earth rotates through the ocean's tidal bulges, that point experiences the ebb and flow of the tides. In addition, friction between the spinning Earth and its tidal bulge drags the oceanic tidal bulge around in the direction of Earth's rotation, as illustrated in Figure 4.12b.

Follow along in Figure 4.12c as you imagine riding on Earth throughout the course of a day. You begin as the rotating Earth carries you through the tidal bulge on the Moonward side of the planet. Because Earth's rotation drags the tidal bulge, the Moon is not exactly overhead but is instead high in the western sky. When you are at the high point in the tidal bulge, the ocean around you has risen higher than average—called a *high tide*. About $6\frac{1}{4}$ hours later, somewhat after the Moon has settled beneath the western horizon, the rotation of Earth carries you through a point where the ocean is lower than average—called a *low tide*. If you wait another $6\frac{1}{4}$ hours, it is again high tide. You are now passing through the region where ocean water is "left behind" (relative to Earth as a whole) in the tidal bulge on the side of Earth that is away from the Moon. The Moon, which is responsible for the tides you see, is itself at that time hidden from view on the far side of Earth. About $6\frac{1}{4}$ hours later, sometime after the Moon has risen above the

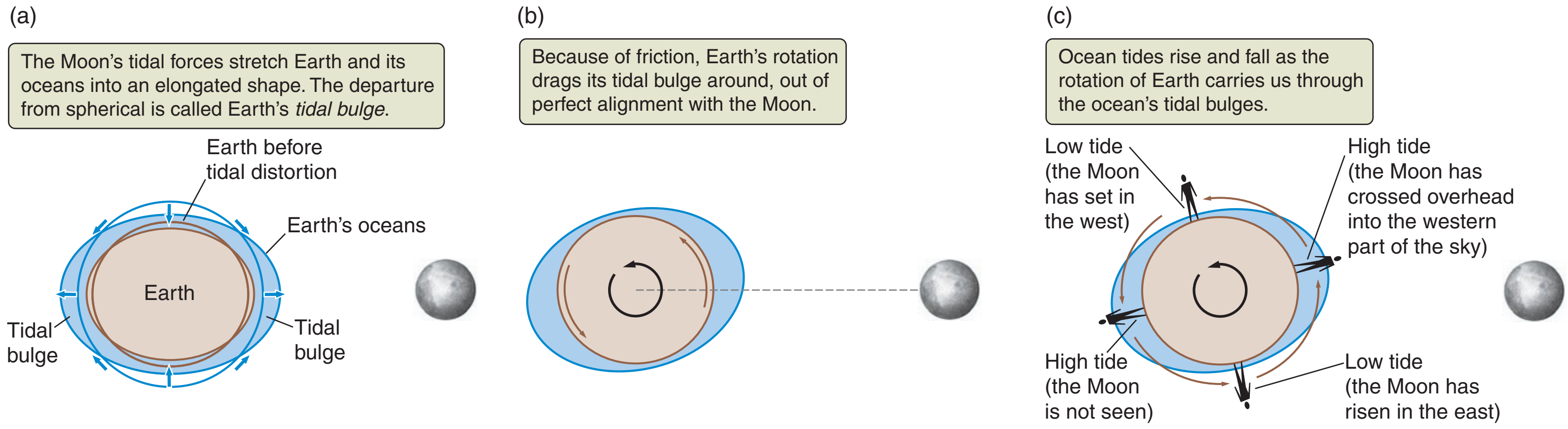


Figure 4.12 (a) Tidal forces pull Earth and its oceans into a tidal bulge. (b) Earth's rotation pulls its tidal bulge slightly out of alignment with the Moon. (c) As Earth's rotation carries us through these bulges, we experience the ocean tides. The magnitude of the tides has been exaggerated in these diagrams for clarity. In these figures, the observer is looking down from above Earth's North Pole. Sizes and distances are not to scale.

eastern horizon, it is low tide. About 25 hours after you started this journey—the amount of time the Moon takes to return to the same point in the sky from which it started—you again pass through the tidal bulge on the near side of the planet. This is the age-old pattern by which mariners have lived their lives for millennia: the twice-daily coming and going of high tide, shifting through the day in lock-step with the passing of the Moon.

Local geography, such as the shapes of Earth's shorelines and ocean basins, complicate the simple picture of tides. In addition, there are oceanwide oscillations similar to water sloshing around in a basin. As they respond to the tidal forces from the Moon, Earth's oceans flow around the various landmasses that break up the water covering our planet. Some places, like the Mediterranean Sea and the Baltic Sea, are protected from tides by their relatively small sizes and the narrow passages connecting these bodies of water with the larger ocean. In other places, the shape of the land funnels the tidal surge from a large region of ocean into a relatively small area, concentrating its effect, as at the Bay of Fundy (**Figure 4.13**). Tidal effects from the Sun and Moon are very slight even in the Great Lakes, where the water is more affected by local weather and geography.

Figure 4.13 The world's most extreme tides are found in the Bay of Fundy in eastern Canada. Water rocks back and forth in this bay with a period of about 13 hours, close to the 12.5-hour period of the tides. The shape of the basin amplifies the tides so that difference in water depth between low tide (a) and high tide (b) is extreme; typically about 14.5 meters and as much as 16.6 meters.

Solar Tides

The tides resulting from the pull of the Moon are called **lunar tides**. The Sun also influences Earth's tides. The gravitational pull of the Sun causes Earth to stretch along a line pointing approximately in the direction of the Sun. The side of Earth closer to the Sun is pulled toward the Sun more strongly than is the side of Earth away from the Sun, just as the side of Earth closest to the Moon is pulled more strongly toward the Moon. Tides on Earth due to differences in the gravitational pull of the Sun are called **solar tides**. Although the absolute strength of the Sun's pull on Earth is nearly 200 times greater than the strength of the Moon's pull on Earth, the Sun's gravitational attraction does not change by much from one side of Earth to the other, because the Sun is much farther away than the Moon. As a result, solar tides are only about half as strong as lunar tides (**Working It Out 4.4**).

4.4 Working It Out Tidal Forces

Earlier you learned that the strength of the gravitational force between two bodies is proportional to their masses and inversely proportional to the square of the distance between them. The strength of tidal forces caused by one body acting on another is also proportional to the mass of the body that is raising the tides, but it is inversely proportional to the *cube* of the distance between them.

The equation for the tidal force comes from the difference of the gravitational force on one side of a body compared with the force on the other side. The tidal force acting on Earth by the Moon is given by

$$F_{\text{tidal}}(\text{Moon}) = \frac{2GM_{\text{Earth}}M_{\text{Moon}}R_{\text{Earth}}}{d^3_{\text{Earth-Moon}}}$$

where R_{Earth} is Earth's radius and $d_{\text{Earth-Moon}}$ is the distance between Earth and the Moon.

As an example, let's compare the tidal force acting on Earth by the Moon with the tidal force acting on Earth by the Sun. F_{tidal} from the Moon is given in the preceding equation; F_{tidal} from the Sun is given by

$$F_{\text{tidal}}(\text{Sun}) = \frac{2GM_{\text{Earth}}M_{\text{Sun}}R_{\text{Earth}}}{d^3_{\text{Earth-Sun}}}$$

We know the Moon is much closer to Earth than the Sun is, but the Sun is much more massive than the Moon. To compare the lunar and solar tides, we can take a ratio of the tidal forces and proceed in a similar way to our comparison of gravitational forces in Working It Out 4.1:

$$\frac{F_{\text{tidal}}(\text{Moon})}{F_{\text{tidal}}(\text{Sun})} = \frac{\dfrac{2GM_{\text{Earth}}M_{\text{Moon}}R_{\text{Earth}}}{d^3_{\text{Earth-Moon}}}}{\dfrac{2GM_{\text{Earth}}M_{\text{Sun}}R_{\text{Earth}}}{d^3_{\text{Earth-Sun}}}}$$

Canceling out the constant G and the terms common in both equations (M_{Earth} and R_{Earth}) gives

$$\frac{F_{\text{tidal}}(\text{Moon})}{F_{\text{tidal}}(\text{Sun})} = \frac{M_{\text{Moon}}}{M_{\text{Sun}}} \times \frac{d^3_{\text{Earth-Sun}}}{d^3_{\text{Earth-Moon}}}$$

$$\frac{F_{\text{tidal}}(\text{Moon})}{F_{\text{tidal}}(\text{Sun})} = \frac{M_{\text{Moon}}}{M_{\text{Sun}}} \times \left(\frac{d_{\text{Earth-Sun}}}{d_{\text{Earth-Moon}}}\right)^3$$

Using the values from Appendix 4, $M_{\text{Moon}} = 7.35 \times 10^{22}$ kg, $M_{\text{Sun}} = 2 \times 10^{30}$ kg, $d_{\text{Earth-Moon}} = 384{,}400$ km, and $d_{\text{Earth-Sun}} = 1.5 \times 10^8$ km gives

$$\frac{F_{\text{tidal}}(\text{Moon})}{F_{\text{tidal}}(\text{Sun})} = \frac{7.35 \times 10^{22}\,\text{kg}}{2 \times 10^{30}\,\text{kg}} \times \left(\frac{1.5 \times 10^8\,\text{km}}{384{,}400\,\text{km}}\right)^3 = 2.2$$

So the tidal force from the Moon is 2.2 times stronger than the tidal force from the Sun, which is why we often hear that tides are caused by the Moon. But the Sun is an important factor, too, and that's why the tides change depending on the alignment of the Moon and the Sun with Earth.

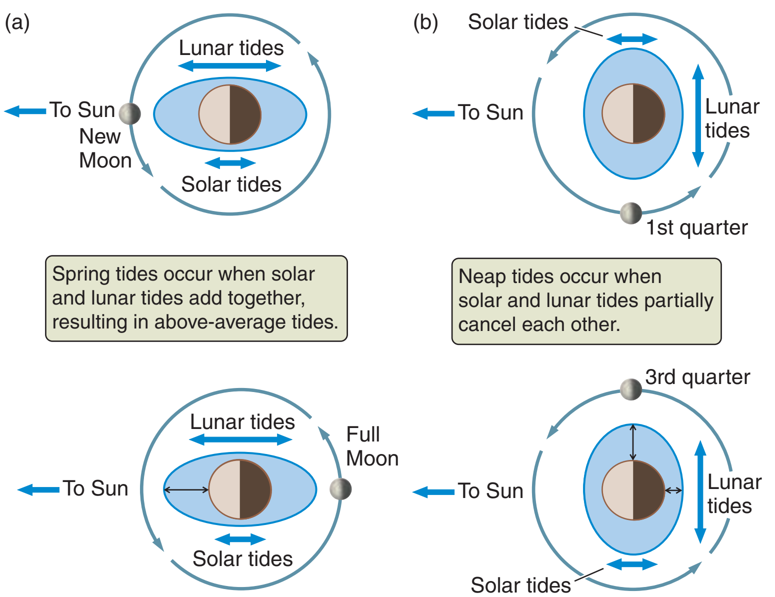


Figure 4.14 Solar tides are about half as strong as lunar tides. The interactions of solar and lunar tides result in either (a) spring tides when they are added together or (b) neap tides when they partially cancel each other.

Solar and lunar tides interact. As shown in **Figure 4.14a**, when the Moon and the Sun are lined up with Earth, at either new or full Moon, the lunar and solar tides on Earth overlap. This creates more extreme tides ranging from extra-high high tides to extra-low low tides. The extreme tides near the new or full Moon are called **spring tides**—not because of the season, but because the water appears to spring out of the sea. Conversely—illustrated in Figure 4.14b—when the Moon, Earth, and Sun make a right angle, at the Moon's first and third quarters, the lunar and solar tidal forces stretch Earth in different directions, creating less extreme tides known as **neap tides**. The word *neap* is derived from the Saxon word *neafte*, which means "scarcity": at these times of the month, shellfish and other food gathered in the tidal region are less accessible because the low tide is higher than at other times. Neap tides are only about half as strong as average tides and only a third as strong as spring tides.

CHECK YOUR UNDERSTANDING 4.4

Rank in order of the strongest tides: (a) new Moon in July; (b) first quarter Moon in July; (c) full Moon in January; (d) third quarter Moon in January.

4.4 Tidal Forces Affect Solid Bodies

In the previous section, we focused on the movements of the liquid of Earth's oceans in response to the tidal forces from the Moon and Sun. But these tidal forces also affect the solid body of Earth. As Earth rotates through its tidal bulge, the solid body of the planet is constantly being deformed by tidal forces. Earth is somewhat elastic (like a rubber ball), and tidal stresses cause a vertical displacement of about 30 centimeters (cm) between high tide and low tide, or roughly a third of the displacement of the oceans. It takes energy to deform the shape of a solid object. (If you want a practical demonstration of this fact, hold a rubber ball in your hand and squeeze and release it a few dozen times.) This energy from the deformation is converted into thermal energy by friction in Earth's interior. This friction opposes and takes energy from the rotation of Earth, causing Earth to gradually slow. Earth's internal friction adds to the slowing caused by friction between Earth and its oceans as the planet rotates through the tidal bulge of the oceans. As a result, Earth's days are currently lengthening by about 1.7 milliseconds (ms) every century. This sounds small but it adds up: when dinosaurs ruled, the day was closer to 23 hours long, and 200 million years into the future, the day will be close to 25 hours.

Tidal Locking

Other solid bodies besides Earth experience tidal forces. For example, the Moon has no bodies of liquid to make tidal forces obvious, but its shape is distorted in the same manner as Earth. Because of Earth's much greater mass and the Moon's smaller radius, the tidal effects of Earth on the Moon are about 20 times as great as the tidal effects of the Moon on Earth. Given that the average tidal deformation of Earth is about 30 cm, the average tidal deformation of the Moon should be about 6 meters. However, what we actually observe on the Moon is a tidal bulge of about 20 meters. This unexpectedly large displacement exists because the Moon's tidal bulge was "frozen" into its relatively rigid crust at an earlier time, when the Moon was closer to Earth and tidal forces were much stronger than they are today. Planetary scientists sometimes call this deformation the Moon's *fossil tidal bulge*.

Recall from Chapter 2 that the Moon's rotation period exactly equals its orbital period. This synchronous rotation of the Moon is a result of **tidal locking**. Early in its history, the period of the Moon's rotation was almost certainly different from its orbital period. As the Moon rotated through its extreme tidal bulge, however, friction within the Moon's crust was tremendous, rapidly slowing the Moon's rotation. After a fairly short time, the period of the Moon's rotation equaled the period of its orbit. When its orbital and rotation periods became equalized, the Moon no longer rotated with respect to its tidal bulge. Instead, the Moon and its tidal bulge rotated *together*, in lockstep with the Moon's orbit around Earth. As illustrated in **Figure 4.15**, this scenario continues today as the tidally distorted Moon orbits Earth, always keeping the same face and the long axis of its tidal bulge toward Earth.

Tidal forces affect not only the rotations of the Moon and Earth, but also their orbits. Because of its tidal bulge, Earth is not a perfectly spherical body. Therefore, the material in Earth's tidal bulge on the side nearer the Moon pulls on the Moon more strongly than does material in the tidal bulge on the back side of

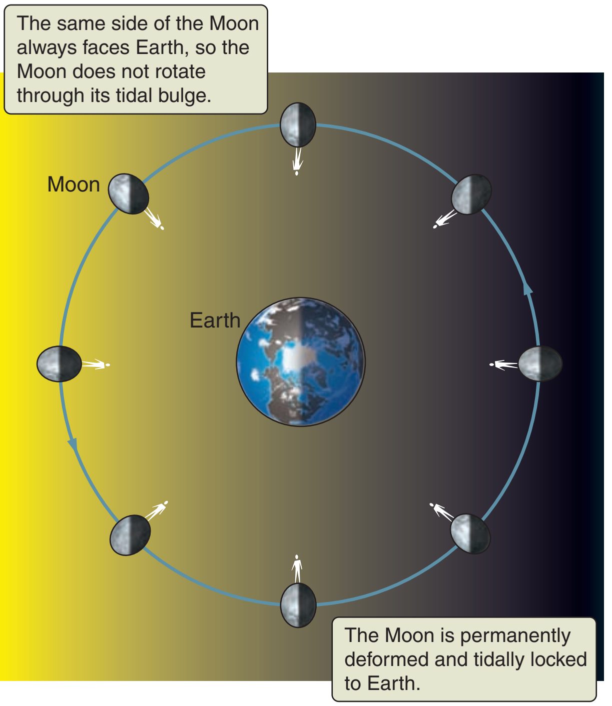


Figure 4.15 Tidal forces due to Earth's gravity lock the Moon's rotation to its orbital period.

