FIFTH EDITION

21ST CENTURY ASTRONOMY

KAY | PALEN | BLUMENTHAL

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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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Part III Stars and Stellar Evolution

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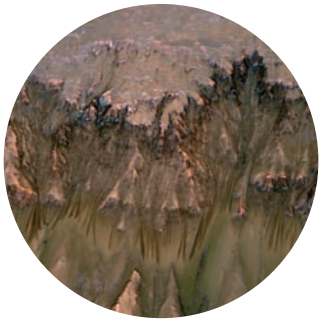

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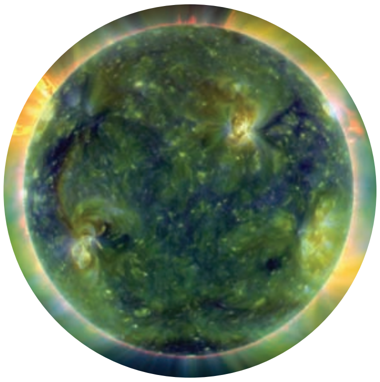

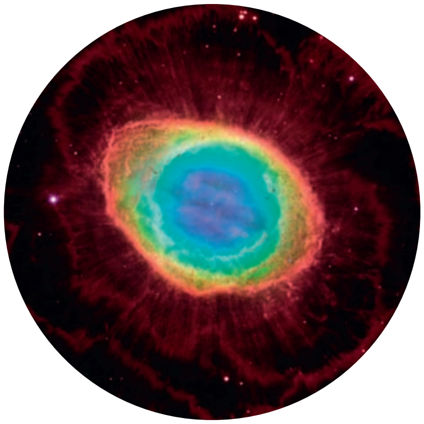

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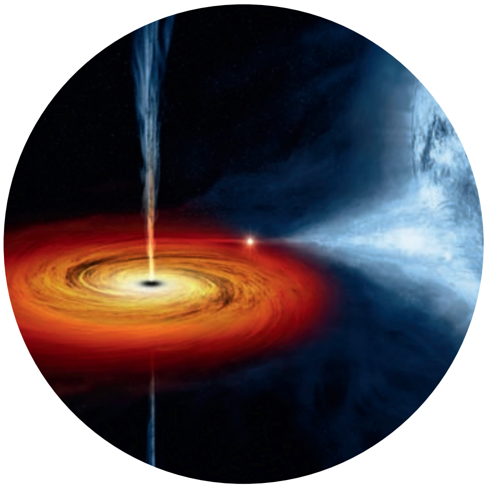

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Working It Out

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

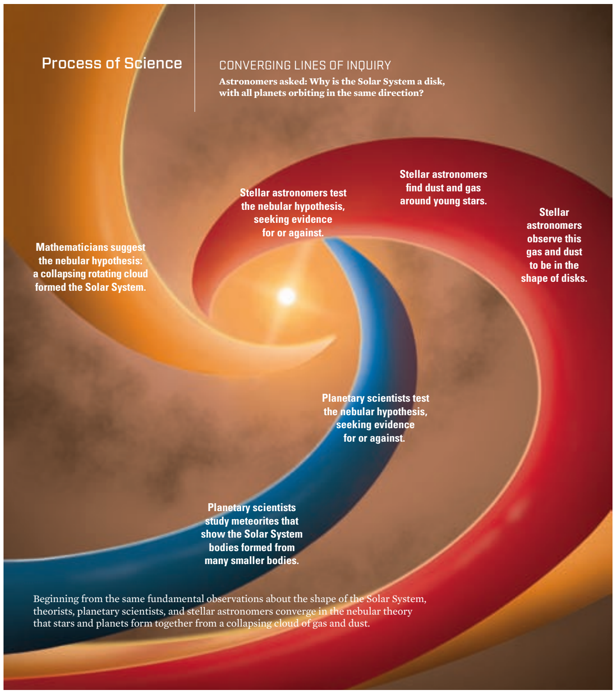
Nebraska Simulations

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.

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.

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 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.

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?

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?

