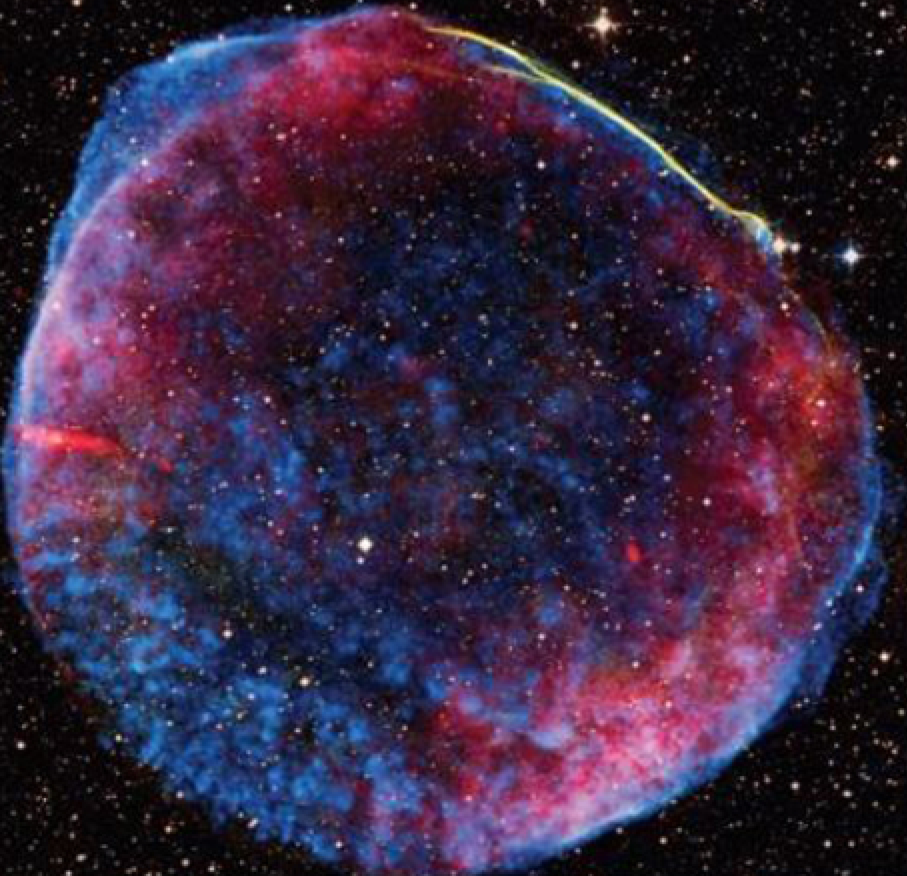
KAY PALEN SMITH BLUMENTHAL



21ST CENTURY ASTRONOMY

FOURTH EDITION

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21st CENTURY ASTRONOMY

FOURTH EDITION

Laura Kay, Stacy Palen, Brad Smith, and George Blumenthal

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ASTRONOMY

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21ST CENTURY ASTRONOMY

LAURA KAY • Barnard College

STACY PALEN • Weber State University

BRAD SMITH • Santa Fe, New Mexico

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NEW YORK • LONDON

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Laura Kay thanks her partner, 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.

Stacy Palen thanks the wonderful colleagues in her department and the crowd at Bellwether Farm, all of whom made room for this project in their lives, even though it wasn't their project.

Brad Smith dedicates this book to his patient and understanding wife, Diane McGregor.

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 III Stars and Stellar Evolution

Part IV Galaxies, the Universe, and Cosmology

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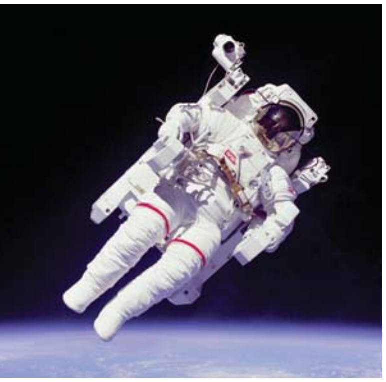

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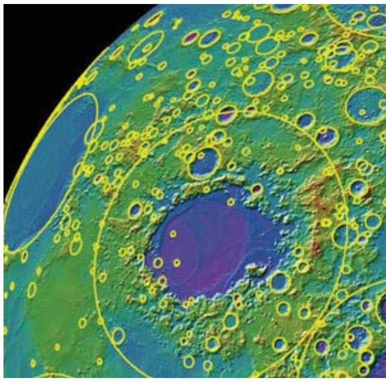

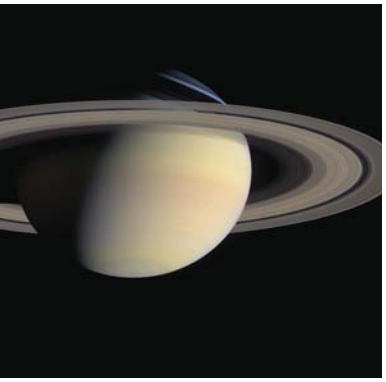

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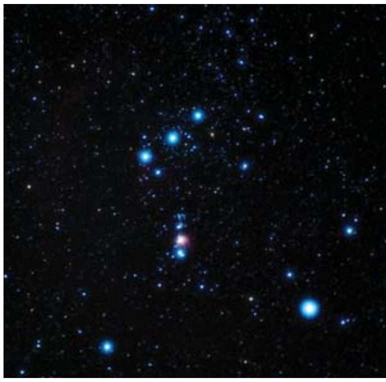

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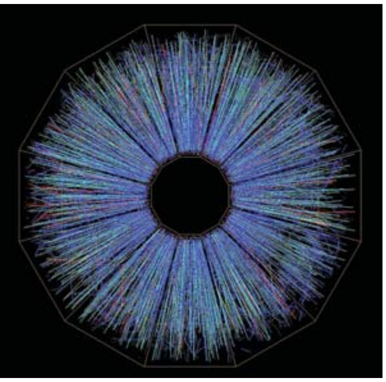

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Math Tools

Connections

AstroTours

AstroTour animations are available from the free StudySpace student website, and they are also integrated into assignable SmartWork exercises. Offline versions of the animations for classroom presentation are available from the Instructor's Resource disc.

Nebraska Simulations

Preface

This introductory astronomy course could be the only science course a student will take in college. As we wrote this book, we considered basic questions such as these: What will students remember 5 years from now about astronomy and about how science works? How should this course change the students who take it? And how can we, as scientists and educators, facilitate those changes within our students?

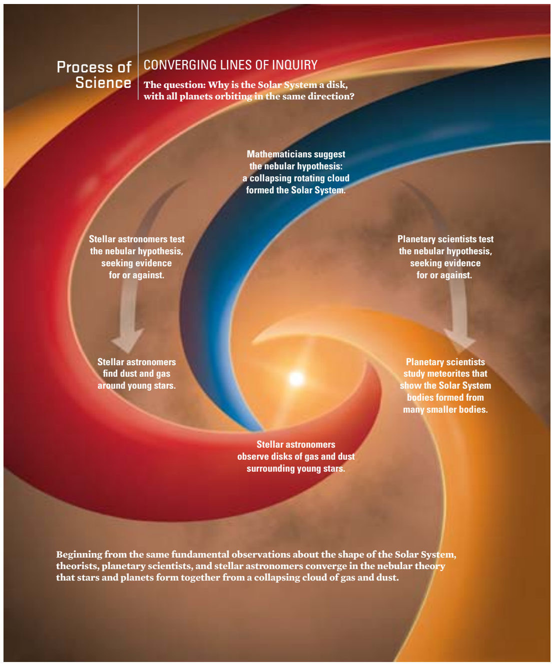
We believe an introductory astronomy course should help students learn to ask questions, make observations, identify patterns and relationships that go beyond the specifics of a particular object or setting, and apply those patterns and relationships broadly. We want students to challenge and test what they learn. This is what it means to think like a scientist.