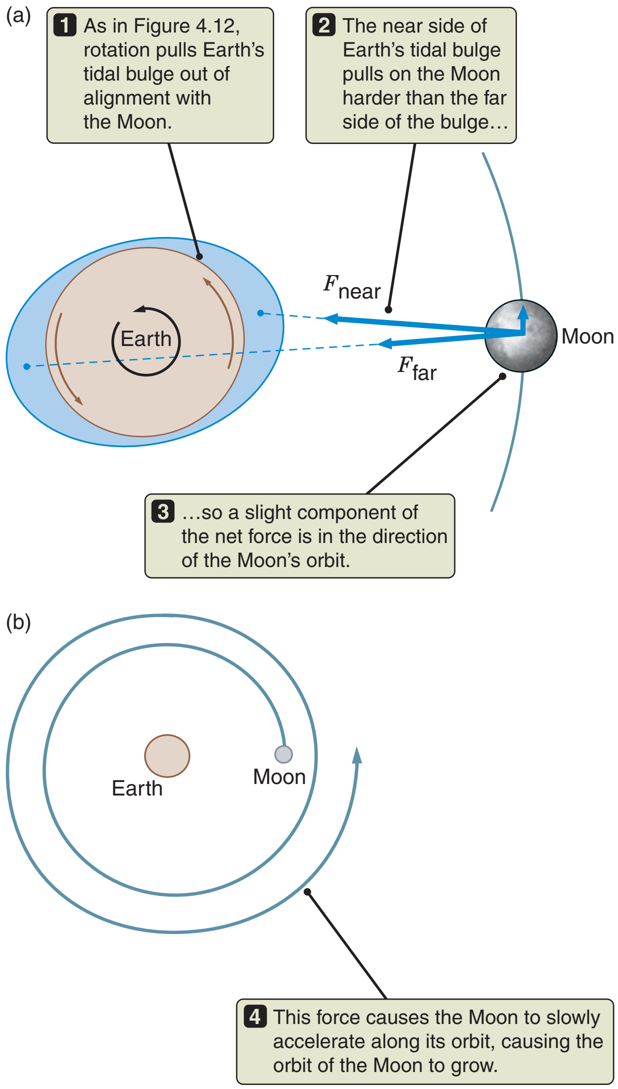


Figure 4.16 Interaction between Earth's tidal bulge and the Moon causes the Moon to accelerate in its orbit and the Moon's orbit to grow.

Earth. Because the tidal bulge on the Moonward side of Earth "leads" the Moon somewhat, as shown in **Figure 4.16**, the gravitational attraction of the bulge causes the Moon to accelerate slightly along the direction of its orbit around Earth. The rotation of Earth is dragging the Moon along with it. The acceleration of the Moon in the direction of its orbital motion causes the orbit of the Moon to grow larger. At present, the Moon is drifting away from Earth at a rate of 3.83 cm per year.

As the Moon grows more distant, the length of the lunar month increases by about 0.014 second each century. If this increase in the radius of the Moon's orbit were to continue long enough (about 50 billion years), Earth would become tidally locked to the Moon, just as the Moon is now tidally locked to Earth. At that point, the period of rotation of Earth, the period of rotation of the Moon, and the orbital period of the Moon would all be exactly the same—about 47 of our current days—and the Moon would be about 43 percent farther from Earth than it is today. However, this situation will never actually occur—at least not before the Sun itself has burned out.

The effects of tidal forces can be seen throughout the Solar System. Most of the moons in the Solar System are tidally locked to their parent planets, and in the case of dwarf planet Pluto and its largest moon, Charon, each is tidally locked to the other.

Tidal locking is only one way that orbits and rotations can be coupled together. Tidal forces have coupled the planet Mercury's rotation to its very elliptical orbit around the Sun. Yet unlike the Moon with its synchronous rotation, Mercury spins on its axis three times for every two trips around the Sun. The period of Mercury's orbit—87.97 Earth days—is exactly $1\frac{1}{2}$ times the 58.64 days that it takes Mercury to spin once on its axis. When Mercury comes to the point in its orbit that is closest to the Sun, one hemisphere faces the Sun, and then in the next orbit the other hemisphere faces the Sun.

Tidal Forces on Many Scales

We normally think of the effects of tidal forces as small compared to the force of gravity holding an object together, yet tidal effects can be extremely destructive. Consider for a moment the fate of a small moon, asteroid, or comet that wanders too close to a massive planet such as Jupiter or Saturn. All objects in the Solar System larger than about a kilometer in diameter are held together by their self-gravity. However, the self-gravity of a small object such as an asteroid, a comet, or a small moon is feeble. In contrast, the tidal forces close to a massive object such as Jupiter can be very strong. If the tidal forces trying to tear an object apart become greater than the self-gravity trying to hold the object together, the object will break into pieces.

The **Roche limit** is the distance at which a planet's tidal forces are greater than the self-gravity of a smaller object—such as a moon, asteroid, or comet—causing the object to break apart. For a smaller object having the same density as the planet, the Roche limit is about 2.45 times the planet's radius. Such an object bound together solely by its own gravity can remain intact when it is outside a planet's Roche limit, but not when it is inside the limit. Objects such as the International Space Station and other Earth satellites are not torn apart, even though they orbit well within Earth's Roche limit, because chemical bonds hold them together, not just self-gravity.

We have concentrated on the role that tidal forces play on Earth and the Moon. We find tidal forces throughout the Solar System and the universe. Any time two objects of significant size or two collections of objects interact gravitationally, the gravitational forces will differ from one place to another within the objects, giving rise to tidal effects. Tidal disruption of small bodies is the source of the particles that make up the rings of the giant planets. Tidal interactions can cause material from one star in a binary pair to be pulled onto the other star. Tidal effects can strip stars from clusters consisting of thousands of stars. Galaxies can pass close enough together to strongly interact gravitationally. When this happens, as in **Figure 4.17**, tidal effects can grossly distort both galaxies taking part in the interaction. Tidal forces even play a role in shaping huge collections of galaxies—the largest known structures in the universe.

Figure 4.17 The tidal "tails" seen here are characteristic of tidal interactions between galaxies.

CHECK YOUR UNDERSTANDING 4.5

The Moon always keeps the same face toward Earth because of: (a) tidal locking; (b) tidal forces from the Sun; (c) tidal forces from Earth; (d) tidal forces from the Earth and Sun.

Origins

Tidal Forces and Life

In this chapter, we noted that Earth's rotation is slowing down as the Moon slowly moves away into a larger orbit. In the distant past the Moon was closer and Earth rotated faster, so tides would have been stronger and the interval between high tides would have been shorter. The tides are also affected by the configuration of the continents and oceans on Earth, so it is not known precisely how much faster Earth rotated billions of years ago. But the stronger and more frequent tides would have provided additional energy to the oceans of the young Earth.

Scientists debate whether life on Earth originated deep in the ocean, on the surface of the ocean, or on land (see Chapter 24). The tides shaped the regions in the margins between land and ocean, such as tide pools and coastal flats. Some think that these border regions, which alternate between wet and dry with the tides, could have been places where concentrations of biochemicals periodically became high enough for more complex reactions to take place. These complex reactions were important to the earliest life. Later, these border regions may have been important as advanced life moved from the sea to the land.

Elsewhere in the Solar System, the giant planets Jupiter and Saturn are far from the Sun, and thus very cold. Jupiter and Saturn each have many moons, and the closest moons would experience strong tidal forces from their respective planet. As you saw in Reading Astronomy News in Chapter 1, several of these moons are thought to have a liquid ocean underneath an icy surface. Tidal forces from Jupiter or Saturn provide the heat to keep the water in a liquid state. Astrobiologists think that these subsurface liquid oceans are perhaps the most probable location for life elsewhere in the Solar System.

We have seen that on Earth, the tidal forces from the Sun are about half as strong as those from the Moon. A planet with a closer orbit would experience much stronger tidal forces from its star. In Chapter 7, you will see that many of the planets detected outside of the Solar System have orbits very close to their stars. These planets experience strong tidal forces, and they might be tidally locked so that they have synchronous rotation as the Moon does around Earth, with one side of the planet always facing the star and one side facing away. How might life on Earth have evolved differently if half of the planet was in perpetual night and half in perpetual day?

ARTICLES QUESTIONS

Astronomers and physicists have wondered if the value of Newton's gravitational constant G has changed over time. This press release reports on one experiment to measure the value of G.

Exploding Stars Prove Newton's Law of Gravity Unchanged over Cosmic Time

By **Swinburne Media Centre**

Australian astronomers have combined all observations of supernovae ever made to determine that the strength of gravity has remained unchanged over the last 9 billion years.

Newton's gravitational constant, known as *G*, describes the attractive force between two objects, together with the separation between them and their masses. It had previously been suggested that *G* could have been slowly changing over the 13.8 billion years since the Big Bang.

If *G* had been decreasing over time, for example, this would mean the Earth's distance to the Sun was slightly smaller in the past, meaning that we would experience longer seasons now compared to much earlier points in the Earth's history.

But researchers at Swinburne University of Technology in Melbourne have now analysed the light given off by 580 supernova explosions in the nearby and far universe and have shown that the strength of gravity has not changed.

"Looking back in cosmic time to find out how the laws of physics may have changed is not new," said Professor Jeremy Mould. "But supernova cosmology now allows us to do this with gravity."

A Type Ia supernova marks the violent death of a star called a white dwarf, which is as massive as our Sun but packed into a ball the size of our Earth.

Telescopes can detect the light from this explosion and use its brightness as a "standard candle" to measure distances in the universe, a tool that helped Australian astronomer Professor Brian Schmidt in his 2011 Nobel Prize–winning work discovering the mysterious force Dark Energy.

Professor Mould and his PhD student Syed Uddin at the Swinburne Centre for Astrophysics and Supercomputing and the ARC Centre of Excellence for All-sky Astrophysics (CAASTRO) assumed that these supernova explosions happen when a white dwarf reaches a critical mass or after colliding with other stars to "tip it over the edge."

"This critical mass depends on Newton's gravitational constant *G* and allows us to monitor it over billions of years of cosmic time—instead of only decades as was the case in previous studies," Professor Mould said.

Despite these vastly different time spans, their results agree with findings from the Lunar Laser Ranging Experiment that has been measuring the distance between the Earth and the Moon since NASA's *Apollo* missions in the 1960s and has been able to monitor possible variations in *G* at very high precision.

"Our cosmological analysis complements experimental efforts to describe and constrain the laws of physics in a new way and over cosmic time," Mr Uddin said.

In their current publication, the Swinburne researchers were able to set an upper limit on the change in Newton's gravitational constant of 1 part in 10 billion per year over the past 9 billion years.

This research was published in *Publications of the Astronomical Society of Australia*.

ARTICLES QUESTIONS

1. Explain how observing very distant supernova means observing back in time.
2. Why are physicists still measuring *G*, centuries after Newton described this constant?
3. What quantities that you studied in the chapter would change if the value of *G* changed over time?
4. Why is it important to the process of science that this result agrees with a result from a totally different experiment?
5. If the distance to the Sun were slightly smaller in the past, would solar tides have been weaker or stronger? Would you expect this to have been as important to tides on Earth as changes in the distance of the Moon?

Summary

Objects stay in orbit because of gravity. Newton's laws of motion and his proposed law of gravity predict the paths of planetary orbits and explain Kepler's laws. Newton's calculations showed that these orbits should be ellipses with the Sun at one focus, that planets should move faster when closer to the Sun, and that the square of the period of a planet's orbit should vary as the cube of the semi-major axis of that elliptical orbit. Newton also showed mathematically Galileo's conclusion that falling objects have an accelerated motion independent of their mass. Tidal forces provide energy to Earth's oceans. Tide pools on Earth may have been a site of early biochemical reactions. Some moons in the outer Solar System might have liquid water because of tidal heating from their respective planet.

LG 1 **Explain the elements of Newton's universal law of gravitation.** Gravity is a force between any two objects due to their masses. As one of the fundamental forces of nature, gravity binds the universe together. The force of gravity is proportional to the mass of each object and inversely proportional to the square of the distance between them.

LG 2 **Use the concepts of motion and gravitation to explain planetary orbits.** An orbit is one body "falling around" another. Planets orbit the Sun in elliptical orbits. All objects affected by gravity move either on bound elliptical orbits or unbound paths. Orbits are ultimately given their shape by the gravitational attraction of the objects involved, which in turn is a reflection of the masses of these objects.

LG 3 **Explain how tidal forces from the Sun and Moon create Earth's tides.** Tides on Earth are the result of differences between how hard the Moon and Sun pull on one part of Earth in comparison with their pull on other parts of Earth. The primary cause of tides is the Moon, which stretches out Earth. The tides are the strongest when the Sun, Moon, and Earth are aligned. As Earth rotates, tides rise and fall twice each day.

LG 4 **Describe the effects of tidal forces on solid bodies.** Tidal forces lock the Moon's rotation to its orbit around Earth. Tidal forces can break up an object if its gets too close to a more massive object. Tidal forces are observed throughout the universe, in planets and moons, pairs of stars, and interacting galaxies.

? UNANSWERED QUESTION

- What range of gravities will support human life? Humans have evolved to live on Earth's surface, but what happens when humans go elsewhere? What are the limits for our hearts, lungs, eyes, and bones? At the higher end of human tolerance, fighter pilots have been trained to experience about 10 times the normal surface gravity on Earth for very short periods of time (too long and they black out). Astronauts who spend several months in near-weightless conditions experience medical problems such as bone loss. On the Moon or Mars, humans will weigh much less than on Earth. Numerous science fiction tales have been written about what happens to children born on a space station or on another planet or moon with low surface gravity: would their hearts and bodies ever be able to adjust to the higher surface gravity of Earth or must they stay in space forever?

Questions and Problems

Test Your Understanding

1. In Newton's universal law of gravitation, the force is
   a. proportional to both masses.
   b. proportional to the radius.
   c. proportional to the radius squared.
   d. inversely proportional to the orbiting mass.

2. Rank the following objects in order of their circular velocities, from smallest to largest.
   a. a 5-kg object orbiting Earth halfway to the Moon
   b. a 10-kg object orbiting Earth just above Earth's surface
   c. a 15-kg object orbiting Earth at the same distance as the Moon
   d. a 20-kg object orbiting Earth one-quarter of the way to the Moon

3. An object in a(n) __________ orbit in the Solar System will remain in its orbit forever. An object in a(n) __________ orbit will escape from the Solar System.
   a. unbound; bound
   b. circular; elliptical
   c. bound; unbound
   d. elliptical; circular
4. Compared to your mass on Earth, on the Moon your mass would be
   a. lower because the Moon is smaller than Earth.
   b. lower because the Moon has less mass than Earth.
   c. higher because of the combination of the Moon's mass and size.
   d. the same, mass doesn't change.
5. If you went to Mars, your weight would be
   a. higher because you are closer to the center of the planet.
   b. lower because Mars has two small moons instead of one big moon, so there's less tidal force.
   c. lower because Mars has lower mass and a smaller radius that together produce a lower gravitational force.
   d. the same as on Earth.
6. Venus has about 80 percent of Earth's mass and about 95 percent of Earth's radius. Your weight on Venus will be
   a. 20 percent more than on Earth.
   b. 20 percent less than on Earth.
   c. 10 percent more than on Earth.
   d. 10 percent less than on Earth.
7. The connection between gravity and orbits enables astronomers to measure the __________ of stars and planets.
   a. distances
   b. sizes
   c. masses
   d. compositions
8. If the Moon had twice the mass that it does, how would the strength of lunar tides change?
   a. The highs would be higher, and the lows would be lower.
   b. Both the highs and the lows would be higher.
   c. The highs would be lower, and the lows would be higher.
   d. Nothing would change.
9. If Earth had half of its current radius, how would the strength of lunar tides change?
   a. The highs would be higher, and the lows would be lower.
   b. Both the highs and the lows would be higher.
   c. The highs would be lower, and the lows would be higher.
   d. Both the highs and the lows would be lower.
10. If the Moon were 2 times closer to Earth than it is now, the gravitational force between Earth and the Moon would be
    a. 2 times stronger.
    b. 4 times stronger.
    c. 8 times stronger.
    d. 16 times stronger.
11. If the Moon were 2 times closer to Earth than it is now, the tides would be
    a. 2 times stronger.
    b. 4 times stronger.
    c. 8 times stronger.
    d. 16 times stronger.
12. If two objects are tidally locked to each other,
    a. the tides always stay on the same place on each object.
    b. the objects always remain in the same place in each other's sky.
    c. the objects are falling together.
    d. both a and b
13. Spring tides occur only when
    a. the Sun is near the vernal equinox.
    b. the Moon's phase is new or full.
    c. the Moon's phase is first quarter or third quarter.
    d. it is either spring or fall.
14. If an object crosses from farther to closer than the Roche limit, it
    a. can no longer be seen.
    b. begins to accelerate very quickly.
    c. slows down.
    d. may be torn apart.
15. Self-gravity is
    a. the gravitational pull of a person.
    b. the force that holds objects like people and lamps together.
    c. the gravitational interaction of all the parts of a body.
    d. the force that holds objects on Earth.

Thinking about the Concepts

16. Both Kepler's laws and Newton's laws tell us something about the motion of the planets, but there is a fundamental difference between them. What is that difference?
17. Explain the difference between circular velocity and escape velocity. Which of these must be larger? Why?
18. Explain the difference between weight and mass.
19. Weight on Earth is proportional to mass. On the Moon, too, weight is proportional to mass, but the constant of proportionality is different on the Moon than it is on Earth. Why? Explain why this difference does not violate the universality of physical law, described in the Process of Science Figure.
20. Two comets are leaving the vicinity of the Sun, one traveling in an elliptical orbit and the other in a unbound orbit. What can you say about the future of these two comets? Would you expect either of them to return eventually?
21. What is the advantage of launching satellites from spaceports located near the equator? Would you expect satellites to be launched to the east or to the west? Why?
22. Explain how to use celestial orbits to estimate an object's mass. What are the observational quantities you need to make this mass estimation?