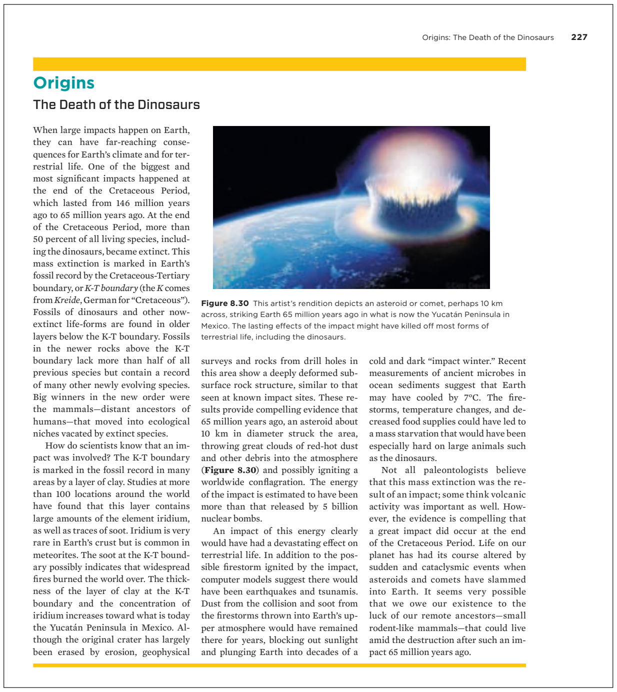
$$0.00077 = \frac{R^2_{\text{Kepler-11c}}}{R^2_{\text{star}}} = \frac{R^2_{\text{Kepler-11c}}}{(7.7 \times 10^5\ \text{km})^2}$$

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

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

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}.

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.



Origins: The Death of the Dinosaurs 227

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.

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.

USING THE WEB

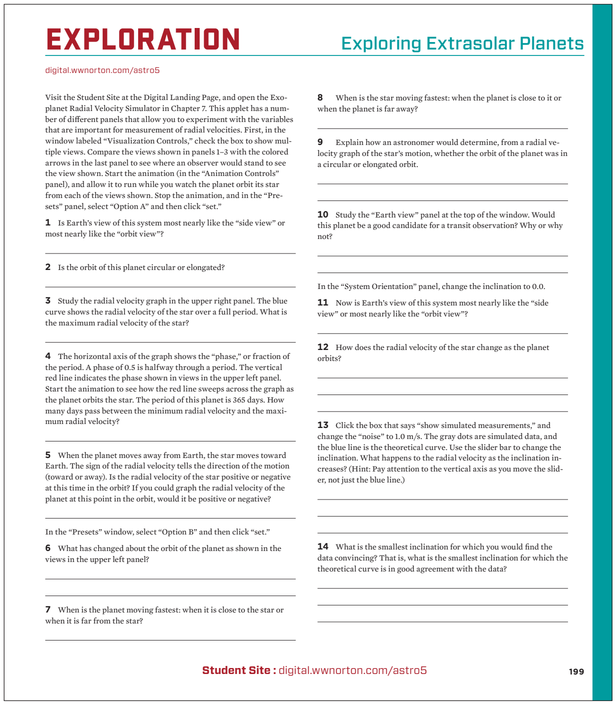
46. Go to the "Extrasolar Planets Global Searches" Web page (http://exoplanet.eu/searches.php) of the Extrasolar Planets Encyclopedia. Click on one ongoing project under "Ground" and one ongoing project under "Space." What method is used to detect planets in each case? Has the selected project found 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?

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.

Astronomy in Action



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.

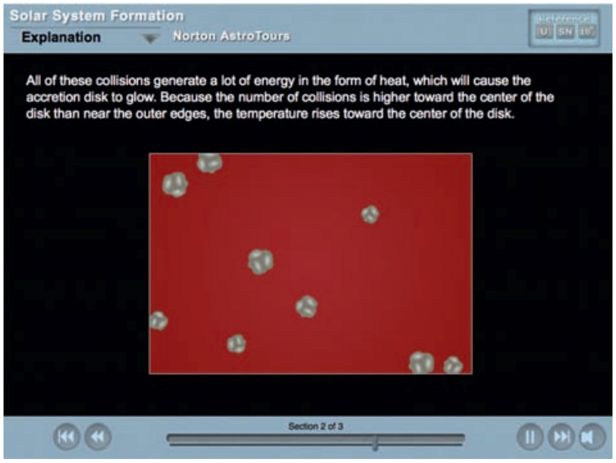
11 Now is Earth's view of this system most nearly like the "side view" or most nearly like the "orbit view"?