We wrote this textbook and built its supporting ancillary package with one goal in mind: to help students understand the world through the eyes of a scientist.

In order to meet that goal, we have tried to tell a story in each chapter and have worked hard to link chapters using a few common threads. The process of science is one of those threads. Helping a student understand a concept as a scientist means guiding that student through the concept, making heavy use of examples and analogies, and tying the concept back to everyday phenomena and experiences that the student can relate to.

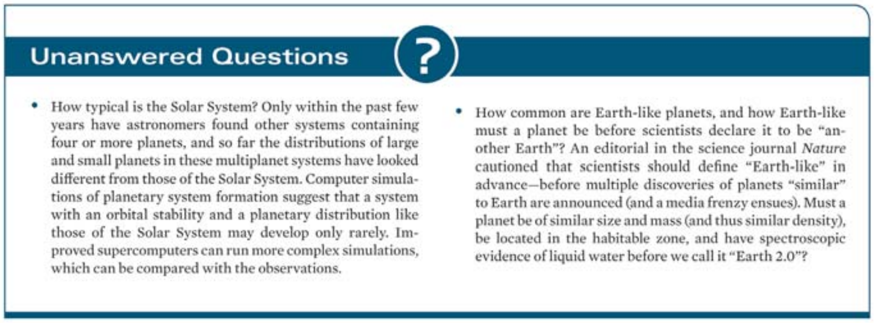
The process of science is in the fabric of the text and incorporates the recurring themes of the physics of matter, energy, radiation, and motion. Why did Newton choose the form that he did for his universal law of gravitation? What are the fundamental differences between Kepler's empirical "laws" and Newton's theoretical derivation of the same relationships? And if Einstein was "right," why wasn't Newton "wrong"? In the Fourth Edition, we have emphasized the process of science in several additional ways: new Process of Science Figures, Unanswered Questions boxes, and expanded Origins sections.

- In each chapter we have chosen one discovery and provided a visual representation of the process used to make that discovery in one of the new **Process of Science** figures. Because science is not a tidy process,



we try to illustrate that discoveries are sometimes made by disparate 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. One example is Chapter 7, where we show how three groups of scientists were all working on the question "Why is the Solar System a disk?" and came to the same conclusion independently.

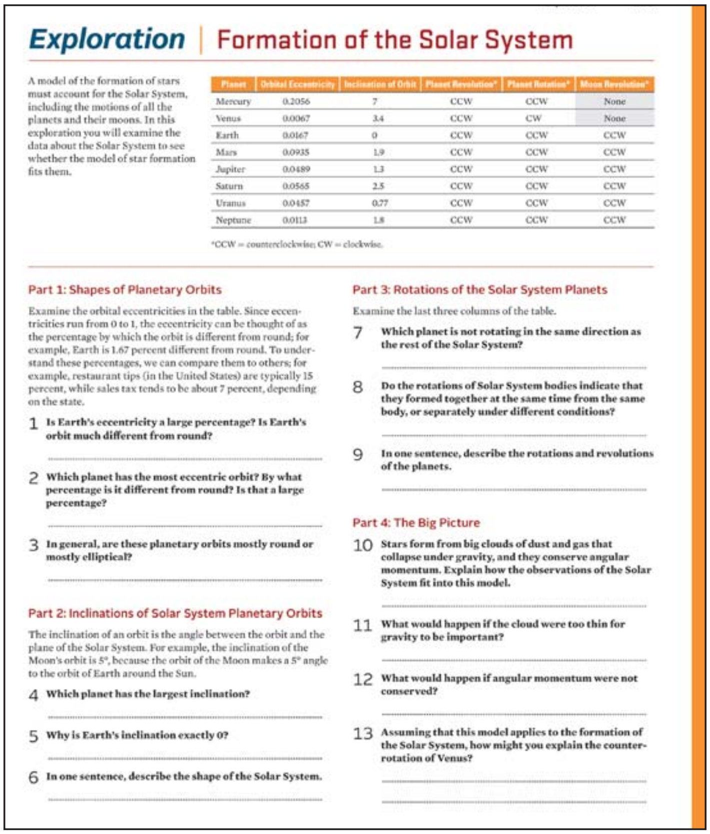
- At the end of every chapter, an **Unanswered Questions** box poses questions like "How typical is the Solar System?" and "How common are Earth-like planets?" to show that we don't have all the answers and that science is an ongoing process.



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 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.
- How common are Earth-like planets, and 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 (and thus similar density), be located in the habitable zone, and have spectroscopic evidence of liquid water before we call it "Earth 2.0"?

A second major thread, **Origins**, shows how astronomers relate the topic of each chapter to the study of the origin of the universe or the origin of life. Since no life outside of Earth has been detected, these sections often illustrate how astrobiologists and other scientists approach the study of a scientific question, using the process of science rather than providing actual answers or results.



Exploration | Formation of the Solar System

A model of the formation of stars must account for the Solar System, including the motions of all the planets and their moons. In this exploration you will examine the data about the Solar System to see whether the model of star formation fits them.

Planet	Orbital Eccentricity	Inclination of Orbit	Planet Revolution*	Planet Rotation*	Moon Revolution*
Mercury	0.2056	7	CCW	CCW	None
Venus	0.0067	3.4	CCW	CW	None
Earth	0.0167	0	CCW	CCW	CCW
Mars	0.0935	1.9	CCW	CCW	CCW
Jupiter	0.0489	1.3	CCW	CCW	CCW
Saturn	0.0565	2.5	CCW	CCW	CCW
Uranus	0.0457	0.77	CCW	CCW	CCW
Neptune	0.0113	1.8	CCW	CCW	CCW

*CCW = counterclockwise; CW = clockwise.

Part 1: Shapes of Planetary Orbits

Examine the orbital eccentricities in the table. Since eccentricities run from 0 to 1, the eccentricity can be thought of as the percentage by which the orbit is different from round; for example, Earth is 1.67 percent different from round. To understand these percentages, we can compare them to others; for example, restaurant tips (in the United States) are typically 15 percent, while sales tax tends to be about 7 percent, depending on the state.

1 **Is Earth's eccentricity a large percentage? Is Earth's orbit much different from round?**

2 **Which planet has the most eccentric orbit? By what percentage is it different from round? Is that a large percentage?**

3 **In general, are these planetary orbits mostly round or mostly elliptical?**

Part 2: Inclinations of Solar System Planetary Orbits

The inclination of an orbit is the angle between the orbit and the plane of the Solar System. For example, the inclination of the Moon's orbit is 5°, because the orbit of the Moon makes a 5° angle to the orbit of Earth around the Sun.

4 **Which planet has the largest inclination?**

5 **Why is Earth's inclination exactly 0?**

6 **In one sentence, describe the shape of the Solar System.**

Part 3: Rotations of the Solar System Planets

Examine the last three columns of the table.