23. Suppose astronomers discovered an object approaching the Sun in an unbound orbit. What would that say about the origin of the object?
24. What determines the strength of gravity at various radii between Earth's center and its surface?
25. The best time to dig for clams along the seashore is when the ocean tide is at its lowest. What phases of the Moon would be best for clam digging? What would be the best times of day during those phases?
26. The Moon is on the meridian at your seaside home, but your tide calendar does not show that it is high tide. What might explain this apparent discrepancy?
27. We may have an intuitive feeling for why lunar tides raise sea level on the side of Earth facing the Moon, but why is sea level also raised on the side facing away from the Moon?
28. Tides raise and lower the level of Earth's oceans. Can they do the same for Earth's landmasses? Explain your answer.
29. Lunar tides raise the ocean surface less than 1 meter. How can tides as large as 5–10 meters occur?
30. Most commercial satellites are well inside the Roche limit as they orbit Earth. Why are they not torn apart?

Applying the Concepts

31. Mars has about one-tenth the mass of Earth and about half of Earth's radius. What is the value of gravitational acceleration on the surface of Mars compared to that on Earth? Estimate your mass and weight on Mars compared with your mass and weight on Earth. Do Hollywood movies showing people on Mars accurately portray this difference in weight?

32. Earth speeds along at 29.8 km/s in its orbit. Neptune's nearly circular orbit has a radius of 4.5×10^9 km, and the planet takes 164.8 years to make one trip around the Sun. Calculate the speed at which Neptune moves along in its orbit.

33. Venus's circular velocity is 35.03 km/s, and its orbital radius is 1.082×10^8 km. Use this information to calculate the mass of the Sun.

34. At the surface of Earth, the escape velocity is 11.2 km/s. What would be the escape velocity at the surface of a very small asteroid having a radius 10^{-4} that of Earth and a mass 10^{-12} that of Earth?

35. How long does it take Newton's cannonball, moving at 7.9 km/s just above Earth's surface, to complete one orbit around Earth?

36. When a spacecraft is sent to Mars, it is first launched into an Earth orbit with circular velocity.
    a. Describe the shape of this orbit.
    b. What minimum velocity must we give the spacecraft to send it on its way to Mars?

37. Earth's average radius is 6,370 km and its mass is 5.97×10^{24} kg. Show that the acceleration of gravity at the surface of Earth is 9.81 m/s^2.

38. Using 6,370 km for Earth's radius, compare the gravitational force acting on a NASA rocket when it is sitting on its launch-pad with the gravitational force acting on it when it is orbiting 350 km above Earth's surface.

39. The International Space Station travels on a nearly circular orbit 350 km above Earth's surface. What is its orbital speed?

40. Rearrange the terms in the last equation in Working It Out 4.1 to calculate the mass of Earth, using the measured values of g, G, and R_{Earth}.

41. As described in Working It Out 4.4, tidal force is proportional to the masses of the two objects and is inversely proportional to the cube of the distance between them. Some astrologers claim that your destiny is determined by the "influence" of the planets that are rising above the horizon at the moment of your birth. Compare the tidal force of Jupiter (mass 1.9×10^{27} kg; distance 7.8×10^8 km) with that of the doctor in attendance at your birth (mass 80 kg, distance 1 meter).

42. The asteroid Ida (mass 4.2×10^{16} kg) is attended by a tiny asteroidal moon, Dactyl, which orbits Ida at an average distance of 90 km. Neglecting the mass of the tiny moon, what is Dactyl's orbital period in hours?

43. Suppose you go skydiving.
    a. Just as you fall out of the airplane, what is your gravitational acceleration?
    b. Would this acceleration be bigger, smaller, or the same if you were strapped to a flight instructor, and so had twice the mass?
    c. Just as you fall out of the airplane, what is the gravitational force on you? (Assume your mass is 70 kg.)
    d. Would the gravitational force be bigger, smaller, or the same if you were strapped to a flight instructor, and so had twice the mass?

44. Assume that a planet just like Earth is orbiting the bright star Vega at a distance of 1 astronomical unit (AU). The mass of Vega is twice that of the Sun.
    a. How long in Earth years will it take to complete one orbit around Vega?
    b. How fast is the Earth-like planet traveling in its orbit around Vega?

45. Suppose in the past the Moon was 80 percent of the distance from Earth that it is now. Calculate how much stronger the lunar tides would have been. How would the neap and spring tides be different from now?

USING THE WEB

46. Go to NASA's "Apollo 15 Hammer-Feather Drop" Web page (http://nssdc.gsfc.nasa.gov/planetary/lunar/apollo_15_feather_drop.html) and watch the video from *Apollo 15* of astronaut David Scott dropping the hammer and falcon feather on the Moon. (You might find a better version on YouTube.) What did this experiment show? What would happen if you tried this on Earth with a feather and a hammer? Would it work? Suppose instead you dropped the hammer and a big nail. How would they fall? How does the acceleration of falling objects on the Moon compare to the acceleration of falling objects on Earth?

47. Go to the Exploratorium's "Your Weight on Other Worlds" Web page (http://exploratorium.edu/ronh/weight), which will calculate your weight on other planets and moons in our Solar System. On which objects would your weight be higher than it is on Earth? What difficulties would human bodies have in a higher-gravity environment? For example, would it be easy to get up out of bed and walk? What are the possible short-term and long-term effects of lower gravity on the human body? Can you think of some types of life on Earth that might adapt well to a different gravity?

48. a. Watch the first 12 minutes of the episode "Gravity" in the *Universe* series (http://www.history.com/shows/the-universe/videos/the-universe-gravity) to see several illustrated examples of gravity. Why does the tennis ball appear to float when dropped at the top of the roller coaster? How was Newton able to imagine a satellite orbiting Earth centuries before it was possible? Why is it the speed of the cannonball that determines whether it goes into orbit? What was the technical difficulty in launching a satellite?

    b. In the same video as in part (a), watch the trip on the zero-G plane, at 23–29 minutes. How does the plane simulate zero-G? Why does it last for only 20–30 seconds? How is this similar to the roller coaster in part (a)?

49. Go to a website that will show you the times for high and low tides; for example, http://saltwatertides.com. Pick a location and bring up the tide table for today and the next 14 days. Why are there two high tides and two low tides every day? What is the difference in the height of the water between high and low tides? In the last few columns of the table, the times of moonrise and moonset are indicated, as well as the percent of lunar illumination. Does the time of the high tide lead or follow the highest position of the Moon in the sky? Compare with Figure 4.12c: what phases of the Moon have the greatest differences in the height of high and low tides?

50. Figure 4.17 shows two galaxies pulling at each other, most likely after they have already collided. Go to http://www.cita.utoronto.ca/~dubinski/nbody/ and scroll down to "Movie 2" to see a simulation of this interaction. Galaxies are not solid objects: they contain stars and gas and dust and a lot of empty space. Explain how these tidal tails can result from this type of interaction.

smartwork5

If your instructor assigns homework in Smartwork5, access your assignments at digital.wwnorton.com/astro5.

digital.wwnorton.com/astro5

In the Exploration of Chapter 3, we used the Planetary Orbit Simulator to explore Kepler's laws for Mercury. Now that we know how Newton's laws explain why Kepler's laws describe orbits, we will revisit the simulator to explore the Newtonian features of Mercury's orbit. Visit the Student Site at the Digital Landing Page, and open the Planetary Orbit Simulator applet.

Acceleration

To begin exploring the simulation, set parameters for "Mercury" in the "Orbit Settings" panel and then click "OK." Click the "Newtonian Features" tab at the bottom of the control panel. Select "show solar system orbits" and "show grid" under "Visualization Options." Change the animation rate to 0.01, and select the "start animation" button.

Examine the graph at the bottom of the panel.

1 Where is Mercury in its orbit when the acceleration is smallest?

2 Where is Mercury in its orbit when the acceleration is largest?

3 What are the values of the largest and smallest accelerations?

In the "Newtonian Features" graph, mark the boxes for vector and line that correspond to the acceleration. Specifying these parameters will insert an arrow that shows the direction of the acceleration and a line that extends the arrow.

4 To what Solar System object does the arrow point?

5 In what direction is the force on the planet?

Velocity

Examine the graph at the bottom of the panel again.

6 Where is Mercury in its orbit when the velocity is smallest?

7 Where is Mercury in its orbit when the velocity is largest?

8 What are the values of the largest and smallest velocities?

Add the velocity vector and line to the simulation by clicking on the boxes in the graph window. Study the resulting arrows carefully.

9 Are the velocity and the acceleration always perpendicular (is the angle between them always 90°)?

10 If the orbit were a perfect circle, what would be the angle between the velocity and the acceleration?

Hypothetical Planet

In the "Orbit Settings" panel, change the semimajor axis to 0.8 AU.

11 How does this imaginary planet's orbital period now compare to Mercury's?

Now change the semimajor axis to 0.1 AU.

12 How does this planet's orbital period now compare to Mercury's?

13 Summarize your observations of the relationship between the speed of an orbiting object and the semimajor axis.

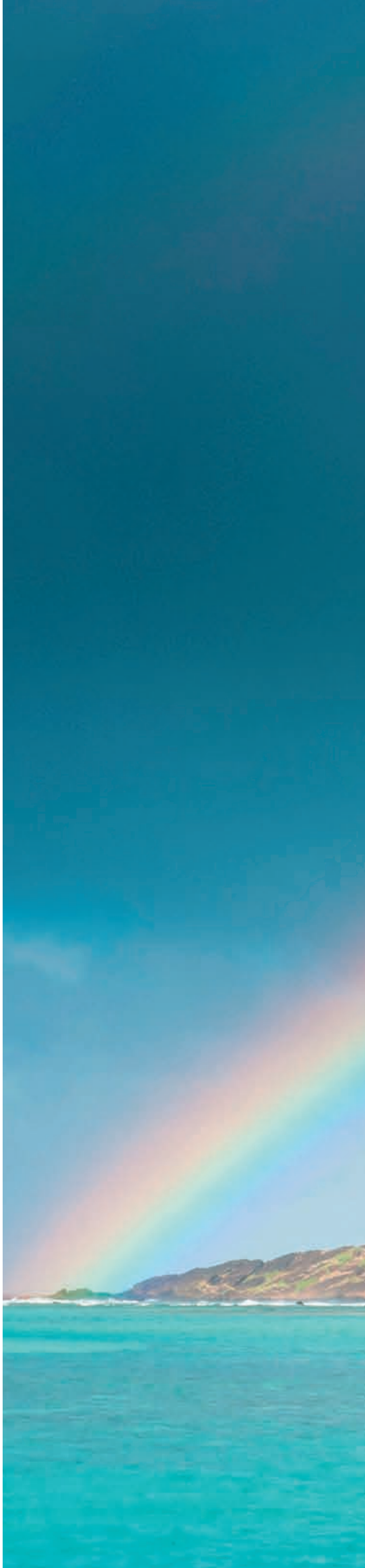
5 Light

Our knowledge of the universe beyond Earth comes from light emitted, absorbed, or reflected by astronomical objects. Light carries information about the temperature, composition, and speed of the objects. Light also tells us about the nature of the material that the light passed through on its way to Earth. Yet light plays a far larger role in astronomy than that of being a messenger. Light is one of the primary means by which energy is transported throughout the universe. Stars, planets, and vast clouds of gas and dust filling the space between the stars heat up as they absorb light and cool off as they emit light. Light carries energy generated in the heart of a star outward through the star and off into space. Light transports energy from the Sun outward through the Solar System, heating the planets; and light carries energy away from each planet, allowing each one to cool. The balance between these two processes establishes each planet's temperature and therefore a planet's possible suitability for life.

LEARNING GOALS

An astronomer must try to understand the universe by the light and other particles that reach Earth from distant objects. By the conclusion of this chapter, you should be able to:

- **LG 1** Describe the wave and particle properties of light, and describe the electromagnetic spectrum.
- **LG 2** Describe how to measure the chemical composition of distant objects using the unique spectral lines of different types of atoms.
- **LG 3** Describe the Doppler effect and how it can be used to measure the motion of distant objects.
- **LG 4** Explain how the spectrum of light that an object emits depends on its temperature.
- **LG 5** Differentiate luminosity from brightness, and illustrate how distance affects each.



The visible part of the electromagnetic spectrum is laid out in the colors of this rainbow. ▶▶▶

What is light?

5.1 Light Brings Us the News of the Universe

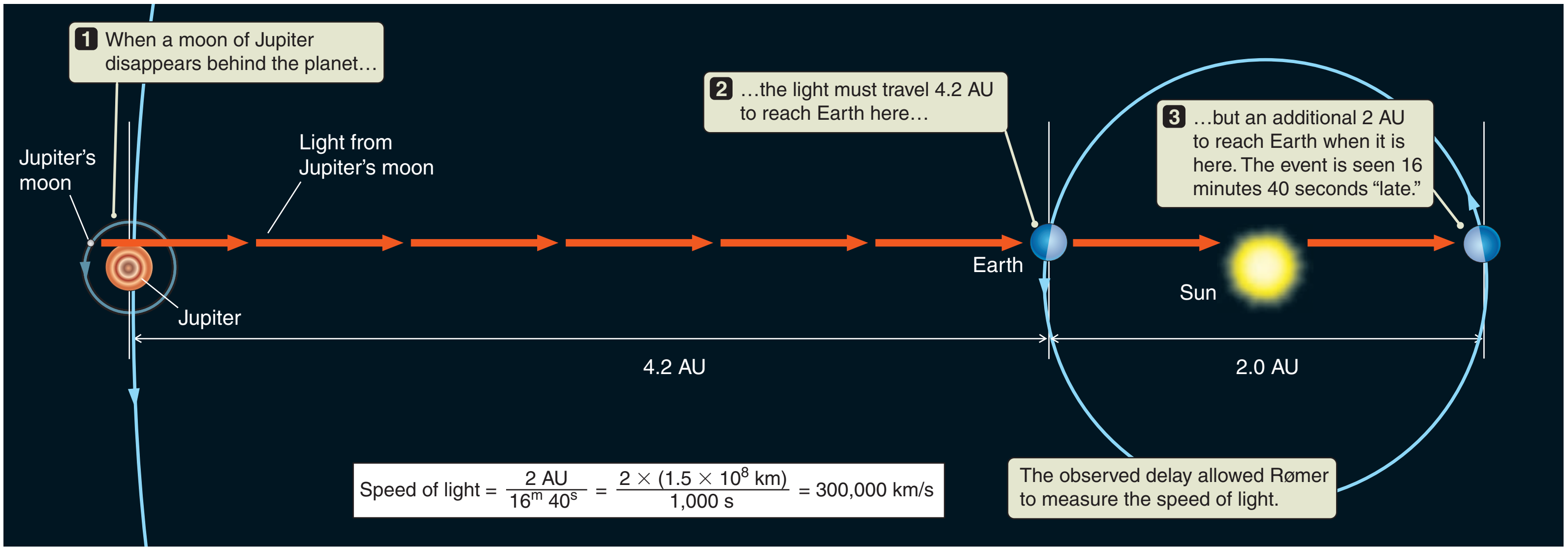
Since the earliest investigations of light, there has been disagreement over the question of whether light is composed of particles or if it is a disturbance that travels from one point to another, called a **wave**. Scientists have since come to understand that light sometimes acts like a wave and at other times acts like a particle. We will begin this section with a discussion of how fast light travels. We will then discuss its wavelike properties. After that we will look at how light behaves as a particle.

The Speed of Light

In the 1670s, Danish astronomer Ole Rømer (1644–1710) studied the movement of the moons of Jupiter, measuring the times when each moon disappeared behind the planet. To his amazement, the observed times did not follow the regular schedule that he predicted from Kepler's laws. Sometimes the moons disappeared behind Jupiter sooner than expected, and at other times they disappeared behind Jupiter later than expected. Rømer realized that the difference depended on where Earth was in its orbit. If he began tracking the moons when Earth was closest to Jupiter, by the time Earth was farthest from Jupiter the moons were almost 17 minutes "late." When Earth was once again closest to Jupiter, the moons again passed behind Jupiter at the predicted times.

Rømer correctly concluded that his observations were not a failure of Kepler's laws. Instead, he was seeing the first clear evidence that light travels at a finite speed. As shown in **Figure 5.1**, the moons appeared "late" when Earth was farther from Jupiter because of the time needed for light to travel the extra distance between the two planets. Over the course of Earth's yearly trip around the Sun, the distance between Earth and Jupiter changes by 2 astronomical units (AU). The speed of light equals this distance divided by Rømer's 16.7-minute delay, or about 3×10^5 kilometers per second (km/s). The value that Rømer actually announced in 1676 was a bit on the low side—2.25×10^5 km/s—because the size of

Figure 5.1 Danish astronomer Ole Rømer realized that apparent differences between the predicted and observed orbital motions of Jupiter's moons depend on the distance between Earth and Jupiter. He used these observations to measure the speed of light. (The superscript letters in the expression "16^m40^s" stand for minutes and seconds of time, respectively.)



Earth's orbit was not well known. Modern measurements of the speed of light give a value of 2.99792458×10^5 km/s in a **vacuum** (a region of space devoid of matter). The speed of light in a vacuum is one of nature's fundamental constants, usually written as *c* (lowercase). The speed of light through any medium, such as air or glass, is always less than *c*.