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.)

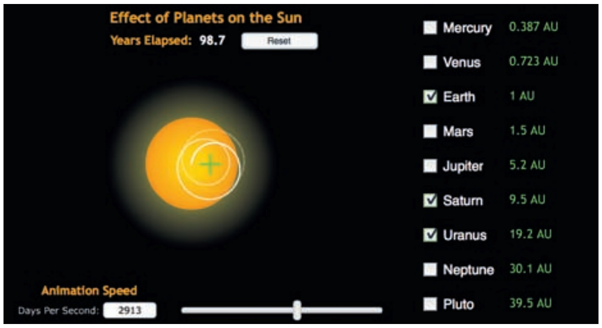
14 What is the smallest inclination for which you would find the data convincing? That is, what is the smallest inclination for which the theoretical curve is in good agreement with the data?

Student Site : digital.wwnorton.com/astro5 199



All of these collisions generate a lot of energy in the form of heat, which will cause the accretion disk to glow. Because the number of collisions is higher toward the center of the disk than near the outer edges, the temperature rises toward the center of the disk.

AstroTour



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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We gratefully acknowledge the contributions of the authors who worked on previous editions of *21st Century Astronomy*: Dave Burstein, Ron Greeley, Jeff Hester, Brad Smith, Howard Voss, and Gary Wegner, with special thanks to Dave for starting the project, to Jeff for leading the original authors through the first edition, and to Brad for leading the second and third editions.

Laura Kay
Stacy Palen
George Blumenthal

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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

21^{ST} 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?