7 **Which planet is not rotating in the same direction as the rest of the Solar System?**

8 **Do the rotations of Solar System bodies indicate that they formed together at the same time from the same body, or separately under different conditions?**

9 **In one sentence, describe the rotations and revolutions of the planets.**

Part 4: The Big Picture

10 **Stars form from big clouds of dust and gas that collapse under gravity, and they conserve angular momentum. Explain how the observations of the Solar System fit into this model.**

11 **What would happen if the cloud were too thin for gravity to be important?**

12 **What would happen if angular momentum were not conserved?**

13 **Assuming that this model applies to the formation of the Solar System, how might you explain the counter-rotation of Venus?**

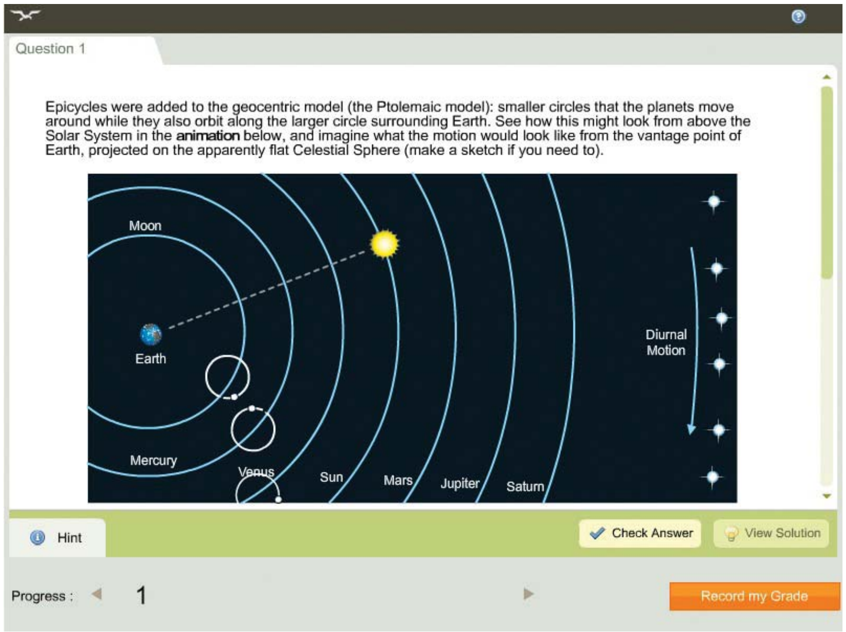
In addition to helping students think like a scientist, we have provided a few opportunities for them to actually do science. We have added **Using the Web** questions at the end of each chapter. Some of these send students to websites of space missions, observatories, experiments, or archives to access recent observations, results, or press releases. Other websites are for "citizen science" projects (for example, Zooniverse), in which students can contribute to the analysis of new data. These web problems can be used for homework, lab exercises, recitations, "news" exercises, or "writing across the curriculum" projects. (Updated Web addresses are posted on StudySpace as needed).

Explorations, also new to the Fourth Edition, are either pencil-and-paper activities or media-based activities that ask students to use Nebraska Simulations or Norton's AstroTours to work through a series of guided questions and apply the concepts they learned in the chapter.

To assess student understanding, versions of the end-of-chapter Explorations, as well as Process of Science Guided Inquiry assignments, based on the Process of Science figures, are available in Norton's online homework and tutorial system, **SmartWork**.

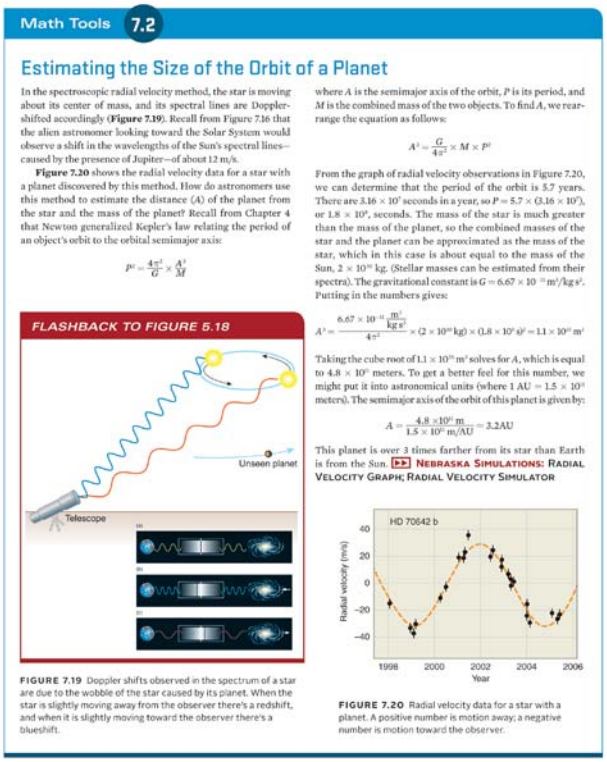
Although mathematics is the language of science, we understand that the amount of math used differs from school to school and instructor to instructor. In order to make the text more accessible to a wider variety of students, the math has been moved out of the main text into **Math Tools** boxes. Each box provides a succinct quantitative explanation of the concept being discussed and can be skipped without losing any qualitative understanding.

We have made some organizational changes to the Fourth Edition. Discussion of basic physics is now 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.



Epicycles were added to the geocentric model (the Ptolemaic model): smaller circles that the planets move around while they also orbit along the larger circle surrounding Earth. See how this might look from above the Solar System in the **animation** below, and imagine what the motion would look like from the vantage point of Earth, projected on the apparently flat Celestial Sphere (make a sketch if you need to).

We start Parts II, III, and IV with the big picture before diving into the smaller details that make up that picture. We cover the development of planetary systems in general before discussing our own Solar System , and the basic properties of stars before the Sun. Part IV begins with the historical discovery of extragalactic objects and Hubble's law, which led to the Big Bang theory. At this point in the school year, we find that student interest is greatly renewed by the introduction of Hubble Deep Field images and the concept of the expanding universe. The next chapter continues with the basics of galaxies, including active galactic nuclei. Then, when the Milky Way is discussed in the following chapter, students have the background for understanding the exciting observational data about the Milky Way's central black hole.



Math Tools 7.2

Estimating the Size of the Orbit of a Planet

In the spectroscopic radial velocity method, the star is moving about its center of mass, and its spectral lines are Doppler-shifted accordingly (**Figure 7.19**). Recall from Figure 7.16 that the alien astronomer looking toward the Solar System would observe a shift in the wavelengths of the Sun's spectral lines—caused by the presence of Jupiter—of about 12 m/s.

Figure 7.20 shows the radial velocity data for a star with a planet discovered by this method. How do astronomers use this method to estimate the distance (A) of the planet from the star and the mass of the planet? Recall from Chapter 4 that Newton generalized Kepler's law relating the period of an object's orbit to the orbital semimajor axis:

$$P^2 = \frac{4\pi^2}{G} \times \frac{A^3}{M}$$

where A is the semimajor axis of the orbit, P is its period, and M is the combined mass of the two objects. To find A, we rearrange the equation as follows:

$$A^3 = \frac{G}{4\pi^2} \times M \times P^2$$

From the graph of radial velocity observations in Figure 7.20, we can determine that the period of the orbit is 5.7 years. There are 3.16×10^7 seconds in a year, so $P = 5.7 \times (3.16 \times 10^7)$, or 1.8×10^8, seconds. The mass of the star is much greater than the mass of the planet, so the combined masses of the star and the planet can be approximated as the mass of the star, which in this case is about equal to the mass of the Sun, 2×10^{30} kg. (Stellar masses can be estimated from their spectra). The gravitational constant is $G = 6.67 \times 10^{-11}$ m^3/kg s^2. Putting in the numbers gives:

$$A^3 = \frac{6.67 \times 10^{-11} \frac{\text{m}^3}{\text{kg s}^2}}{4\pi^2} \times (2 \times 10^{30}\ \text{kg}) \times (1.8 \times 10^8\ \text{s})^2 = 1.1 \times 10^{34}\ \text{m}^3$$

Taking the cube root of 1.1×10^{34} m^3 solves for A, which is equal to 4.8×10^{11} meters. To get a better feel for this number, we might put it into astronomical units (where 1 AU = 1.5×10^{11} meters). The semimajor axis of the orbit of this planet is given by:

$$A = \frac{4.8 \times 10^{11}\ \text{m}}{1.5 \times 10^{11}\ \text{m/AU}} = 3.2\text{AU}$$

This planet is over 3 times farther from its star than Earth is from the Sun. ⏩ **NEBRASKA SIMULATIONS: RADIAL VELOCITY GRAPH; RADIAL VELOCITY SIMULATOR**

FIGURE 7.19 Doppler shifts observed in the spectrum of a star are due to the wobble of the star caused by its planet. When the star is slightly moving away from the observer there's a redshift, and when it is slightly moving toward the observer there's a blueshift.