The International Space Station moves around Earth at a speed of about 28,000 kilometers per hour (km/h), taking 91 minutes to complete one orbit. Light travels almost 40,000 times faster than this and can circle Earth in only $\frac{1}{7}$ of a second. Because light is so fast, the travel time of light is a convenient way of expressing cosmic distances. It takes light $1\frac{1}{4}$ seconds to travel between Earth and the Moon, so we say that the Moon is $1\frac{1}{4}$ light-*seconds* from Earth. The Sun is $8\frac{1}{3}$ light-*minutes* away, and the next-nearest star is $4\frac{1}{3}$ light-*years* distant. Thus, a *light-year* is defined as the distance traveled by light in 1 year, or about 9.5 trillion km. Although it is sometimes misused as a measure of time, the light-year is a measure of distance.

As light travels at this high speed, it carries energy from place to place. **Energy** is the ability to do work, and it comes in many forms. **Kinetic energy** is the energy of moving objects. **Thermal energy** is closely related to kinetic energy and is the sum of all the random motion of atoms, molecules, and particles, by which we measure their temperature. For example, when light from the Sun strikes the pavement, the pavement heats up. That energy was carried from the Sun to the pavement by light. Rømer knew how long it took for light to travel a given distance, but it would take more than 200 years for physicists to figure out what light actually is.

Light as an Electromagnetic Wave

In the late 19th century, the Scottish physicist James Clerk Maxwell (1831–1879) introduced the concept that electricity and magnetism are two components of the same physical phenomenon. An **electric force** is the push or pull between electrically charged particles that make up atoms, such as protons and electrons, arising from their electric charges. Particles with opposite charges attract, and those with like charges repel. A **magnetic force** is a force between electrically charged particles arising from their motion.

To describe these electric and magnetic forces, Maxwell considered what happens when charged particles move in *electric fields* and *magnetic fields*. An **electric field** is a measure of the electric force on a charge at any point in space. Similarly, a **magnetic field** is a measure of the magnetic force acting on a small magnet at any point in space.

Maxwell summarized the behavior of electric fields and magnetic fields in four elegant equations. Among other things, these equations say that a changing electric field causes a magnetic field, and that a changing magnetic field causes an electric field. A change in the motion of a charged particle causes a changing electric field, which causes a changing magnetic field, which causes a changing electric field, and so on. You can see this interaction in **Figure 5.2**. Once the process starts, a self-sustaining procession of oscillating electric and magnetic fields moves out in all directions through space. In other words, an accelerating charged particle gives rise to an **electromagnetic wave**. These electromagnetic waves, and the accelerating charges that generate them, are the sources of electromagnetic radiation. Maxwell's equations also predict the speed at which an electromagnetic wave should travel, which agrees with the measured speed of light (*c*).

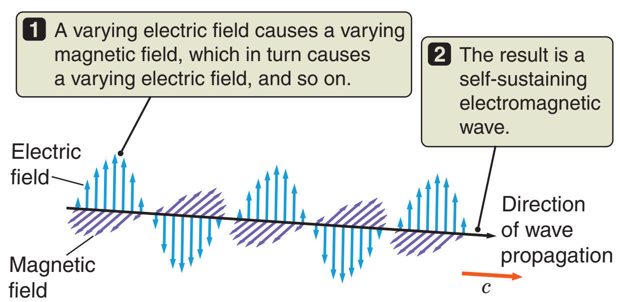


Figure 5.2 An electromagnetic wave consists of oscillating electric and magnetic fields that are perpendicular both to each other and to the direction in which the wave travels.

Maxwell's wave description of light also gives us an idea of how light originates and how it interacts with matter. When a drop of water falls from the faucet into a sink full of water, it causes a disturbance, or wave, like the one shown in **Figure 5.3a**. The wave moves outward as a ripple on the surface of the water. As shown in Figure 5.3b, electromagnetic waves resulting from periodic changes in the strength of the electric and magnetic fields move out through space away from their source in much the same way. However, the ripples in the sink are distortions of the water's surface, and they require a **medium**: a substance to travel through. Light waves move through empty space—what we call a vacuum—in the absence of a medium.

Now imagine that a soap bubble is floating in the sink, illustrated in **Figure 5.4a**. The bubble remains stationary until the ripple from the dripping faucet reaches it. As the ripple passes by, the rising and falling water causes the bubble to rise and fall. This can only happen if the wave is carrying energy—a conserved quantity that gives objects and particles the ability to do work. Light waves similarly carry energy through space and cause electrically charged particles to vibrate, as in Figure 5.4b.

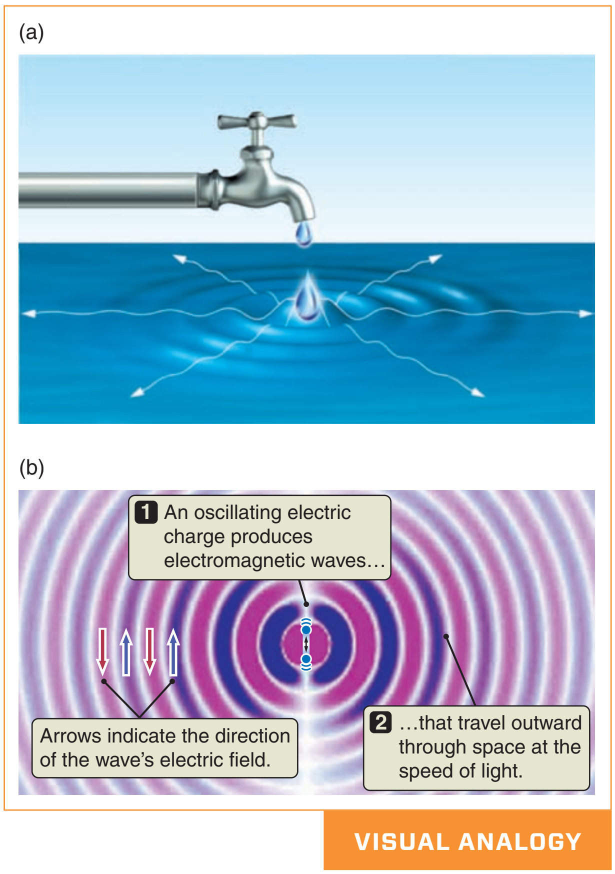


Figure 5.3 (a) A drop falling into water generates waves that move outward across the water's surface. (b) In similar fashion, an oscillating (accelerated) electric charge generates electromagnetic waves that move away at the speed of light.

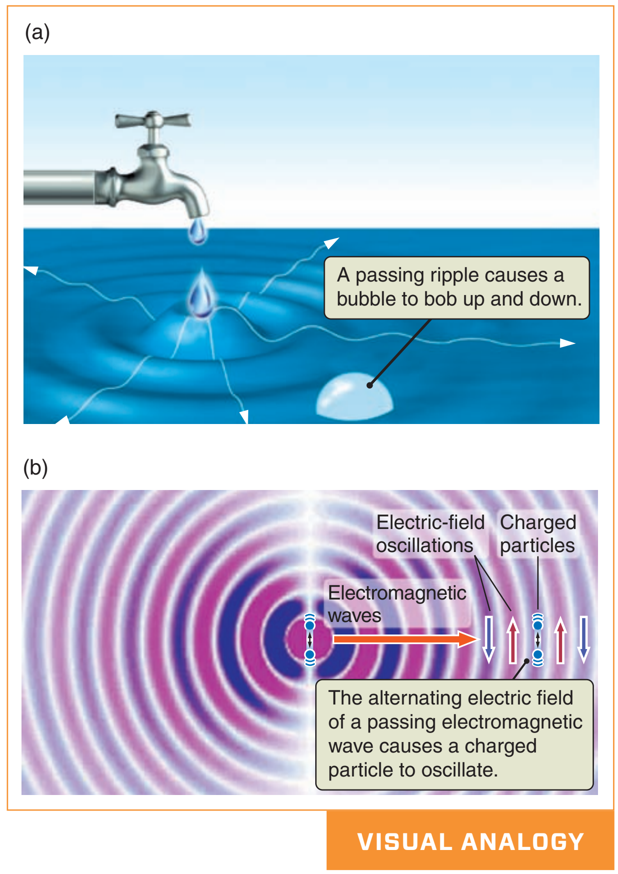


Figure 5.4 (a) When waves moving across the surface of water reach a bubble, they cause the bubble to bob up and down. (b) Similarly, a passing electromagnetic wave causes an electric charge to oscillate in response to the wave.

Characterizing Waves

In this book you will learn about several kinds of waves, including electromagnetic waves crossing the vast expanse of the universe and earthquakes traveling through Earth. Waves are generally characterized by four quantities: *amplitude*, *speed*, *frequency*, and *wavelength*. Each of these quantities is illustrated in **Figure 5.5**. The **amplitude** of a wave is the height of the wave above the undisturbed position (Figure 5.5a). For water waves, the amplitude is how far the water is lifted up by the wave. In the case of light, the amplitude of a light wave is related to the brightness of the light. A water wave travels at a particular speed, v (Figure 5.5b), through the water. The water itself doesn't travel; it just moves up and down at the same location. For waves like those in water, this speed is variable and depends on the density of the substance the wave moves through, among other things. Light, in contrast, always moves through a vacuum at the same speed, $c \approx 300{,}000$ km/s.

The distance from one crest of a wave to the next is the **wavelength**, usually denoted by the Greek letter lambda, λ (Figure 5.5c). The number of wave crests passing a point in space each second is called the wave's **frequency**, f. The unit of frequency is cycles per second, which is called **hertz** (abbreviated **Hz**) after the 19th century physicist Heinrich Hertz (1857–1894), who was the first to experimentally confirm Maxwell's predictions about electromagnetic radiation. Panels (c) and (d) of Figure 5.5 show that waves with longer wavelengths have lower frequencies, and waves with shorter wavelengths have higher frequencies. Higher-frequency waves carry more energy. Think about standing on an ocean beach: if the ocean waves are more frequent, they will be more energetic.

Waves travel a distance of one wavelength each cycle, so the speed of a wave can be found by multiplying the frequency and the wavelength. Translating this idea into math, we have $v = \lambda f$. The speed of light in a vacuum is always c, so once the wavelength of a wave of light is known, its frequency is known, and vice versa. Because light travels at constant speed, its wavelength and frequency are inversely proportional to each other: if the wavelength increases, the frequency decreases. A tremendous amount of information can be carried by waves; for example, complex and beautiful music, which travels by sound waves. As you continue your study of the universe, time and time again you will find that the information you receive, whether about the interior of Earth or about a distant star or galaxy, rides in on a wave.

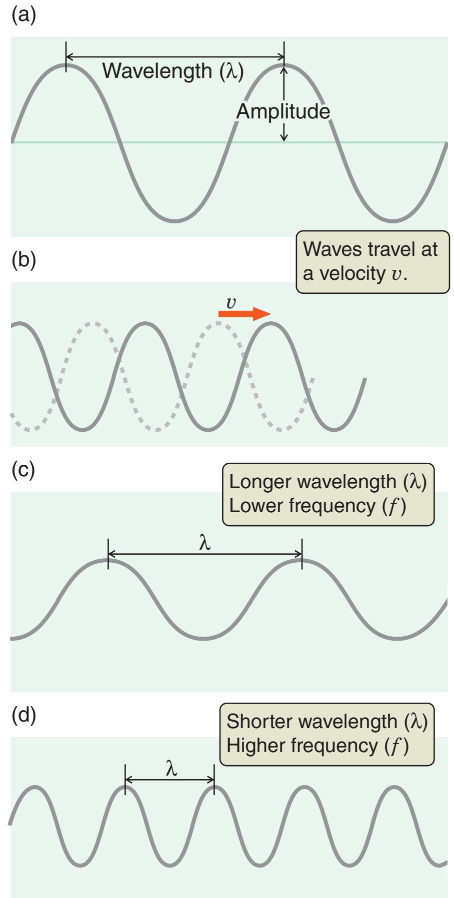


Figure 5.5 A wave is characterized by the distance from one peak to the next (wavelength, λ), the frequency of the peaks (f), the maximum deviations from the medium's undisturbed state (amplitude), and the speed (v) at which the wave pattern travels from one place to another. In an electromagnetic wave, the amplitude is the maximum strength of the electric field, and the speed of light is written as c.

The Electromagnetic Spectrum

Most light signals are made up of many wavelengths. You have almost certainly seen a rainbow, spread out across the sky, as in the chapter opening figure. A rainbow is created when white light interacts with water droplets and is spread out into its component colors. Light spread out by wavelength is called a **spectrum**. At the long-wavelength (and therefore low-frequency) end of the visible spectrum is red light. At the other end is violet light. A commonly used unit for the wavelength of visible light is the **nanometer**, abbreviated **nm**. A nanometer is one-billionth (10^{-9}) of a meter. Human eyes can see light between violet (about 380 nm) and red (750 nm). Stretched out between the two, in a rainbow, is the rest of the visible spectrum.

The light-sensitive cells in our eyes respond to visible light. But this is only a small sample of the range of possible wavelengths for electromagnetic radiation.

Light can have wavelengths that are much shorter or much longer than your eyes can perceive. The whole range of different wavelengths of light is collectively called the **electromagnetic spectrum**, illustrated in **Figure 5.6**. Most of the electromagnetic spectrum, and therefore most of the information in the universe, is invisible to the human eye. To detect light outside the visible, we must use specialized detectors of various kinds, as we will discuss in Chapter 6.

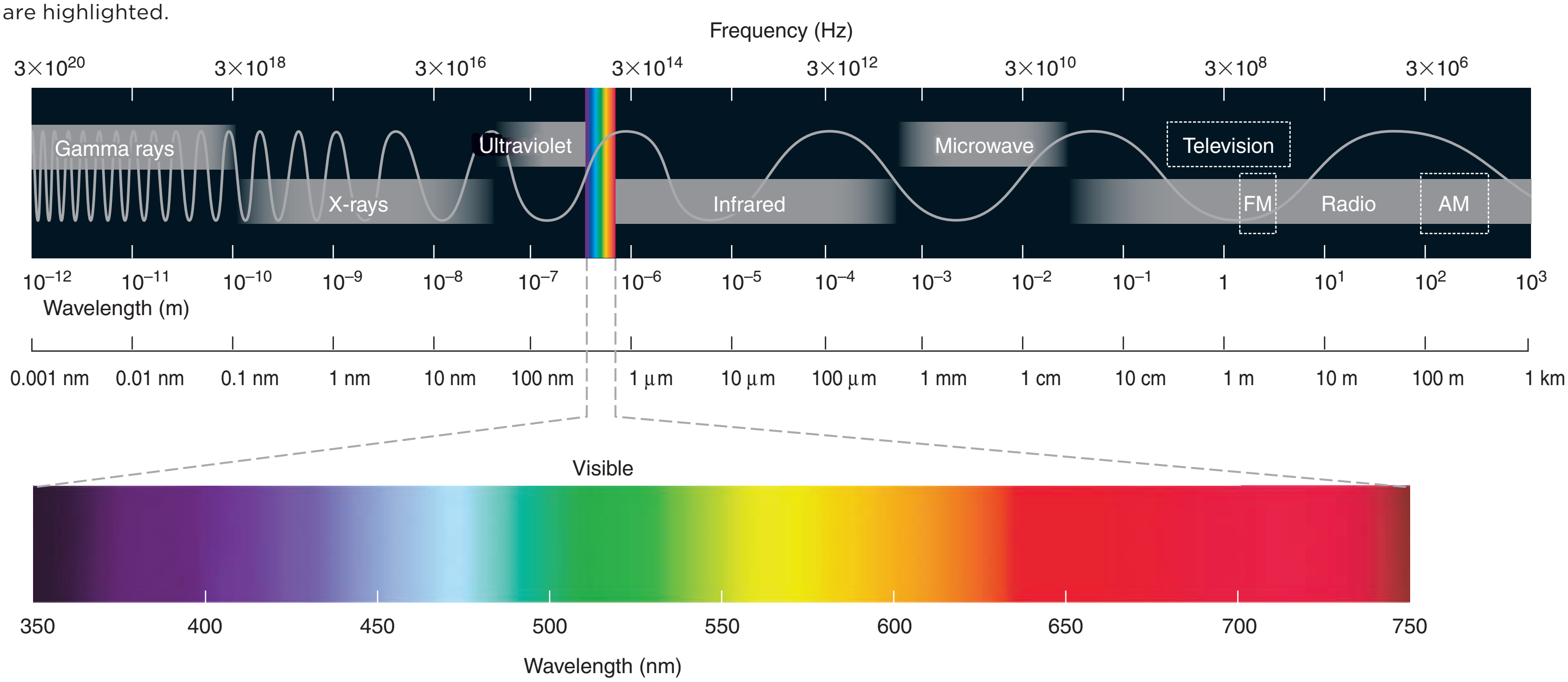
Refer to Figure 5.6 as we take a tour of the electromagnetic spectrum, beginning with the shortest wavelengths and working our way to the longest ones. The very shortest wavelengths of light are called **gamma rays**, or sometimes gamma radiation. Because this light has the shortest wavelengths, it has the highest frequency and the highest energy, so it penetrates matter easily. Wavelengths between 0.1 nm and 40 nm are called **X-rays**. You have probably encountered X-rays at the dentist or in an emergency room—X-ray light has enough energy to penetrate through skin and muscle but is stopped by denser bone. **Ultraviolet (UV) radiation** has wavelengths between 40 and about 380 nm—longer than X-rays but shorter than visible light. You are familiar with this type of light from sunburns: UV light has enough energy to penetrate into your skin, but not much farther.

Nebraska Simulation: EM Spectrum Module

Infrared (IR) radiation has longer wavelengths than the reddest wavelengths in the visible range. You are familiar with a small wavelength range of this kind of radiation because you often feel it as heat. When you hold your hand next to a hot stove, some of the heat you feel is carried to your hand by infrared radiation emitted from the stove. In this sense, you could think of your skin as being a giant infrared eyeball—it is sensitive to infrared wavelengths. Infrared radiation is also used in television remote controls, and night vision goggles detect infrared radiation from warm objects such as animals. A useful unit for infrared light is the **micron** (abbreviated **μm**, where μ is the Greek letter mu). One micron is 1,000 nm, or one-millionth (10^{-6}) of a meter. Infrared wavelengths are longer than red light and shorter than 500 microns.

Microwave radiation has even longer wavelengths than infrared radiation. The microwave in your kitchen heats the water in food using light of these

Figure 5.6 By convention, the electromagnetic spectrum is divided into loosely defined regions ranging from gamma rays to radio waves. Throughout the book, we use the following labels to indicate the form of radiation used to produce astronomical images, with an icon to remind you: G = gamma rays; X = X-rays; U = ultraviolet; V = visible; I = infrared; R = radio. If more than one region is represented, multiple labels are highlighted.



wavelengths. The longest-wavelength light, which has wavelengths longer than a few centimeters, is called **radio waves**. Light of these wavelengths in the form of FM, AM, television, and cell phone signals is used to transmit information from place to place.

CHECK YOUR UNDERSTANDING 5.1

Rank the following in order of decreasing wavelength: (a) gamma rays; (b) visible light; (c) infrared light; (d) ultraviolet light; (e) radio waves.

Light as a Particle

Although the wave theory of light describes many observations, it does not provide a complete picture of the properties of light. Many of the difficulties with the wave model of light have to do with the way in which light interacts with small particles such as atoms and molecules.

The work of Albert Einstein and other scientists modified our understanding of light to show that light sometimes acts like a wave and sometimes acts like a particle. In 1905, Einstein explained the *photoelectric effect*, in which electrons are emitted when surfaces are illuminated by electromagnetic radiation greater than a certain frequency. He showed that the rate at which electrons are emitted depends only on the amount of incoming light, and that the speed of the electrons depends only on the frequency of the incoming radiation. This work earned Einstein a Nobel Prize in 1921. In the particle model, light is made up of massless particles called **photons** (*phot*- means "light," as in *photograph*; and -*on* signifies a particle). Photons always travel at the speed of light (**Process of Science Figure**), and they carry energy. A photon is a *quantum* of light; *quantized* means that something is subdivided into individual units. **Quantum mechanics** is a branch of physics that deals with the quantization of energy and of other properties of matter.

The energy of a photon and the frequency of the electromagnetic wave are directly proportional to each other: the higher the frequency of the light wave, the greater the energy each photon carries. This relationship connects the particle and the wave concepts of light. For example, photons with higher frequencies carry more energy than that carried by photons with lower frequencies. The constant of proportionality between the energy, E, and the frequency, f, is called Planck's constant, h, which is equal to 6.63×10^{-34} joule-seconds (a joule is a unit of energy). Specifically, $E = hf$, where E = the energy of the photon, h = Planck's constant, and f = frequency. Because the wavelength and frequency of electromagnetic waves are inversely proportional, this also means that the photon energy is inversely proportional to the wavelength. In visible light, high-energy light is blue, and low-energy light is red. **Working It Out 5.1** explores the relationships among wavelength, frequency, and energy of light.

In the particle description of light, the electromagnetic spectrum is a spectrum of photon energies. The higher the frequency of the electromagnetic wave, the greater the energy carried by each photon. Photons of shorter wavelength (higher frequency) carry more energy than that carried by photons of longer wavelength (lower frequency). For example, photons of blue light carry more energy than that carried by photons of longer-wavelength red light. Ultraviolet photons carry more energy than that carried by photons of visible light, and X-ray photons carry more energy than that carried by ultraviolet photons. The lowest-energy photons are radio wave photons.

AstroTour: Light as a Wave, Light as a Photon

Process of Science

AGREEMENT BETWEEN FIELDS

Scientists working on very different problems in different fields all find the same result: light has a speed and can be measured.

Ole Rømer studies eclipses of Jupiter's moons.

Rømer calculates the speed of light from eclipse delays of Jupiter's moons.

James Bradley studies the apparent motion of stars, which appear to make small circles because of the relative motion of Earth.

A half century after Rømer's measurement, Bradley's motion studies lead to a more accurate measurement of the speed of light.

James Clerk Maxwell studies electricity and magnetism.

Einstein builds on Maxwell's theory in 1905 to claim that the speed of light is the same for all observers.

Astronomers and physicists converge on an understanding that photons travel at the speed of light—a fundamental constant of the universe that is the same for all observers.

5.1 Working It Out Working with Electromagnetic Radiation

Wavelength and Frequency

When you tune to a radio station at, say, 770 AM, you are receiving an electromagnetic signal that travels at the speed of light and is broadcast at a frequency of 770 kilohertz (kHz), or 7.7×10^5 Hz. We can use the relationship between wavelength and frequency, $c = \lambda f$ to calculate the wavelength of the AM signal:

$$\lambda = \frac{c}{f} = \left(\frac{3 \times 10^8 \text{ m/s}}{7.7 \times 10^5\text{/s}}\right) = 390 \text{ m}$$

This AM wavelength is about 4 times the length of a football field. FM wavelengths are much shorter than AM wavelengths.

The human eye is most sensitive to light in green and yellow wavelengths, about 500–590 nm. If we examine green light with a wavelength of 530 nm, we can compute its frequency:

$$f = \frac{c}{\lambda} = \left(\frac{3 \times 10^8 \text{ m/s}}{530 \times 10^{-9} \text{ m}}\right) = 5.66 \times 10^{14}\text{/s} = 5.66 \times 10^{14} \text{ Hz}$$

This frequency corresponds to 566 *trillion* wave crests passing by each second.

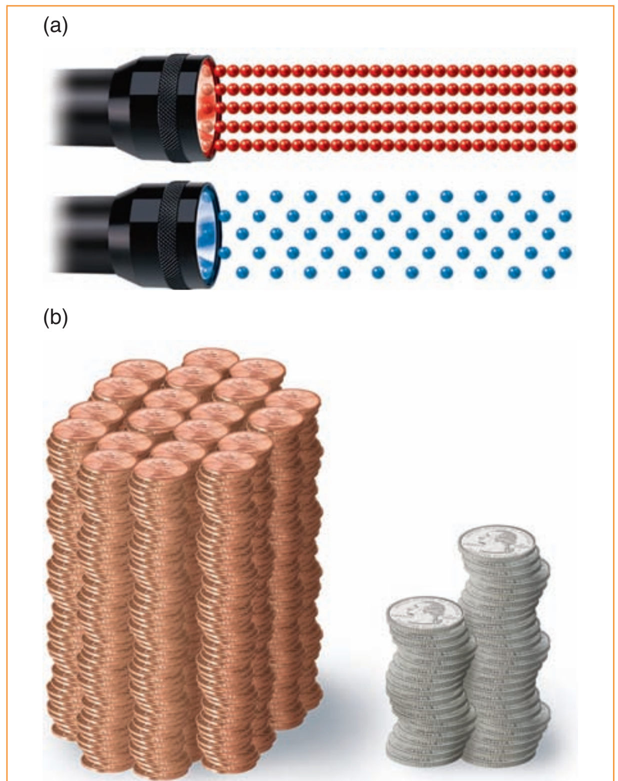
Photon Energy

Let's compare the energy of an X-ray photon with a wavelength of 1 nm and the energy of a visible light photon with a wavelength of 530 nm as used in the previous calculation. The equation for the energy of a photon is $E = hf$. Because $f = c/\lambda$, substituting c/λ for f yields the inverse relationship, $E = hc/\lambda$, with c = the speed of light = 3×10^8 m/s, and h = Planck's constant. Because we are making a *comparison*, we can take a ratio, and then the constants h and c cancel out:

$$\frac{E_{\text{X-ray photon}}}{E_{\text{visible photon}}} = \frac{hc/\lambda_{1\,\text{nm}}}{hc/\lambda_{500\,\text{nm}}} = \frac{\cancel{hc}}{\cancel{hc}} \times \frac{530 \text{ nm}}{1 \text{ nm}} = 530$$

The X-ray photon has 530 times the energy of the visible light photon.

The *total* amount of energy that a beam of the light carries is called its **intensity**. A beam of red light can be just as intense as a beam of blue light—that is, it can carry just as much energy—but because the energy of a red photon is less than the energy of a blue photon, maintaining that same intensity requires more red photons than blue photons. This relationship, illustrated in **Figure 5.7**, is a lot like money: \$10 is \$10, but it takes a lot more pennies (low-energy photons) than quarters (high-energy photons) to make up \$10.



VISUAL ANALOGY

Figure 5.7 (a) Red light carries less energy than that carried by blue light, so it takes more red photons than blue photons to make a beam of a particular intensity. (b) Similarly, pennies are worth less than quarters, so it takes more pennies than quarters to add up to \$10.

CHECK YOUR UNDERSTANDING 5.2

As wavelength increases, the energy of a photon __________ and its frequency __________. (a) increases; decreases (b) increases; increases (c) decreases; decreases (d) decreases; increases

5.2 The Quantum View of Matter Explains Spectral Lines

Light and matter interact, and this interaction allows us to detect matter even at great distances in space. To understand this interaction, we must understand the building blocks of matter. In this section, we will review atomic structure and the process by which astronomers identify the chemical elements in astronomical objects.

Atomic Structure

Matter is anything that occupies space and has mass. Atoms are composed of a central massive **nucleus**, which contains **protons** with a positive charge and **neutrons**, which have no charge. A cloud of negatively charged **electrons**

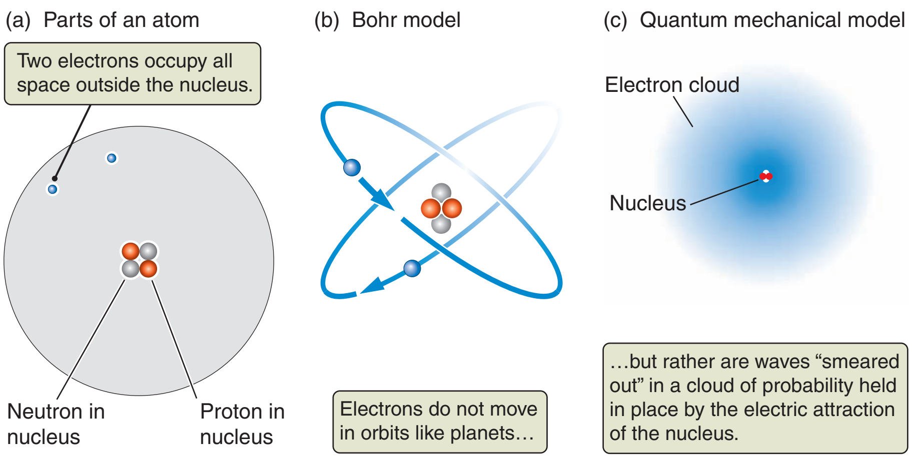


Figure 5.8 (a) An atom (in this case helium) is made up of a nucleus consisting of positively charged protons and electrically neutral neutrons and surrounded by less massive negatively charged electrons. (b) Atoms are often drawn as miniature "solar systems," but this model is incorrect. (c) Electrons are actually smeared out around the nucleus in quantum mechanical clouds of probability.

surrounds the nucleus. Atoms with the same number of protons are all of the same type, known as an **element**. For example, an atom with two protons, shown in **Figure 5.8a**, is the element helium. An atom with six protons is the element carbon; one with eight protons is the element oxygen; and so forth. An element may have many **isotopes**: atoms with the same number of protons but different numbers of neutrons. **Molecules** are groups of atoms bound together by shared electrons. A single teaspoon of water contains about 10^{23} atoms—about as many atoms as there are stars in the observable universe.

For an atom to be electrically neutral, it must have the same number of electrons as protons. Electrons have much less mass than protons or neutrons have, so almost all the mass of an atom is found in its nucleus. This description led to a model of an atom with the massive nucleus sitting in the center and the smaller electrons orbiting around it, much as planets orbit around the Sun (Figure 5.8b). It is called the **Bohr model** after the Danish physicist Niels Bohr (1885–1962), who proposed it in 1913.

AstroTour: Atomic Energy Levels and the Bohr Model

However, Bohr's model is not a complete description of an atom. Just as waves of light have particle-like properties, particles of matter also have wavelike properties. With this realization, the Bohr model of the atom was modified so that the positively charged nucleus is surrounded by electron "clouds" or "waves," as shown in Figure 5.8c. In this model, it is not possible to know precisely where the electron is in its orbit. The wave characteristics of particles make it impossible to pin down simultaneously their exact location and their exact velocity; there will always be some uncertainty. This is why a featureless cloud is used to represent electrons in orbit around an atomic nucleus.

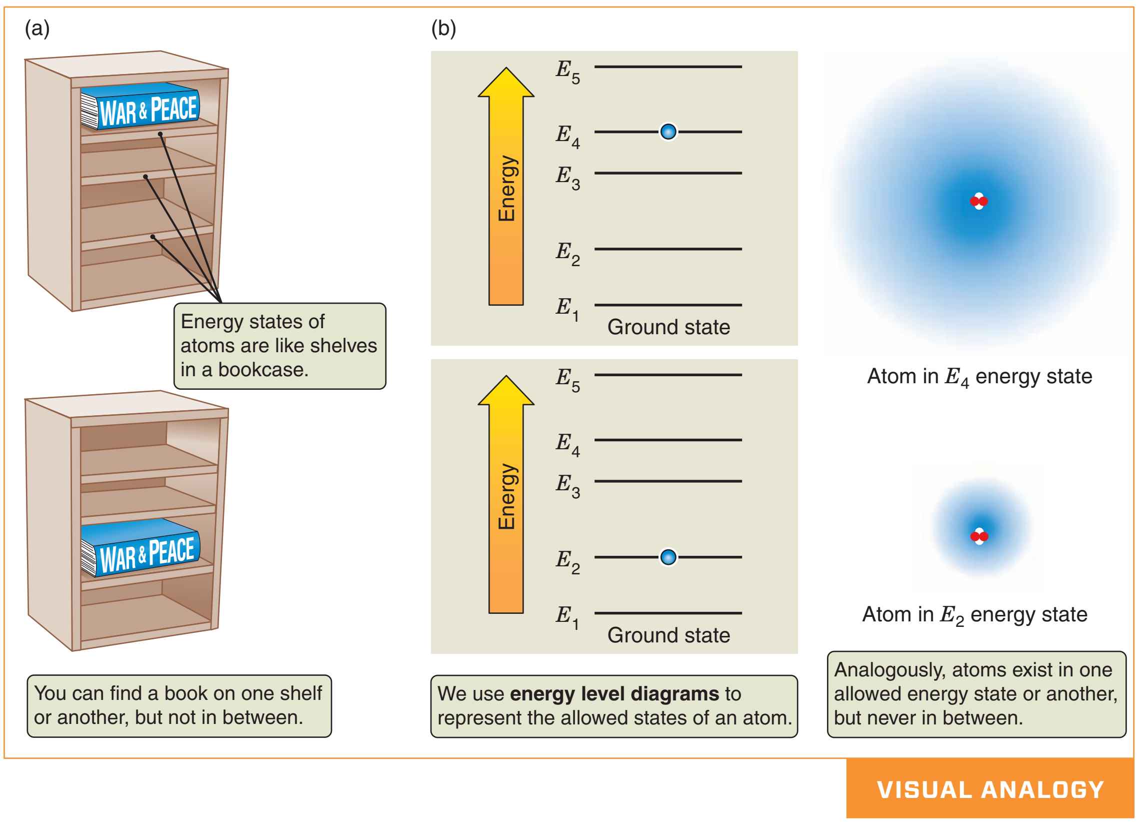


Figure 5.9 (a) Energy states of an atom are analogous to shelves in a bookcase. You can move a book from one shelf to another, but books can never be placed between shelves. (b) Atoms exist in one allowed energy state or another but never in between. There is no level below the ground state.

Atomic Energy Levels

Because of their wavelike properties, electrons in an atom can take on only certain specific energies that depend on the energy states of the atom. The form that the electron waves take depends on the possible energy states of atoms. We can imagine the energy states of atoms as being like a bookcase with a set of shelves, as depicted in **Figure 5.9a**. The energy of an atom might correspond to the energy of one state or to the energy of the next state, but the energy of the atom is never found between the two states, just as a book can be on only one shelf at a time and cannot be partly on one shelf and partly on another. A given atom may have many different energy states available to it, but these states are *discrete*.