FIGURE 7.20 Radial velocity data for a star with a planet. A positive number is motion away; a negative number is motion toward the observer.

In this edition we made pedagogical upgrades, as well as numerous updates and revisions throughout the book to reflect contemporary research and scientific thought. Some of those changes include:

- Updating each chapter's Learning Goals and correlating them with the end-of-chapter Summary, to help students review what is most important in each chapter.
- Expanding discussions of Copernicus, Tycho Brahe, and Galileo in Chapter 3, "Motions of Astronomical Bodies." The chapter now ends with Newton's laws of motion.
- Revising Chapter 4, "Gravity and Orbits," to include all of gravity, including tides.
- Thoroughly updating Part II with the latest information about the Solar System. We added material in Chapter 9 to cover climate change on the terrestrial planets, and how planetary science aids in the study of global climate change on Earth.
- Adding a new chapter, "Relativity and Black Holes" (Chapter 18), which separates out this material and expands some examples in Math Tools.

- Revising Chapter 22 to include the latest ideas about the accelerating universe.
- In Chapter 23, adding material on the first stars, first galaxies, and the recent observations of very high-redshift objects.
- Adding new Origins sections that reflect current thinking in astrobiology or cosmology.
- Significantly upgrading and expanding the types of problems at the end of each chapter, including new True/False and Multiple Choice questions, Applying the Concepts problems that use graphs from the chapter, and problems associated with the Math Tools boxes.

Learning Resources for Students

SmartWork

SmartWork Online Homework: smartwork.wwnorton.com

Steven Desch, *Guilford Technical Community College*
Violet Mager, *Susquehanna University*
David A. Wood, *San Antonio College*
Todd Young, *Wayne State College, Nebraska*

Over 1,500 questions support the Fourth Edition of *21st Century Astronomy*—all with answer-specific feedback, hints, and ebook links. Questions include Summary Self-Tests, Process of Science Guided Inquiry assignments (based on the concept discussed in the Process of Science figure in each chapter), and versions of the Explorations (based on AstroTours and the Nebraska Simulations). Interactive, image-based questions based on both book art and NASA images help instructors to assess students' conceptual understanding.

StudySpace

StudySpace: wwnorton.com/studyspace

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

- Study plans and outlines for each chapter.
- Twenty-eight AstroTour animations, which now include audio. These animations, some of which are interactive, use art from the text to help students visualize important physical and astronomical concepts.
- University of Nebraska Simulations (sometimes called applets; or NAAPs, for Nebraska Astronomy Applet Programs), organized to match the goals of the text. Nebraska Simulations enable students to manipulate variables and see how physical systems work.
- Quiz+ diagnostic multiple-choice quizzes, which provide students with feedback on any incorrect answers, also include links to the ebook, AstroTours, and Nebraska Simulations.
- Vocabulary flashcards.
- "Astronomy in the News" feed.
- Updated website addresses for the end-of-chapter problems.

Starry Night Planetarium Software (College Version) and Workbook

Steven Desch, *Guilford Technical Community College*
Donald Terndrup, *Ohio State University*

Starry Night is a realistic, user-friendly planetarium simulation program designed to allow students in urban areas to perform observational activities on a computer. 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. The workbook is fully integrated with *21st Century Astronomy*, Fourth Edition.

For Instructors

Instructor's Manual

Ana M. Larson, *University of Washington*
Gregory D. Mack, *Ohio Wesleyan University*
Ben Sugerman, *Goucher College*

Revised and expanded for the Fourth Edition, this is now the most complete and innovative Instructor's Manual available for introductory astronomy. This impressive resource contains suggested classroom demonstrations, class-tested classroom activities with handouts, and additional Explorations to help facilitate collaborative learning and conceptual understanding. It also contains brief chapter overviews and discussion points, notes on the AstroTour animations contained on the Norton Resource Disc and StudySpace, and worked solutions to all end-of-chapter problems.

Interactive Instructor's Guide

This online, searchable database places all of Norton's astronomy resources at instructors' fingertips. Included are the contents of the Instructor's Manual, the lecture PowerPoint slides with lecture notes, all art and tables in JPEG and PowerPoint formats, the AstroTour animations, and the Nebraska Simulations. With its search tools and export capability, the Interactive Instructor's Guide will help instructors search for exactly the resources they need by topic and resource type, and will alert subscribing instructors as new resources are made available.

Test Bank

Carol Hood, *California State University–San Bernardino*
Michael Hood, *Mt. San Antonio College*
Michael Lopresto, *Henry Ford Community College*
Tammy Smecker-Hane, *University of California–Irvine*
Donald Terndrup, *Ohio State University*

The Test Bank has been developed using the Norton Assessment Guidelines and provides a high-quality bank of over 2,000 items. Each chapter of the Test

Bank consists of three question types classified according to Norton's taxonomy of knowledge types:

1. Factual questions test students' basic understanding of facts and concepts.
2. Applied questions require students to apply knowledge in the solution of a problem.
3. Conceptual questions require students to engage in qualitative reasoning and to explain why things are as they are.

Questions are further classified by section and difficulty, making it easy to construct tests and quizzes that are meaningful and diagnostic. Each chapter contains short-answer, multiple-choice, and true/false questions.

PowerPoint Lecture Slides

Gregory D. Mack, *Ohio Wesleyan University*

These ready-made lecture slides integrate selected art from the text, "clicker" questions, and links to the AstroTour animations. Designed with accompanying lecture outlines, these lecture slides are fully editable and are available in Microsoft PowerPoint format.

Norton Instructor's Resource Site

This Web resource contains the following teaching aids 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 PowerPoint formats.
- Twenty-eight AstroTour animations. These animations, some of which are interactive, use art from the text to help students visualize important physical and astronomical concepts.
- Nebraska Simulations. These interactive simulations enable students to manipulate variables and see how physical systems work.
- Coursepacks, available in BlackBoard, Angel, Desire2Learn, and Moodle formats.

Coursepacks

Norton's Coursepacks, available for use in various Learning Management Systems (LMSs), feature all Quiz+ and Test Bank questions, along with links to the AstroTours and applets. Coursepacks are available in BlackBoard, Angel, Desire2Learn, and Moodle formats.

Instructor's Resource Folder

This two-disc set contains the Instructor's Resource DVD—which contains the same files as the Instructor's Resource website—and the Test Bank on CD-ROM in ExamView format.