Astronomers keep track of the allowed states of an atom using energy level diagrams, as shown in Figure 5.9b, where each energy level is like a shelf on the bookcase. Both the bookcase and the energy level diagram are simplifications of the possible energies of a three-dimensional system. The lowest possible energy state for a system (or part of a system) such as an atom is called the **ground state**. When the atom is in the ground state, the electron has its minimum energy. It can't give up any more energy to move to a lower state, because there isn't a lower state. An atom will remain in its ground state forever unless it gets energy from outside. In the bookcase analogy, a book sitting on the bottom shelf at the floor is in its ground state. It has nowhere left to fall, and it cannot jump to one of the higher shelves of its own accord.

Energy levels above the ground state are called **excited states**. Just as a book on an upper shelf might fall to a lower shelf, an atom in an excited state might **decay** to a lower state by getting rid of some of its extra energy. An important difference between the atom and the book on the shelf, however, is that whereas a snapshot might catch the book falling between the two shelves, the atom will never be caught between two energy states. When the transition from one higher state to a lower one occurs, the difference in energy between the two states is carried off all at once. A common way for an atom to do this is to emit a photon. The photon emitted by the atom carries away exactly the amount of energy lost by that atom as it goes from the higher energy state to the lower energy state. In a similar fashion, atoms moving from a lower energy state to a higher energy state can absorb only certain specific energies.

To make an analogy with money, suppose you have a penny (1 cent), a nickel (5 cents), and a dime (10 cents), totaling 16 cents. Now imagine that you give away the nickel and are left with 11 cents. You never had exactly 13 cents or 13.6 cents. You had 16 cents, and then 11 cents. Atoms don't accept and give away money to change energy states, but they do accept and give away photons with well-defined energy.

Emission Spectra Imagine a hypothetical atom that has only two available energy states. The energy of the lower energy state (the ground state) is E_1, and the energy of the higher energy state (the excited state) is E_2. The energy levels of this atom can be represented in an energy level diagram like the one in **Figure 5.10a**. An atom in the excited state moves to the ground state by getting rid of the "extra" energy all at once. It does this when the electron emits a photon. The atom goes from one energy state to another, but it never has an amount of energy in between.

In Figure 5.10b, the downward arrow indicates that the atom went from the higher state with energy E_2 to the lower state with energy E_1. The atom lost an amount of energy equal to the difference between the two states, or $E_2 - E_1$. Because energy is never truly lost or created, the energy lost by the atom has to show up somewhere. In this case, the energy shows up in the form of a photon that is emitted by the atom. The energy of the photon emitted exactly matches the energy lost by the atom; that is, $E_{photon} = E_2 - E_1$.

An atom can emit photons with energies corresponding *only* to the difference between two of its allowed energy states. Because the energy of a photon is related to the frequency or wavelength of electromagnetic radiation, in the

Astronomy in Action: Emission and Absorption

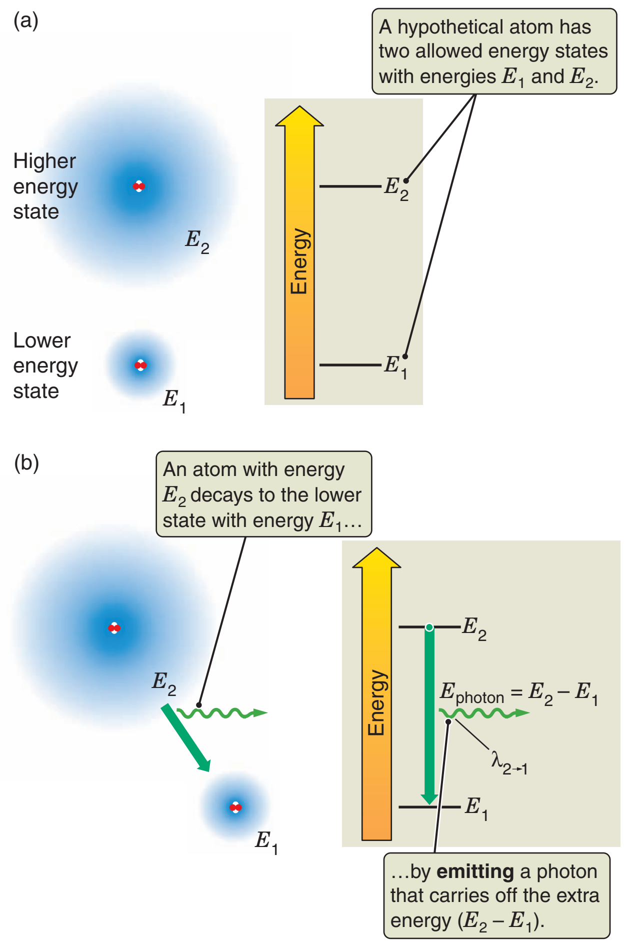


Figure 5.10 (a) The energy levels of a hypothetical two-level atom. (b) A photon with energy $E_{photon} = E_2 - E_1$ is emitted when an atom in the higher energy state decays to the lower energy state.

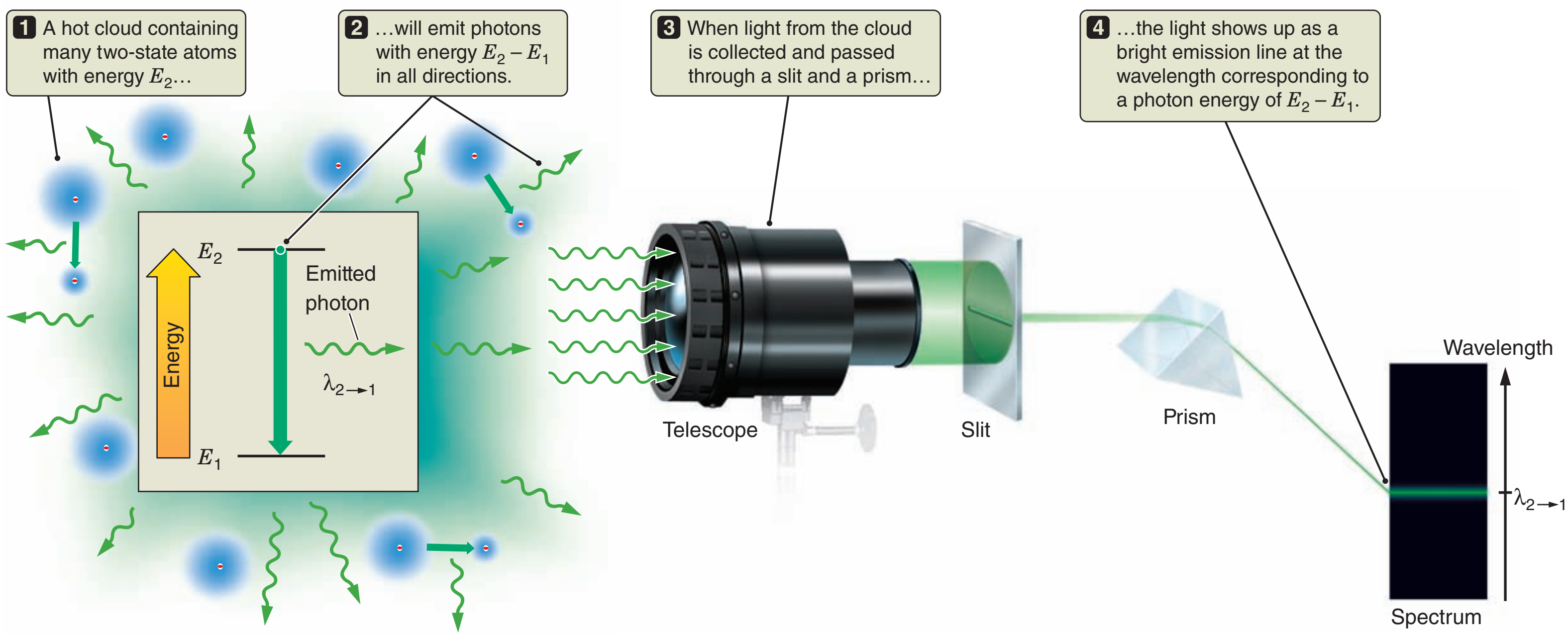


Figure 5.11 A cloud of gas containing atoms with two energy states, E_1 and E_2, emits photons with an energy $E_{photon} = E_2 - E_1$, which appear in the spectrum (right) as a single bright *emission line*.

transition from level 2 to level 1, a photon of energy $E_{photon} = E_2 - E_1$ has a specific wavelength $\lambda_{2\to1}$ and a specific frequency $f_{2\to1}$. Therefore, these emitted photons have a very specific color, and every photon emitted in any transition from E_2 to E_1 will have this same color defined by a specific wavelength. The energy level structure of an atom determines the wavelengths of the photons it emits—the color of the light that the atom gives off.

Figure 5.11 illustrates the light coming from a cloud of gas consisting of the hypothetical two-state atoms in Figure 5.10. Any atom in the higher energy state (E_2) quickly decays and emits a photon in a random direction, and an enormous number of photons come pouring out of the cloud of gas. Instead of containing photons of all different energies—light of all different colors—this light contains only photons with the specific energy $E_2 - E_1$ and wavelength $\lambda_{2\to1}$. In other words, all of the light coming from these atoms in the cloud is the same color. If you spread the light out into its component colors, there would be only one color—a single bright line called an **emission line**.

Why was the atom in the excited state E_2 in the first place? An atom sitting in its ground state will remain there unless it absorbs just the right amount of energy to kick it up to an excited state. In general, the atom either absorbs the energy of a photon or it collides with another atom or an unattached electron and absorbs some of the other particle's energy. In a neon sign, an alternating electric field inside the glass tube pushes electrons in the gas back and forth through the neon gas inside the tube. Some of these electrons crash into atoms of the gas, knocking them into excited states. The atoms then drop back down to their ground states by emitting photons, causing the gas inside the tube to glow.

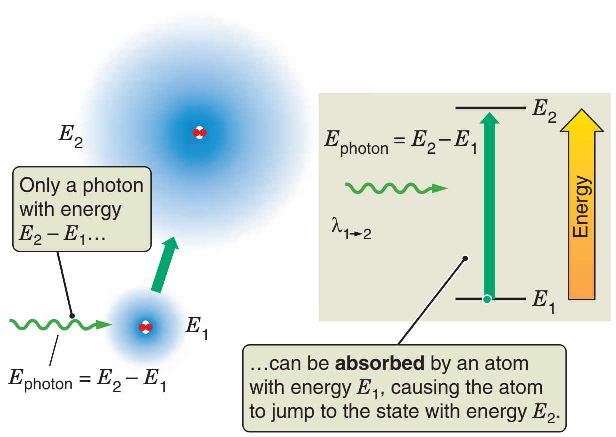


Figure 5.12 An atom in a lower energy state may absorb a photon of energy $E_{photon} = E_2 - E_1$, leaving the atom in a higher energy state.

Absorption Spectra In the opposite process, an atom in a low energy state can absorb the energy of a passing photon and jump up to a higher energy state as shown in **Figure 5.12**. Once again, the energy required to go from E_1 to E_2 is the difference in energy between the two states, $E_2 - E_1$. For a photon to cause an atom to jump from E_1 to E_2, it must provide exactly this much energy. The only photons capable of exciting atoms from E_1 to E_2 are photons with $E_{photon} = E_2 - E_1$. As with emission, these photons have a corresponding frequency and wavelength $f_{1\rightarrow2} = E_{photon}/h$ and $\lambda_{1\rightarrow2} = hc/E_{photon}$. These photons have exactly the same energy—the same color of light—emitted by the atoms when they decay from E_2 to E_1. This is not a coincidence. The energy difference between the two levels is the same whether the atom is emitting a photon or absorbing one, so the energy of the photon involved will be the same in either case.

In **Figure 5.13a**, white light (with all wavelengths of photons in it) passes directly though a glass prism, which breaks up the light into a rainbow of colors. However, when the white light passes through a cool cloud composed of our hypothetical gas of two-state atoms, as illustrated in Figure 5.13b, some photons will be absorbed. Almost all of the photons will pass through the cloud of gas unaffected, because they do not have the right energy ($E_2 - E_1$) to be absorbed by atoms of the gas. However, photons with just the right amount of energy can be absorbed, and as a result, these photons will be missing in the light passing

Nebraska Simulation: Three Views Spectrum Demonstrator

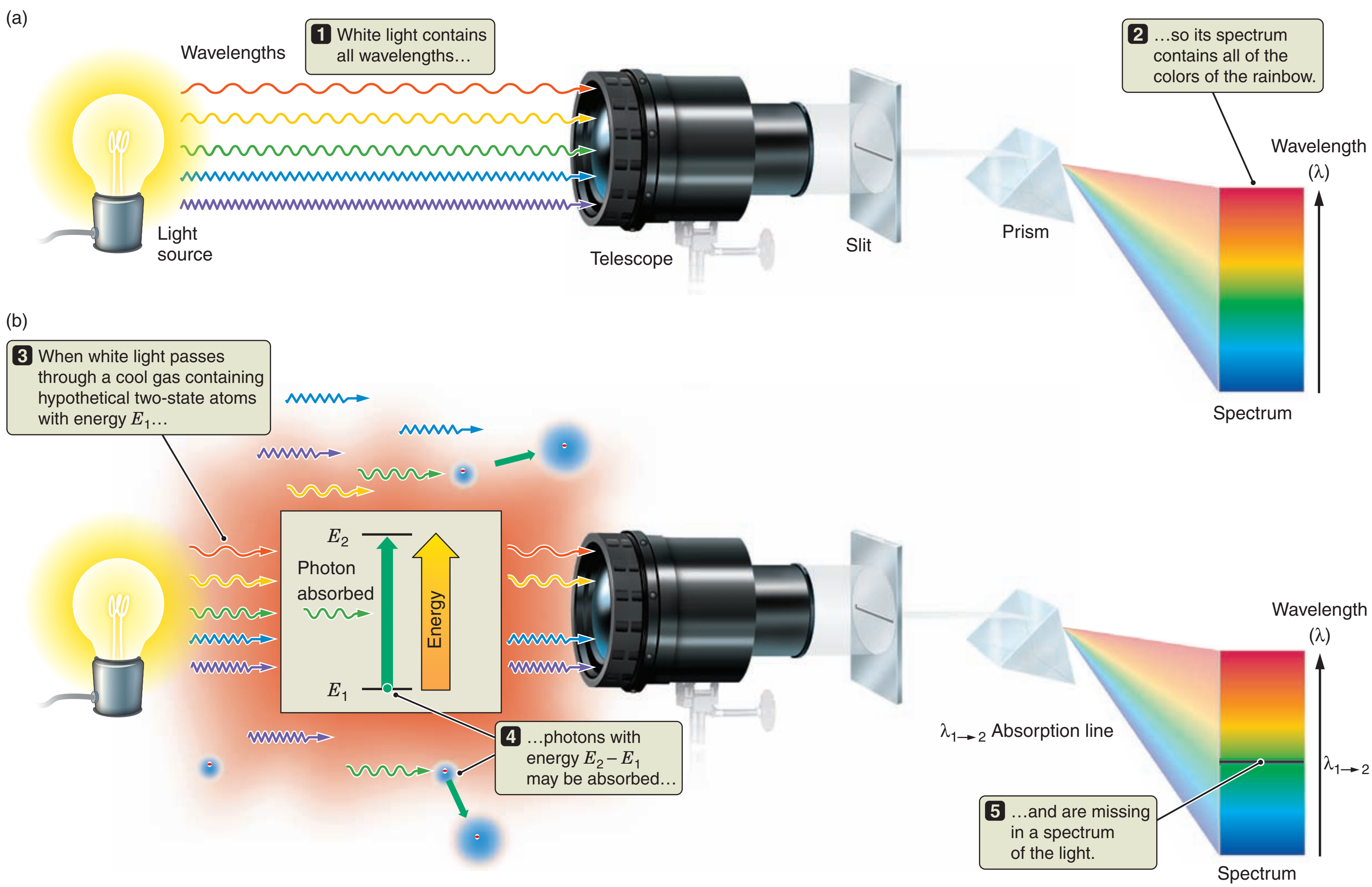


Figure 5.13 (a) When passed through a prism, white light produces a spectrum containing all colors. (b) When light of all colors passes through a cloud of hypothetical two-state atoms, photons with energy $E_{photon} = E_2 - E_1$ may be absorbed, leading to the dark absorption line in the spectrum.

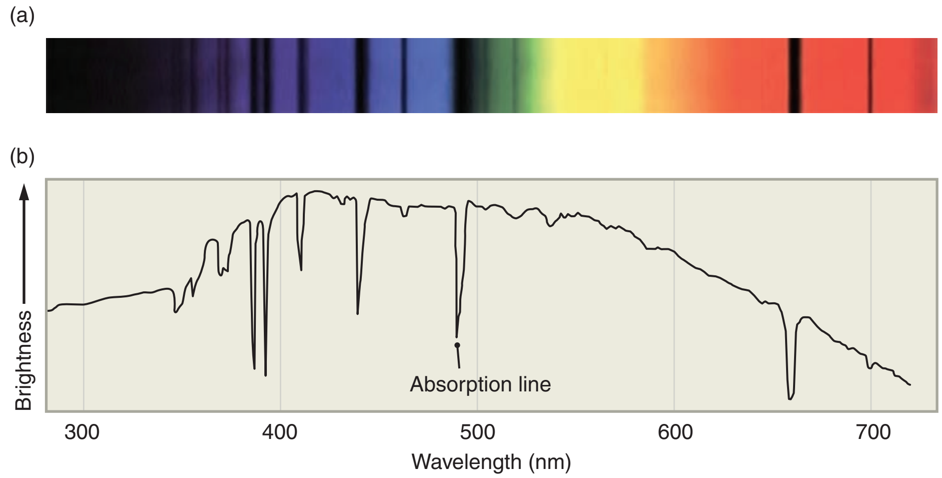


Figure 5.14 Absorption lines in the spectrum of a star as an image (a) and a graph (b).

through the prism. Where the color corresponding to each of these missing photons should be, there is instead a sharp, dark line at the wavelength corresponding to this energy. This process by which atoms capture the energy of passing photons is called **absorption**, and the dark line seen in the spectrum is called an **absorption line**. **Figure 5.14a** shows such absorption lines in the spectrum of a star. The spectrum is shown in two different ways here: as a rainbow with light missing, and then again in Figure 5.14b as a graph of the brightness at every wavelength. Comparing the top and bottom versions of the spectrum, you can see that where there are dark lines, the brightness drops abruptly at a particular wavelength. Places between the dark lines are brighter and therefore higher on the graph than the absorption lines.