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Laura Kay
Stacy Palen
Brad Smith
George Blumenthal

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Brad Smith is a retired professor of planetary science. He has served as an associate professor of astronomy at New Mexico State University, as a professor of planetary sciences and astronomy at the University of Arizona, and as a research astronomer at the University of Hawaii. Through his interest in Solar System astronomy, he participated as a team member or imaging team leader on several U.S. and international space missions, including Mars *Mariners 6*, *7*, and *9*; *Viking*; *Voyagers 1* and *2*; and the Soviet *Vega* and *Phobos* missions. He later turned his interest to extrasolar planetary systems, investigating circumstellar debris disks as a member of the Hubble Space Telescope NICMOS experiment team. Smith has four times been awarded the NASA Medal for Exceptional Scientific Achievement. He is a member of the IAU Working Group for Planetary System Nomenclature and is chair of the Task Group for Mars Nomenclature.

George Blumenthal is chancellor at the University of California–Santa Cruz, where he has been a professor of astronomy and astrophysics since 1972. Chancellor Blumenthal 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, Chancellor Blumenthal'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, Chancellor Blumenthal has served as the 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, has been both the chair and vice chair of the California Association for Research in Astronomy (which runs Keck Observatory), and has served as the faculty representative to the UC Board of Regents.

FOURTH EDITION

21ST CENTURY
ASTRONOMY

The Virgo cluster of galaxies at a distance of about 50 million light-years.

01

Why Learn Astronomy?

The most beautiful thing we can experience is the mysterious.
It is the source of all true art and all science.
He to whom this emotion is a stranger,
who can no longer pause to wonder and stand rapt in awe,
is as good as dead: his eyes are closed.

Albert Einstein (1879–1955)

LEARNING GOALS

We'll begin this chapter by sketching out a rough map of the universe and our place within it. Then we'll present some of the tools that you will need to take along as you look at the wonders of the universe through the eyes of a scientist. By the conclusion of this chapter, you should be able to:

- Identify our planet Earth's place in the universe.
- Explain the process of science.
- Describe the scientific approach to understanding our world and the universe.

1.1 Getting a Feel for the Neighborhood

The title of this book—*21st Century Astronomy*—emphasizes that this is the most fascinating time in history to be studying this most ancient of sciences. Loosely translated, the word **astronomy** means "patterns among the stars." But modern astronomy—the astronomy we will talk about in this book—has progressed beyond merely looking at the sky and cataloging what is visible there. Our intent is to provide reliable answers to many of the questions that you might have asked yourself as a child when you looked at the sky. What are the Sun and Moon made of? How far away are they? What are stars? How do they shine? Do they have anything to do with me?

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 beginnings, or *origins*. Who or what is responsible for our existence? How did the Sun, stars, and Earth form? The topic of scientific origins is a recurring theme in this book. The answers that scientists are finding to these questions are changing not only our view of the cosmos, but our view of ourselves.

Glimpsing Our Place in the Universe

Most people have a permanent address—building number, street, city, state, country. It is where the mail carrier delivers our postal mail. But let's expand our view for a moment. We also live somewhere within an enormously vast universe. What, then, is our "cosmic address"? It might look something like this: planet, star, galaxy, galaxy group, galaxy cluster.

We all reside on a planet called Earth, which is orbiting under the influence of gravity about a star called the Sun. The **Sun** is an ordinary, middle-aged star, more massive and luminous than some stars but less massive and luminous than others. The Sun is 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.

The Sun is located about halfway out from the center of a flattened collection of stars, gas, and dust referred to as the **Milky Way Galaxy**. Our Sun is just one among approximately 200–400 billion stars scattered throughout the galaxy, and many of these stars are themselves surrounded by planets, suggesting that other planetary systems may be common.

The Milky Way is a member of a collection of a few dozen galaxies called the **Local Group**. Looking farther outward, the Local Group is part of a vastly larger collection of thousands of galaxies—a **supercluster**—called the Virgo Supercluster.

We can now define our cosmic address—Earth, Solar System, Milky Way Galaxy, Local Group, Virgo Supercluster—as illustrated in **Figure 1.1**. Yet even this address is not complete, because the vast structure we just described is only the *local universe*. Astronomers use the term **light-year** to refer to the *distance* that light travels within one year, about 9.5 trillion kilometers (km) or 6 trillion miles. The part of the universe that we can see extends far beyond the local universe—13.7 billion light-years—and within this volume we estimate that there are *hundreds of billions* of galaxies, roughly as many galaxies as there are stars in the Milky Way. In addition, scientists have concluded that our universe contains much more than the observed planets, stars, and galaxies. Up to 95 percent of the universe is made up of matter that does not emit light (called *dark matter*) and a form of energy that permeates all of space (*dark energy*)—neither of which is well understood.

What is Earth's cosmic address?

The Scale of the Universe

One of the first conceptual hurdles that we face as we begin to think about the universe is its sheer size. If a hill is big, then a mountain is very big. If a mountain is very big, then Earth is enormous. But where do we go from there? We quickly run out of superlatives as the scale begins to dwarf our human experience. One technique that can help us develop a sense for the size of things in the universe is to discuss time as well as distance. If you are driving down the highway at 60 kilometers per hour (km/h), a kilometer is how far you travel in a minute. Sixty kilometers is how far you travel in an hour. Six hundred kilometers is how far you travel in 10 hours. So to get a feeling for the difference in size between 600 km and 1 km, you can think about the difference between 10 hours and a single minute.

The travel time of light helps us understand the scale of the universe.

We can think this same way about astronomy, but the speed of a car on the highway is far too slow to be useful. Instead we use the greatest speed in the universe—the speed of light. Light travels at 300,000 kilometers per second (km/s), circling Earth (a distance of 40,000 km) in

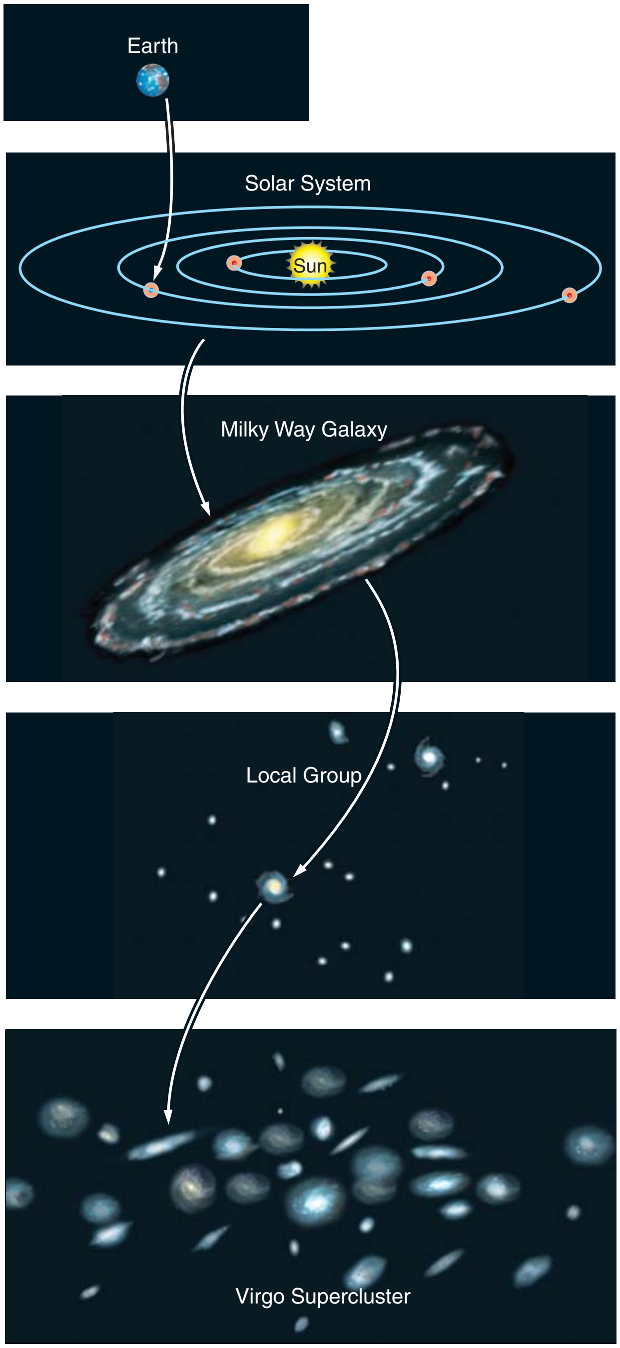


FIGURE 1.1 Our cosmic address is: Earth, Solar System, Milky Way Galaxy, Local Group, Virgo Supercluster. We live on Earth, a planet orbiting the Sun in our Solar System, which is a star in the Milky Way Galaxy. The Milky Way is a large galaxy within the Local Group of galaxies, which in turn is located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