▶II **AstroTour:** Atomic Energy Levels and Light Emission and Absorption

When an atom absorbs a photon, it may quickly decay to its previous lower energy state, emitting a photon with the same energy as the photon it just absorbed. If the atom reemits a photon just like the one it absorbed, why does the absorption matter? The photon that was taken out of the passing light was replaced, but all of the absorbed photons were originally traveling in the same direction, whereas the emitted photons are traveling in random directions. In other words, some of the photons with energies equal to $E_2 - E_1$ are diverted from their original paths by their interaction with atoms. If you look at a white light through the cloud in Figure 5.13b, you will observe an absorption line at a wavelength of $\lambda_{1\rightarrow2}$, but if you look at the cloud from another direction, you will observe an emission line at this same wavelength.

Nebraska Simulation: Hydrogen Atom Simulator

Spectral Fingerprints of Atoms

Spectra of astronomical objects are fundamental to our understanding of the universe. Astronomers who study spectra will say "a spectrum is worth a thousand pictures" because of the wealth of information that can come from it. We will refer to spectra in every chapter in this book. So now let's move beyond the hypothetical atom with two energy levels to see what we can learn from real atoms. Atoms can occupy many more than just two possible energy states; therefore, any given type of atom will be capable of emitting and absorbing photons at many different wavelengths. An atom with three energy states, for example, might jump from state 3 to state 2, or from state 3 to state 1, or from state 2 to state 1. The three

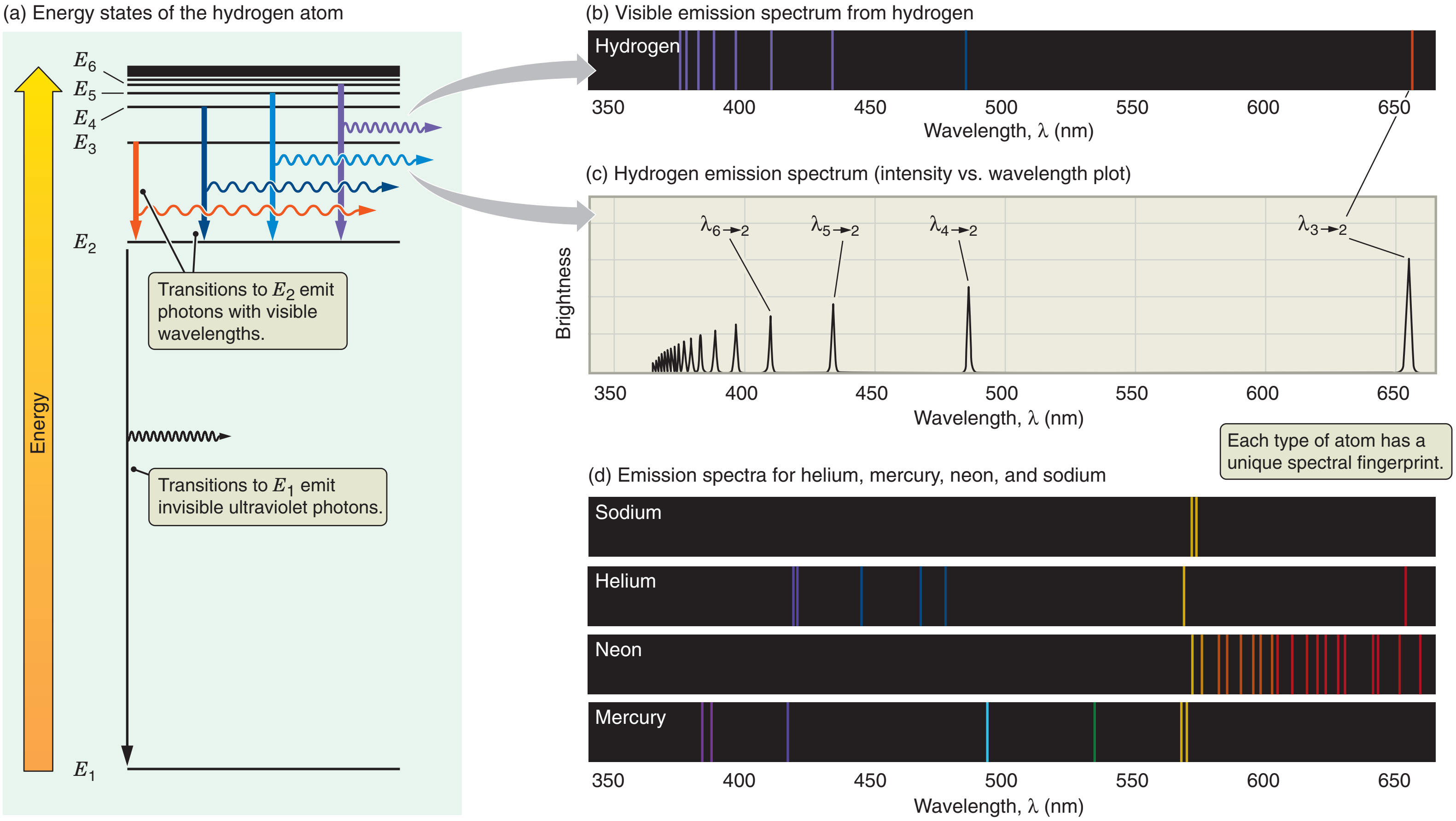


Figure 5.15 (a) The energy states of the hydrogen atom. Decays to level E_2 emit photons in the visible part of the spectrum. (b) This spectrum is what you might see if you looked at the light from a hydrogen lamp projected through a prism onto a screen. (c) This graph of the brightness (intensity) of spectral lines versus their wavelength illustrates how spectra are traditionally plotted. (d) Emission spectra from several other gases: helium, mercury, neon, and sodium.

distinct emission lines in the spectrum from a gas made up of these atoms would have wavelengths of $hc/(E_3 - E_2)$, $hc/(E_3 - E_1)$, and $hc/(E_2 - E_1)$, respectively.

The allowed energy states of an atom are determined by the complex interactions among the electrons and the nucleus. Every neutral hydrogen atom consists of a nucleus containing one proton, plus a single electron in a cloud surrounding the nucleus. Therefore, every hydrogen atom has the same energy states available to it, and all hydrogen atoms have the same emission and absorption lines. **Figure 5.15a** shows the energy level diagram of hydrogen. Figure 5.15b illustrates the visible emission spectrum from hydrogen. Figure 5.15c displays this same information as a graph.

Each different type of atom, that is, each chemical element, has a unique set of available energy states and therefore a unique set of wavelengths at which it can emit or absorb radiation. Figure 5.15d shows the emission spectra of four different kinds of atoms. These unique sets of wavelengths serve as unmistakable spectral "fingerprints" for each chemical element.

Spectral fingerprints are of crucial importance to astronomers. They let astronomers figure out what types of atoms (or molecules) are present in distant objects by simply looking at the spectrum of light from those objects. If the spectral lines of hydrogen, helium, carbon, oxygen, or any other element are visible in

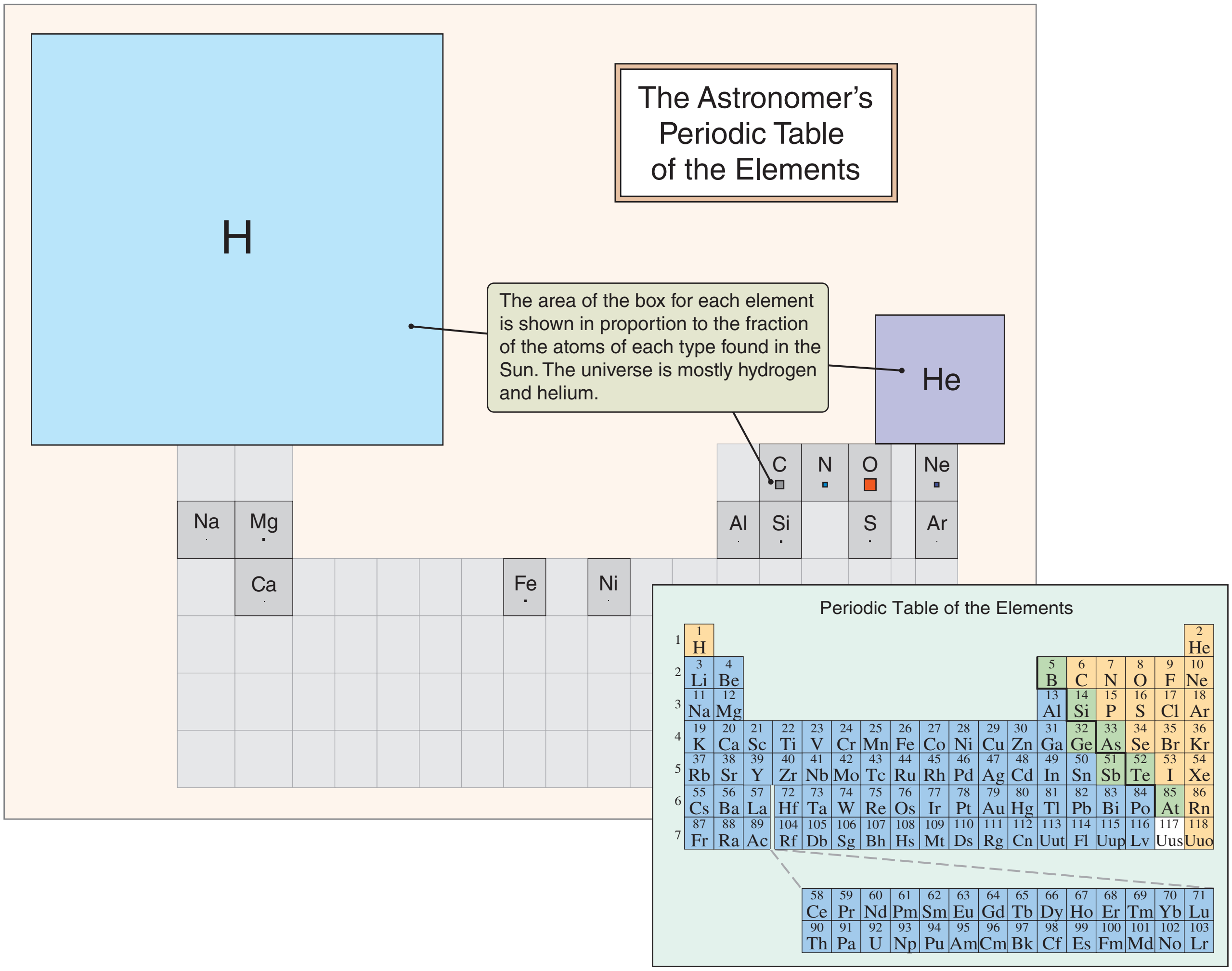


Figure 5.16 The traditional periodic table of the elements (lower right) shows the chemical elements laid out in ascending order according to the number of protons in the nucleus of each. But the "astronomer's periodic table" displays the abundances of the Sun's elements in boxes of relative size, showing hydrogen and helium as the most abundant. See Appendix 3 for a full periodic table of the elements.

the light from a distant object, then we know that element is present in that object. The strength of a line is determined in part by how many atoms of that type are present in the source. By measuring the strength of the lines from different types of atoms in the spectrum of a distant object, astronomers can often infer the relative amounts of elements that make up the object. Additionally, by looking at the relative strength of different lines from the same element, it is often possible to determine the temperature, density, and pressure of the material as well.

This is how we know what makes up the stars and planets, and that we on Earth are composed of the same elements. Astronomers use the relative abundance of the elements in the Sun as a standard reference, termed **solar abundance**. As illustrated in **Figure 5.16**, hydrogen (H) is the most abundant element in the Sun, followed by helium (He) and 13 others. These 15 elements make up 99.99 percent of the mass of the Sun. The majority of the elements on the regular periodic table (in the lower right) make up less than 0.01 percent of the mass of the Sun.

Excitement and Decay

Return to the analogy between the emission of a photon and a book falling off a shelf. If a book on a level shelf is not disturbed, it will sit there forever; something must *cause* the book to fall off the shelf. Similarly, physicists have wondered what causes an atom in an excited state to jump down to a lower energy state and emit a photon. Sometimes an atom in a higher energy state can be "stimulated" into emitting a photon—but under most circumstances nothing causes the atom to jump to the lower energy state. Instead, the atom decays *spontaneously*. While scientists can determine on average how long the atom is likely to remain in the excited state, exactly when a given atom will decay cannot be known until after the decay has happened. An atom decays at a random moment that is not influenced by anything in the universe and cannot be known ahead of time.

An example of this phenomenon is in toys that glow in the dark. Photons in sunlight or from a lightbulb are absorbed by certain phosphorescent atoms in the toy, knocking those atoms into excited energy states. The excited states of the atoms in the toy live for many seconds, unlike the excited energy states of many atoms that tend to decay in a small fraction of a second. If on average these atoms tend to remain in their excited state for 1 minute before decaying and emitting a photon, then after 1 minute there is a 50-50 chance that any particular atom in the toy will have decayed and a 50-50 chance that the atom will remain in its excited state. Although it is impossible to say exactly which atoms will decay, about half of the trillions and trillions of atoms in the toy will decay within 1 minute, and the brightness of the glow from the toy will have dropped to half of what it was. After each minute, half of the remaining excited atoms decay, and the glow from the toy drops to half of what it was 1 minute earlier. The glow from the toy slowly fades away.

In deep space, where atoms can remain undisturbed for long periods of time, there are certain excited states of atoms that last, on average, for tens of millions of years or even longer. An atom may have been in such an excited energy state for a few seconds, a few hours, or 50 million years when, in an instant, it decays to the lower energy state without anything causing it to do so. Physicists can only calculate the *probabilities* that certain events would take place.

CHECK YOUR UNDERSTANDING 5.3

How can spectra tell us the chemical composition of a distant star?

5.3 The Doppler Shift Indicates Motion Toward or Away from Us

You have already seen that light is a tightly packed bundle of information that can reveal a wealth of information about the physical state of material located tremendous distances away. In this section, we shall see how light can be used to measure one of the most straightforward questions about a distant astronomical object: is it moving away from us or toward us, and at what speed?

Astronomy in Action: Doppler Shift

Have you ever listened to an ambulance speed by with sirens blaring? As the ambulance comes toward you, its siren has a certain high pitch, but as it passes by, the pitch of the siren drops noticeably. If you close your eyes and listen, you have no trouble knowing when the ambulance passed; the change in the pitch of its siren indicates that it has passed you by. You do not even need an ambulance to hear this effect. The sound of normal traffic behaves in the same way. As a car drives past, the pitch of the sound that it makes suddenly drops.

AstroTour: The Doppler Effect

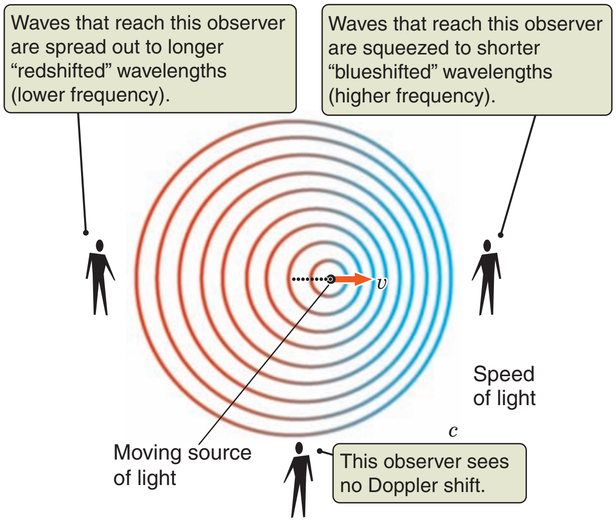


Figure 5.17 Motion of a light or sound source relative to an observer may cause waves to be spread out (*redshifted*, or lower in pitch) or squeezed together (*blueshifted*, or higher in pitch). A change in the wavelength of light or the frequency of sound is called a *Doppler shift*.

Nebraska Simulation: Doppler Shift Demonstrator

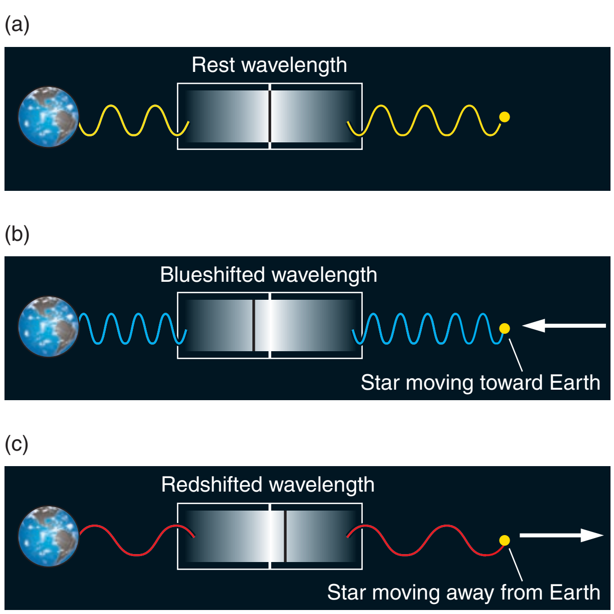


Figure 5.18 From their rest wavelength (a), spectral lines of astronomical objects are blueshifted if they are moving toward the observer (b) and redshifted if they are moving away from the observer (c).

The pitch of a sound is like the color of light: it is determined by the wavelength or, equivalently, the frequency of the sound wave. What you perceive as higher pitch corresponds to sound waves with higher frequencies and shorter wavelengths. Sounds that you perceive as lower in pitch are waves with lower frequencies and longer wavelengths. When an object is moving toward you, the waves that it emits, whether light or sound or waves in the water, "crowd together" in front of the object. You can see how this works by looking at **Figure 5.17**, which shows the locations of successive wave crests emitted by a moving object. The waves that reach you have a shorter wavelength and therefore a higher frequency than the waves given off by the object when it is not moving. Conversely, if an object is moving away from you, the waves reaching you from the object are spread out. This change in frequency due to motion is known as the **Doppler effect**, named after physicist Christian Doppler (1803–1853).

The Doppler effect causes a shift in the light emitted from a moving object. If the object were at rest, it would emit light with the **rest wavelength** (λ_{rest}), as shown in **Figure 5.18a**. If an object such as a star is moving toward you, the light reaching you from the object has a shorter wavelength than its rest wavelength—so we say the light is "bluer" than the rest wavelength, and the light is described as **blueshifted**, as shown by the blue wave in Figure 5.18b. In contrast, light from a source that is moving away from you is shifted to longer wavelengths. The light that you see is "redder" than if the source were not moving away from you, and is described as **redshifted**, as shown by the red waves in Figure 5.18c. The faster the object is moving with respect to you, the larger the shift. The amount by which the wavelength of light is shifted by the Doppler effect is called the **Doppler shift** of the light, and it depends on the speed of the object emitting the light.

The Doppler shift provides information only about the **radial velocity** (v_r) of the object, which is the part of the motion that is toward you or away from you. The radial velocity is the rate at which the distance between you and the object is changing: if v_r is positive, the object is getting farther away from you; if v_r is negative, the object is getting closer. At the moment the ambulance is passing you, it is getting neither closer nor farther away, so the pitch you hear is the same as the pitch heard by the crew riding on the truck. Similarly, an object moving across the sky does not move toward or away from you, and so its light will not be Doppler shifted from your point of view.

Doppler shifts become especially useful when you are looking at an object that has emission or absorption lines in its spectrum. These spectral lines enable astronomers to determine how rapidly the object is moving toward or away from Earth. To determine this velocity, astronomers first identify the spectral line as being from a certain chemical element, which has a unique rest wavelength (λ_{rest}) measured in a lab on Earth. They then measure the observed wavelength (λ_{obs}) in the spectrum of the distant object. The difference between the rest wavelength and the observed wavelength indicates the object's radial velocity. This is further explored in **Working It Out 5.2**.

CHECK YOUR UNDERSTANDING 5.4

Which of the following Doppler shifts indicates the fastest approaching object (blueshifted)? (a) 0.04 nm; (b) 0.06 nm; (c) −0.04 nm; (d) −0.06 nm

5.2 Working It Out Making Use of the Doppler Effect

The Doppler formula for objects moving at a radial velocity (v_r) that is much less than the speed of light is given by

$$v_r = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} \times c$$

A prominent spectral line of hydrogen atoms has a rest wavelength, λ_{rest}, of 656.3 nm (see Figure 5.15b). Suppose that you measure the wavelength of this line in the spectrum of a distant object and find that instead of seeing the line at 656.3 nm, you see the line at a wavelength, λ_{obs}, of 659.0 nm. How fast is its radial velocity? Using the above equation,

$$v_r = \frac{659.0\,\text{nm} - 656.3\,\text{nm}}{656.3\,\text{nm}} \times (3 \times 10^5\,\text{km/s})$$

$$v_r = 1{,}200\,\text{km/s}$$

In this way, you determine that the object is moving away from you with a radial velocity of 1,200 km/s.

For another example, suppose you know the velocity and want to compute the wavelength at which you would observe the spectral line? Earth's nearest stellar neighbor, Proxima Centauri, is moving toward us at a radial velocity of −21.6 km/s. What is the observed wavelength, λ_{obs}, of a magnesium line in Proxima Centauri's spectrum that has a rest wavelength, λ_{rest}, of 517.27 nm? We can rearrange the above equation to solve for λ_{obs}:

$$\lambda_{obs} = \left(1 + \frac{v_r}{c}\right) \times \lambda_{rest}$$

$$\lambda_{obs} = \left(1 + \frac{-21.6\,\text{km/s}}{3 \times 10^5\,\text{km/s}}\right) \times 517.27\,\text{nm} = 517.23\,\text{nm}$$

Although the observed Doppler blueshift ($\lambda_{obs} - \lambda_{rest} = 517.23 - 517.27$) is only −0.04 nm, it is easily measured with modern instrumentation.

5.4 Temperature Affects the Spectrum of Light That an Object Emits

The temperature of any object results from the balance between heating and cooling in an object. If an object's temperature is constant, then these two must be in balance with each other. In this section, we will examine this balance and see how we can use it to predict the temperatures of planets and stars.

Equilibrium and Balance

Your body is heated by the release of chemical energy inside it. Sometimes your body is also heated by energy from your surroundings. If you are standing in sunshine on a hot day, the hot air around you and the sunlight falling on you both heat you. In response to this heating, your body cools itself off by perspiration: water seeps from the pores in your skin and evaporates. The energy to evaporate the water comes from your body. As the perspiration evaporates, it cools your body down. For your body temperature to remain stable, the heating must be balanced by the cooling. If there is more heating than cooling, then your body temperature climbs. If there is more cooling than heating, then your body temperature drops.

Imagine two well-matched teams struggling in a tug-of-war contest. Each team pulls steadfastly on the rope, but the force of one team's pull is only enough to match, not overcome, the force exerted by the other team. A picture taken now and another taken 5 minutes from now would not differ in any significant way. In this static equilibrium, opposing forces balance each other exactly.

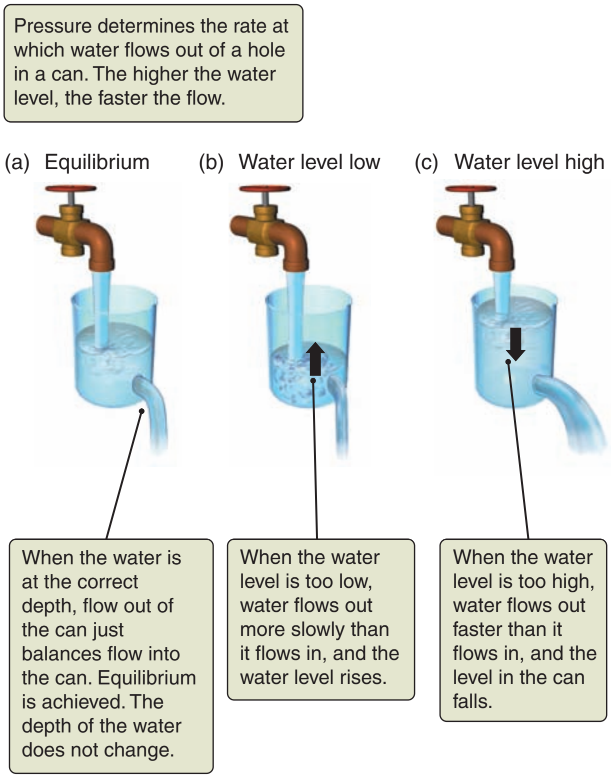


Figure 5.19 Water flowing into and out of a can determines the water level in the can. This is an example of dynamic equilibrium.

Astronomy in Action: Changing Equilibrium

Static equilibrium can be stable, unstable, or neutral. A nut in a bowl is in a stable equilibrium: if it moves it will return to its original position at the bottom of the bowl. An example of an unstable equilibrium would be a book standing on its edge, unsupported on either side. If you nudged the book, it would fall over rather than settling back into its original position. When an unstable equilibrium is disturbed, it moves further away from equilibrium rather than back toward it.

Equilibrium can also be dynamic, which means the system is constantly changing so that one source of change is exactly balanced by another source of change, and the configuration of the system remains the same. Examine the demonstration illustrated in **Figure 5.19**. Placing a can with a hole cut in the bottom under an open water faucet provides a simple example of dynamic equilibrium. The depth of the water in the can determines how fast water pours out through the hole in the bottom of the can. When the water reaches just the right depth, as shown in Figure 5.19a, water pours out of the hole in the bottom of the can at exactly the same rate it pours into the top of the can from the faucet. The water leaving the can balances the water entering, and equilibrium is established. If you took a picture now and another picture in a few minutes, little of the water in the can would be the same, but the pictures would be indistinguishable.

If a system is not in equilibrium, its configuration will change. If the level of the water in the can is too low, as shown in Figure 5.19b, water will not flow out of the bottom of the can fast enough to balance the water flowing in. The water level will begin to rise until the amount coming in equals the amount going out. A picture taken now and another taken a short time later would not look the same. Conversely, if the water level in the can is too high (Figure 5.19c), water will flow out of the can faster than it flows into the can. The water level will begin to fall until the amount coming in equals the amount going out. Once again, if the system is not in equilibrium, its configuration will change.

When heating is balanced by cooling, we call it **thermal equilibrium**. Planets have a dynamic but stable thermal equilibrium, and electromagnetic radiation plays a crucial role in maintaining this. Energy from sunlight heats the surface of a planet, driving its temperature up, and the planet emits thermal radiation into space, cooling it down. For a planet to remain at the same average temperature over time, the energy it radiates into space must exactly balance the energy it absorbs from the Sun. **Figure 5.20** illustrates that the equilibrium temperature of a planet is analogous to the water level in Figure 5.19. We will return to planetary equilibrium later in the chapter. There are many kinds of equilibrium besides thermal equilibrium, some of which we will encounter later in the book.

Temperature

In everyday life, we define hot and cold subjectively: something is hot when it feels hot or cold. When we measure *temperature*, we use degrees on a thermometer, but the way we define a degree is arbitrary. If you grew up in the United States, you probably think of temperatures in degrees Fahrenheit (°F), whereas if you grew up almost anywhere else in the world, you think of temperatures in degrees Celsius (°C).

Temperature is a measurement of how energetically the atoms that make up an object are moving about. The air around us is composed of vast numbers of atoms and molecules. Those molecules are moving about every which way. Some move slowly; some move more rapidly. All atoms and molecules are constantly in motion. The average kinetic energy (E_K) is given by $E_K = \frac{1}{2}mv^2$, where m is the mass of an atom or molecule and v is its velocity. The more energetically the atoms or molecules are bouncing about, the higher is the object's temperature. In fact, the random motions of atoms and molecules are often called their **thermal motions**, to emphasize the connection between these motions and temperature. **Figure 5.21** illustrates that when the temperature of a gas is increased, the kinetic energy is increased, and therefore the atoms move faster.

The atoms and molecules in a solid body (like you) cannot move about feely but still move back and forth around their normal location, and temperature measures the amount of that movement. If something is hotter than you are, thermal energy flows from that object into you. At the atomic level, that means the object's atoms are bouncing more energetically than are the atoms in your body, so if you touch the object, its atoms collide with your atoms, causing the atoms in your body to move faster. Your body gets hotter as thermal energy flows from the object to you. At the same time, these collisions rob the particles in the object of some of their energy. Their motions slow down, and the hotter object cools. Heating processes increase the average thermal energy of an object's particles, and cooling processes decrease the average thermal energy of those particles.

On the Fahrenheit scale, there are 180 degrees between the freezing point (32°F) and the boiling point (212°F) of water at sea level. On the Celsius scale, water freezes at 0°C and boils at 100°C. Because there is a different number of degrees between freezing and boiling on these two scales, a 1-degree change measured in Fahrenheit is not the same as a 1-degree change measured in Celsius.

There is a lowest possible physical temperature below which no object can fall. As the motions of the particles in an object slow down, the temperature drops lower and lower. The lowest possible temperature, where thermal motions have nearly come to a standstill, is called **absolute zero**. Absolute zero corresponds to −273.15°C, or −459.57°F. Scientists found it useful to define a temperature scale that begins at absolute zero, called the **Kelvin scale**. The size of one unit on the Kelvin scale, called a **kelvin (K)**, is the same as the Celsius degree. Zero kelvin (0 K) is set equal to absolute zero. Other temperatures are equal to Celsius plus 273.15, so water freezes at 273.15 K and water boils at 373.15 K. There are no negative temperatures on the Kelvin scale.

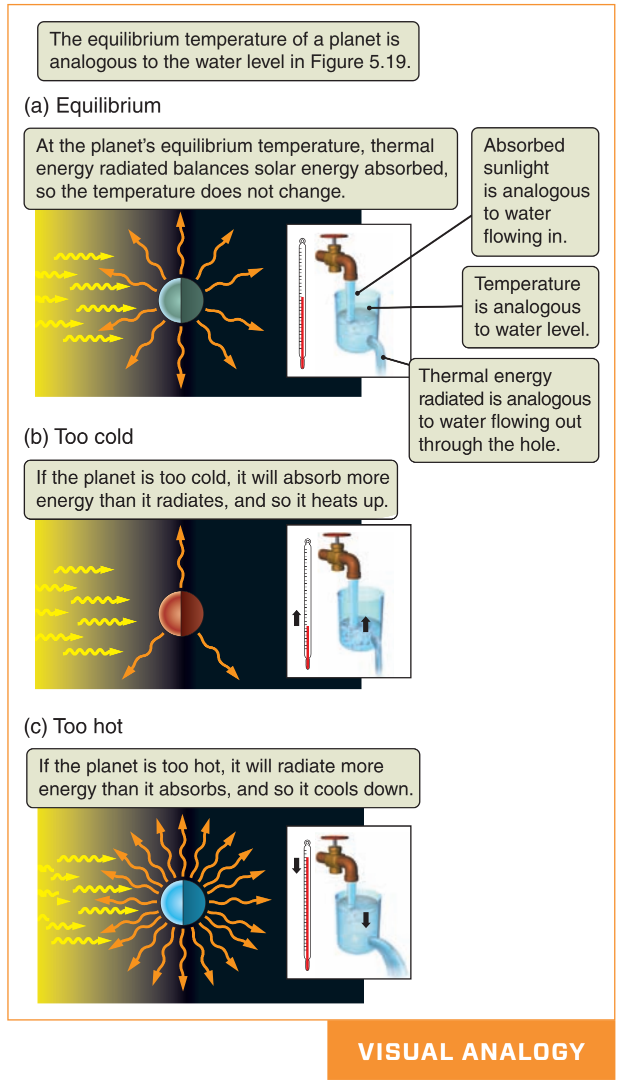


Figure 5.20 Planets are heated by absorbing sunlight (and sometimes by internal heat sources) and cooled by emitting thermal radiation into space. If there are no other sources of heating or means of cooling, then the equilibrium between these two processes determines the temperature of the planet.

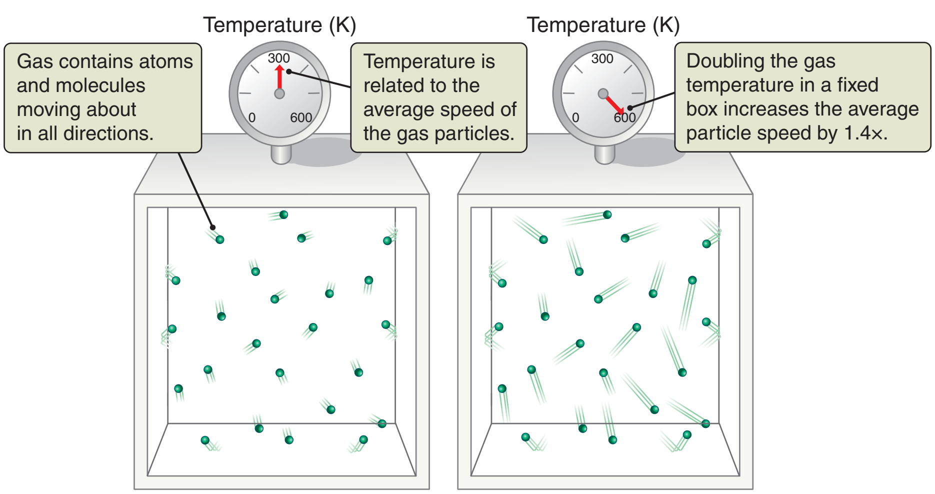


Figure 5.21 Hotter gas temperatures correspond to faster motions of atoms.