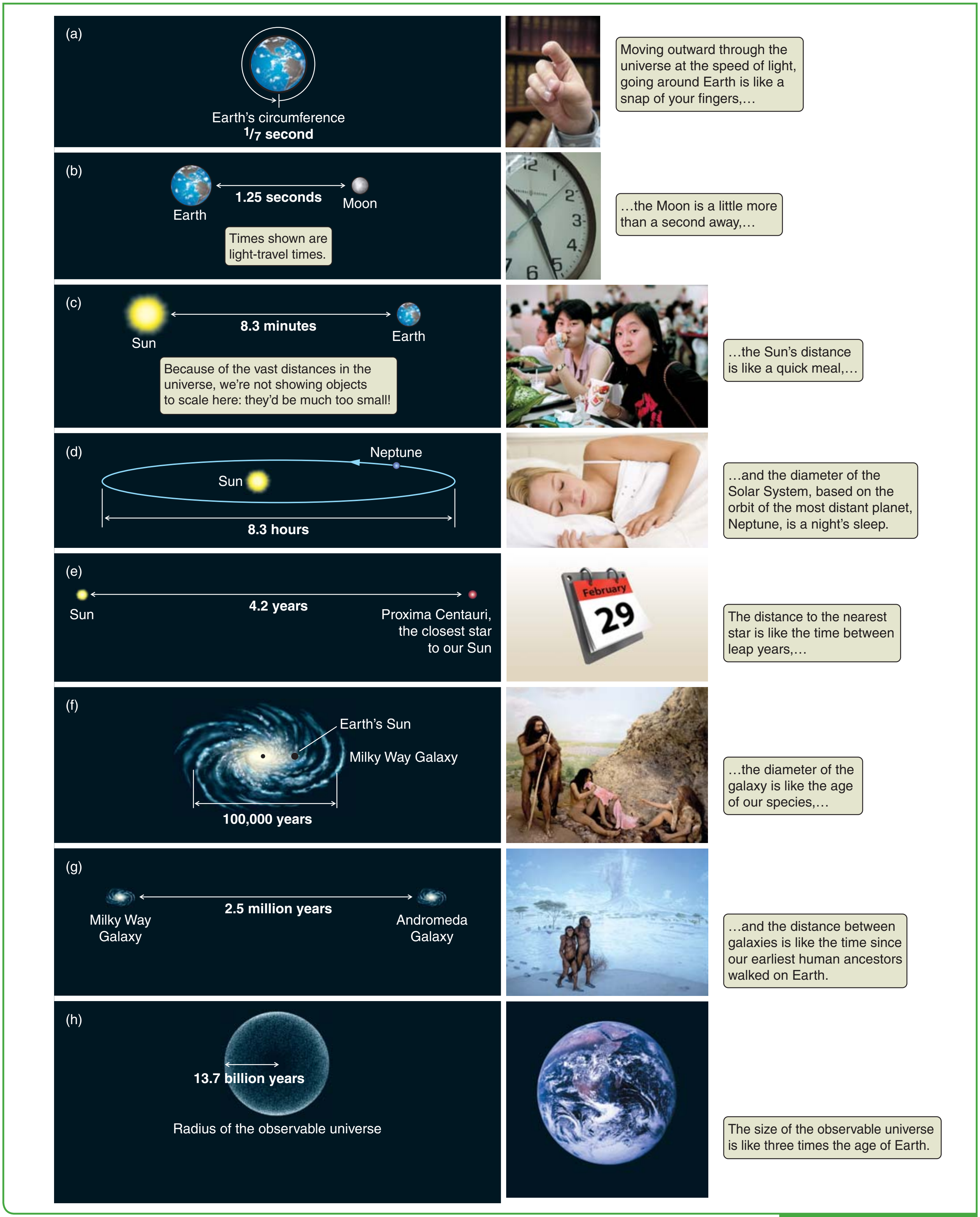
just under 1⁄7 of a second—about the time it takes you to snap your fingers. So we say that the circumference of Earth is 1⁄7 a light-second. Fix that comparison in your mind. The size of Earth is like a snap of your fingers.

Now follow along in **Figure 1.2** as we move outward into the universe. The first thing we encounter is the Moon, 384,000 km away, or a bit over 1¼ second when we're moving at the speed of light. If the size of Earth is a snap of your fingers, the distance to the Moon is about the time it takes to turn a page in this book. Continuing further, we find that at this speed the Sun is 8⅓ minutes away, or the duration of a hurried lunch at the student union. Crossing from one side of the orbit of Neptune, the outermost planet in our Solar System, to the other takes about 8.3 hours. Think about that for a minute. Comparing the size of Neptune's orbit to the circumference of Earth is like comparing the time of a good night's sleep to a single snap of your fingers.

In crossing Neptune's orbit, however, we have only just begun to consider the scale of the universe. Many steps remain. It takes a bit more than 4 years—the time between leap years—to cover the distance from Earth to the nearest star (other than the Sun). At this point, our analogy of using the travel time of light can no longer bring astronomical distance to a human scale. Light takes about 100,000 years to travel across our galaxy (the Milky Way). To reach the nearest large galaxies takes a few million years. To reach the limits of the currently observable universe takes 13.7 billion years—the age of the universe, or about 3 times the age of Earth. ▶▶ **NEBRASKA SIMULATION: LOOK BACK TIME SIMULATOR**

The Origin and Evolution of the Chemical Elements

While seeking knowledge about the universe and how it works, modern astronomy and physics have repeatedly come face-to-face with a number of age-old questions long thought to be solely within the domain of religion or philosophy. The nature of the chemical evolution of the universe is such a case. Theory and observation indicate that the universe was created in a "Big Bang" some 13.7 billion years ago. As a result of both observation and theoretical work, scientists now know that the only chemical elements found in substantial amounts in the early universe were the lightest elements: hydrogen and helium, plus tiny amounts of lithium, beryllium, and boron. Yet 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. Our bodies are built of carbon, nitrogen, oxygen, calcium, phosphorus, and a host of other chemical elements—again all heavier than hydrogen and



Times shown are light-travel times.

Because of the vast distances in the universe, we're not showing objects to scale here: they'd be much too small!

Moving outward through the universe at the speed of light, going around Earth is like a snap of your fingers,…

…the Moon is a little more than a second away,…

…the Sun's distance is like a quick meal,…

…and the diameter of the Solar System, based on the orbit of the most distant planet, Neptune, is a night's sleep.

The distance to the nearest star is like the time between leap years,…

…the diameter of the galaxy is like the age of our species,…

…and the distance between galaxies is like the time since our earliest human ancestors walked on Earth.

The size of the observable universe is like three times the age of Earth.

VISUAL ANALOGY

FIGURE 1.2 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.)

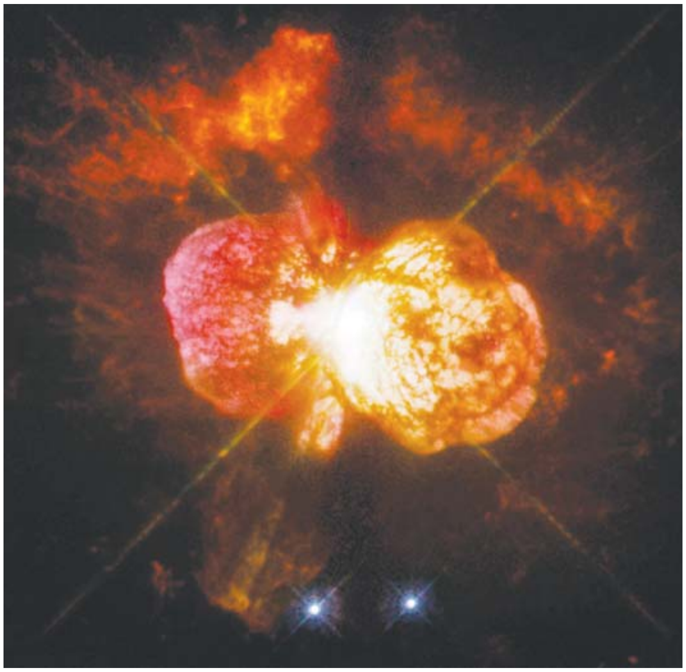


FIGURE 1.3 You and everything around you are composed of atoms forged in the interior of stars that lived and died before the Sun and Earth were formed. The supermassive star Eta Carinae, shown here, is currently ejecting a cloud of chemically enriched material just as earlier generations of stars once did to enrich our Solar System.

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 1.3**). Nuclear fusion reactions occurring deep within the interiors of stars combine atoms of light elements such as hydrogen to form more massive atoms. When a star exhausts its nuclear fuel and nears the end of its life, it often loses much of its mass—including some of the new atoms formed in its interior—by blasting it back into interstellar space. We will talk later about the life and death of stars. For now it is enough to note that our Sun and Solar System are recycled—formed from a cloud of interstellar gas and dust that had been "seeded" by earlier generations of stars. This chemical legacy supplies the building blocks for the interesting chemical processes that go on around us—chemical processes such as life. The atoms that make up much of what we see were formed in the hearts of stars. The singer-songwriter Joni Mitchell wrote, "We are stardust," and this is not just poetry. Literally, we are made of the stuff of stars.

We are stardust.

1.2 Astronomy Involves Exploration and Discovery

As you look at the universe through the eyes of astronomers, you can also learn something of how science works. It is beyond the scope of this book to provide a detailed justification for all that we will say. However, we will try to offer some explanation of where key ideas come from and why scientists think these ideas are valid. We will be honest when we are on uncertain, speculative ground, and we will admit it when the truth is that we really do not know. This book is not a compendium of revealed truth or a font of accepted wisdom. Rather, it is an introduction to a body of knowledge and understanding that was painstakingly built (and sometimes torn down and rebuilt) brick by brick.

Science is vitally important to our civilization. Electricity, cars, computers—all of these technologies are derived from science. Another manifestation of science is the technology that has enabled us to explore well beyond our planet. Since the 1957 launch of Sputnik, the first human-made **satellite** (an object in orbit about a more massive body), we have lived in an age of space exploration. Nearly six decades later, satellites are used for weather observation, communication, and global positioning (GPS); humans have walked on the Moon (**Figure 1.4**); and unmanned probes have visited planets. Spacecraft have flown past asteroids, comets, and even the Sun. Human inventions have landed on Mars, Venus, Titan (Saturn's largest moon), and asteroids, and have plunged into the atmosphere of Jupiter. Most of what we know of the Solar System has resulted from these past six decades of exploration.

Satellite observatories in orbit around Earth have also given us many new perspectives on the universe. Space astronomy continues to show us vistas hidden from the gaze of ground-based telescopes by the protective but obscuring blanket

Space exploration has expanded our view of the universe.

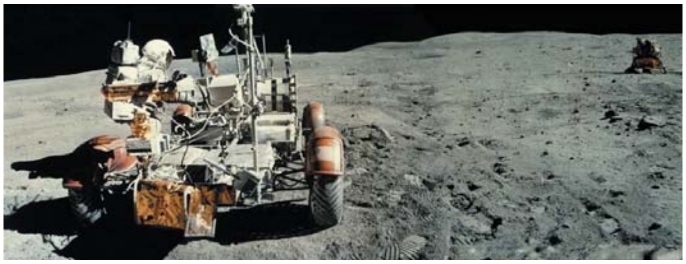


FIGURE 1.4 *Apollo 15* astronaut James B. Irwin stands by the lunar rover during an excursion to explore and collect samples from the Moon.

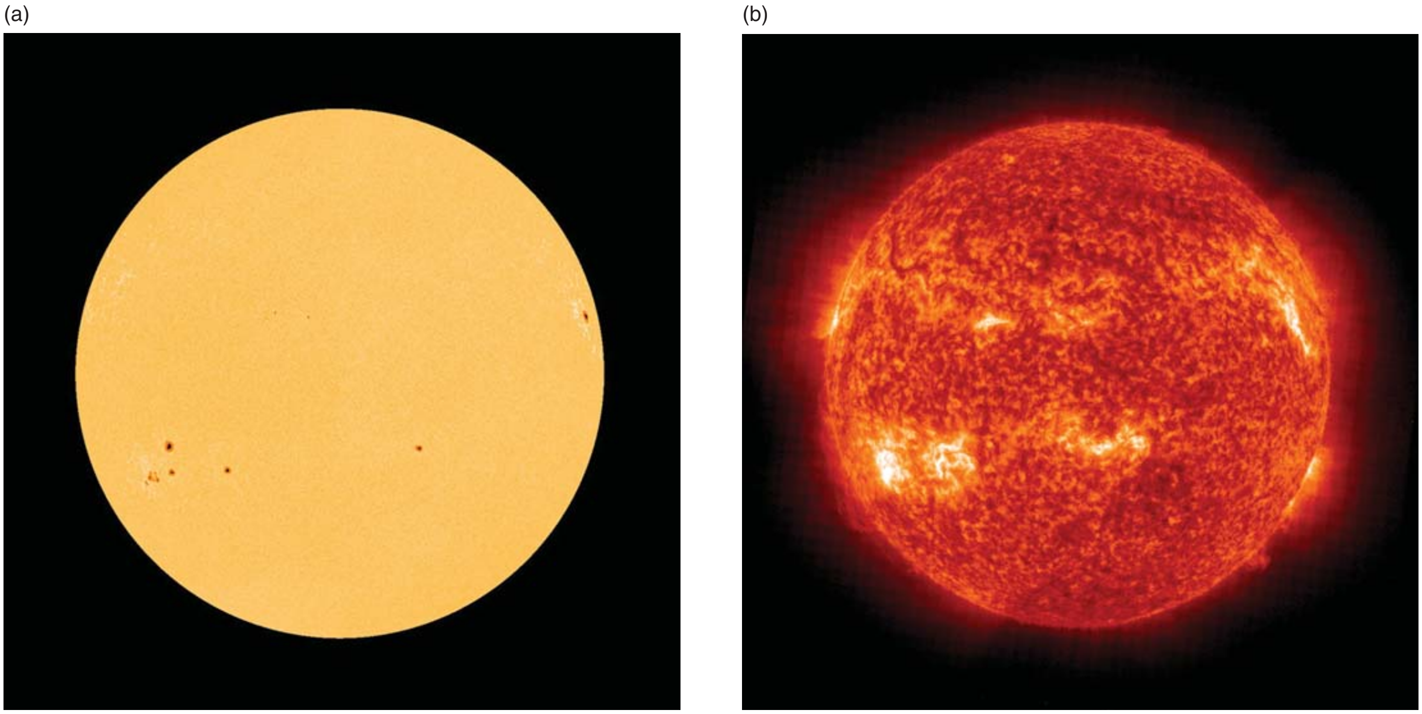


FIGURE 1.5 Visible-light (a) and X-ray (b) telescopic images of the Sun.

of our atmosphere. Satellites capable of detecting the full spectrum of radiation—from the highest-energy gamma rays and X-rays, through ultraviolet and infrared radiation, to the lowest-energy microwaves—have brought surprising discovery after surprising discovery. Since the beginning of the 21st century, large astronomical observatories have been constructed on the ground as well. The objects in the sky are now seen by gamma-ray, X-ray, infrared, and radio telescopes (**Figure 1.5**), extending our observations into light that has shorter or longer wavelengths than we can see with our eyes.

A great deal of frontline astronomy is now carried out in large physics facilities like the particle collider shown in **Figure 1.6**. Today astronomers work along with their colleagues in related fields, such as physics, chemistry, geology, and planetary science, to sharpen their understanding of the physical laws that govern the behavior of matter and energy and to use this understanding to make sense of our observations of the cosmos. Astronomy has also benefited enormously from the computer revolution. The 21st century astronomer spends far more time staring at a computer screen than peering through the eyepiece of a telescope. Astronomers use computers to collect and analyze data from telescopes, calculate physical models of astronomical objects, and prepare and disseminate the results of their work.

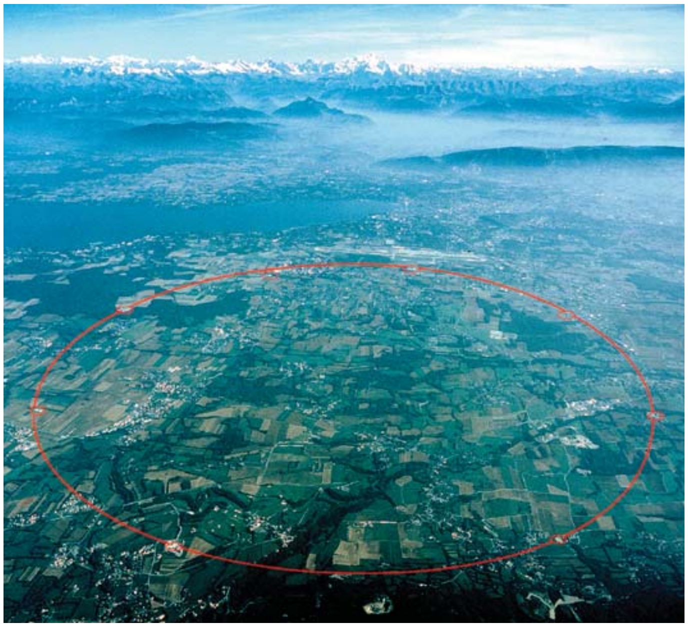


FIGURE 1.6 The Large Hadron Collider (which is buried along the path indicated by the red circle) is a particle accelerator near Geneva, Switzerland, that provides clues about the physical environment during the birth of the universe. Laboratory astrophysics, in which astronomers model important physical processes under controlled conditions as they do at this facility, has become an important part of astronomy.

1.3 Science Is a Way of Viewing the World

The Scientific Method and Scientific Principles

What is the scientific method? Consider a scientist coming up with an idea that might explain a particular observation or phenomenon. She presents the idea to her colleagues as a hypothesis. Her colleagues then look for testable predictions capable of *disproving* her hypothesis. *This is an important property of the scientific method*: a scientific hypothesis must be *falsifiable*—in other words, *disprovable*. (Note that a falsifiable hypothesis—one capable of being shown false—may not be testable using current technology, but scientists must at least be able to outline an experiment or observation that could prove the idea wrong.) If continuing tests fail to disprove a hypothesis, the scientific community will come to accept it as a theory and, after enough confirmation, eventually treat it as a law of nature. Scientific theories are accepted only as long as their predictions are borne out. A classic example is Einstein's theory of relativity, which we cover in some depth in Chapter 18. The theory of relativity has withstood a century of scientific efforts to disprove its predictions.

The scientific method includes trying to *falsify* ideas.

Science is sometimes misunderstood because of the ways that scientists use everyday words. An example is the word *theory*. In everyday language, *theory* may mean a conjecture or a guess: "Do you have a theory about who might have done it?" "My theory is that a third party could win the next election." In everyday parlance a theory is something worthy of little serious regard. "After all," people say, "it's only a theory."

In stark contrast, a *scientific* **theory** is a carefully constructed proposition that takes into account all the relevant data and all our understanding of how the world works. A theory makes testable predictions about the outcome of future observations and experiments. It is a well-developed idea that is ready to be tested by what is observed in nature. A well-corroborated theory is a theory that has survived many such tests. Far from being simple speculation, scientific theories represent and summarize bodies of knowledge and understanding that provide fundamental insights into the world around us. A successful and well-corroborated theory is the pinnacle of human knowledge about the world.

In science, a **hypothesis** is an idea that leads to testable predictions. The scientific method consists of observation or ideas, followed by hypothesis, followed by prediction, followed by further observation or experiments to test the prediction, and ending with a tested theory (see the **Process of Science Figure** on the next page). A hypothesis may be the forerunner of a scientific theory, or it may be based on an existing theory, or both. Scientists build **theoretical models** that are used to connect theories with the behavior of complex systems. Ultimately, the basis for deciding among competing theories is the success of their predictions. Some theories become so well tested and are of such fundamental importance that people refer to them as **physical laws**.

A scientific **principle** is a general idea or sense about how the universe is that guides the construction of new theories. **Occam's razor**, for example, is a guiding principle in science stating that when we are faced with two hypotheses that explain a particular phenomenon equally well, we should adopt the simpler of the two, unless the more complicated answer better matches the results of observations or experiment. Another principle comes from the late astronomer Carl Sagan (1934–1996) and is often phrased as "Extraordinary Claims Require Extraordinary Evidence," meaning that when making a new and truly extraordinary claim that has not been tested, confirmed, or proven, extraordinary evidence is required.

At the heart of modern astronomy is the adoption of an additional principle: the **cosmological principle**. The cosmological principle states that on a large scale, the universe looks the same everywhere. That is, when people look out around in every direction, what they see is representative of what the universe is generally like. In other words, there is nothing special about our particular location. 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 assumption is important because it means that the same physical laws that we observe and apply in terrestrial laboratories can be used to understand what goes on in the centers of stars or in the hearts of distant galaxies. Each new success that comes from applying the cosmological principle to observations of the universe around us adds to our confidence in the validity of this cornerstone of our worldview. We will discuss the cosmological principle in more detail in Chapter 19.

There is nothing special about our place in the universe.

Science as a Way of Knowing

The path to scientific knowledge is solidly based on the **scientific method**. This concept is so important to an understanding of how science works that we should emphasize it once again. The scientific method consists of observation