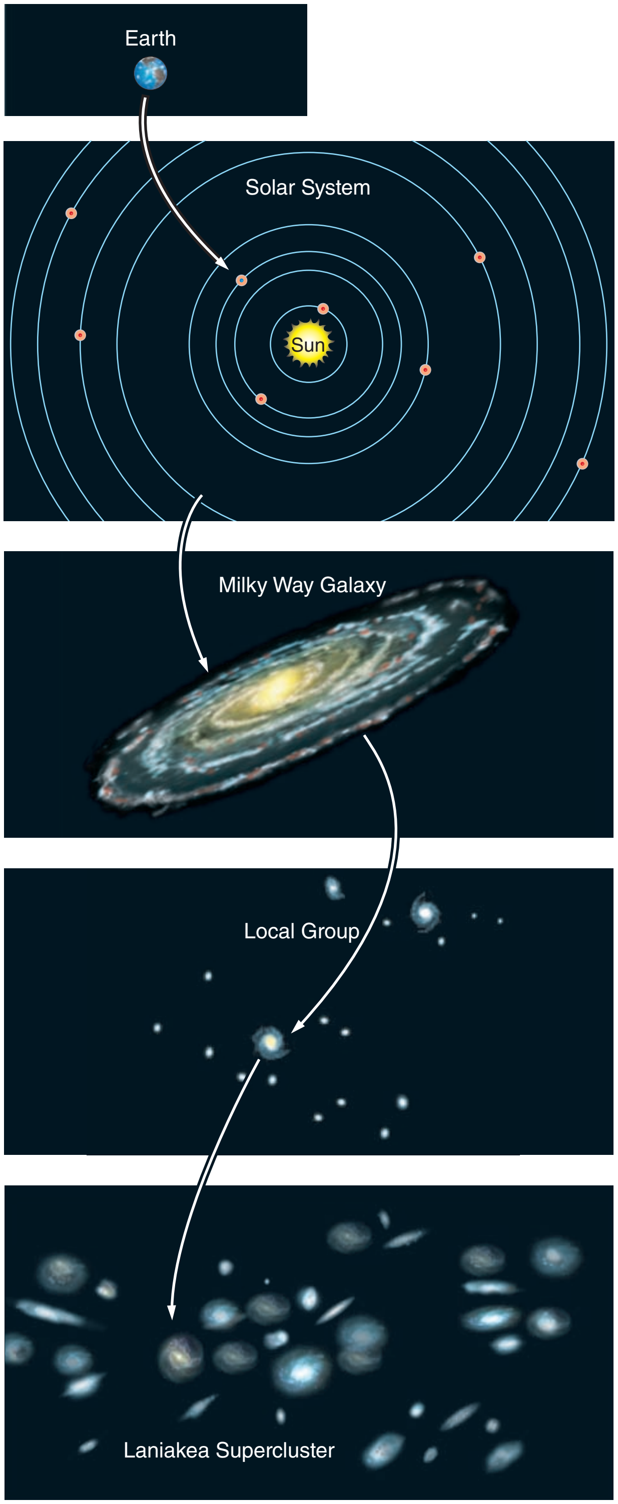


Figure 1.1 Our cosmic address is Earth, Solar System, Milky Way Galaxy, Local Group, Laniakea Supercluster. We live on Earth, a planet orbiting the Sun in our Solar System, which is a star in the Milky Way Galaxy. The Milky Way is a large galaxy within the Local Group of galaxies, which in turn is located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

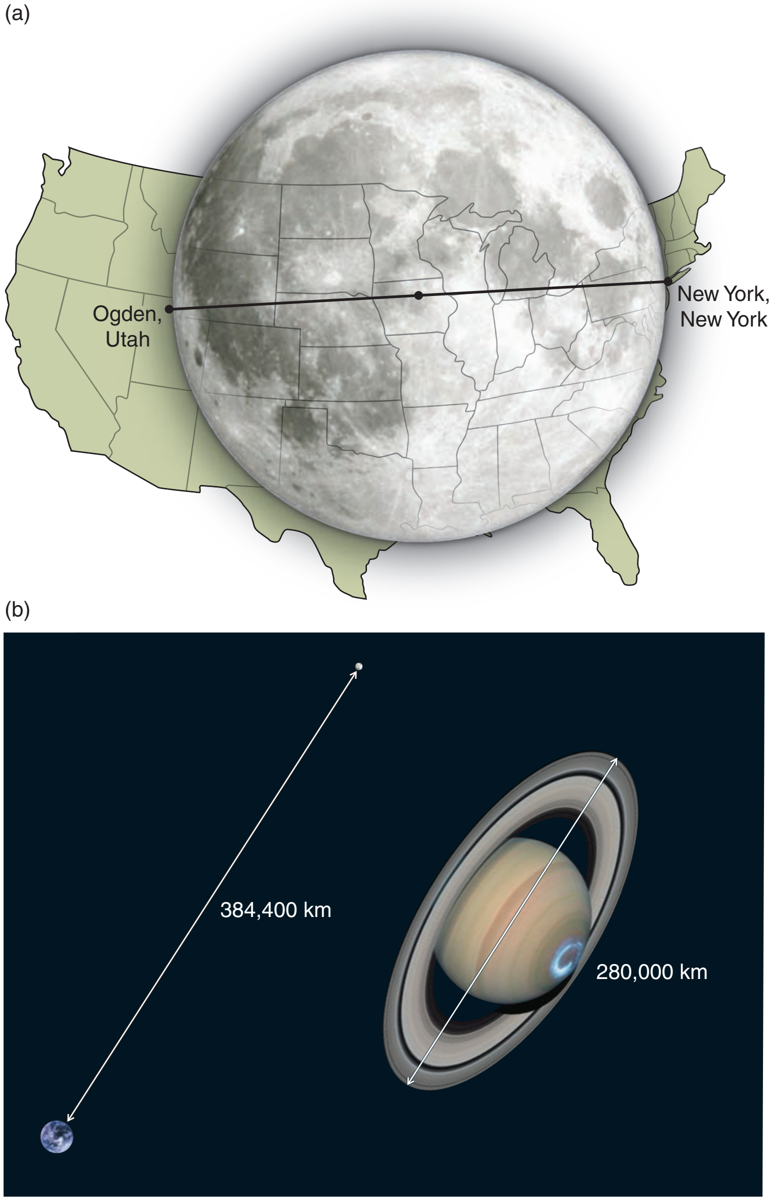
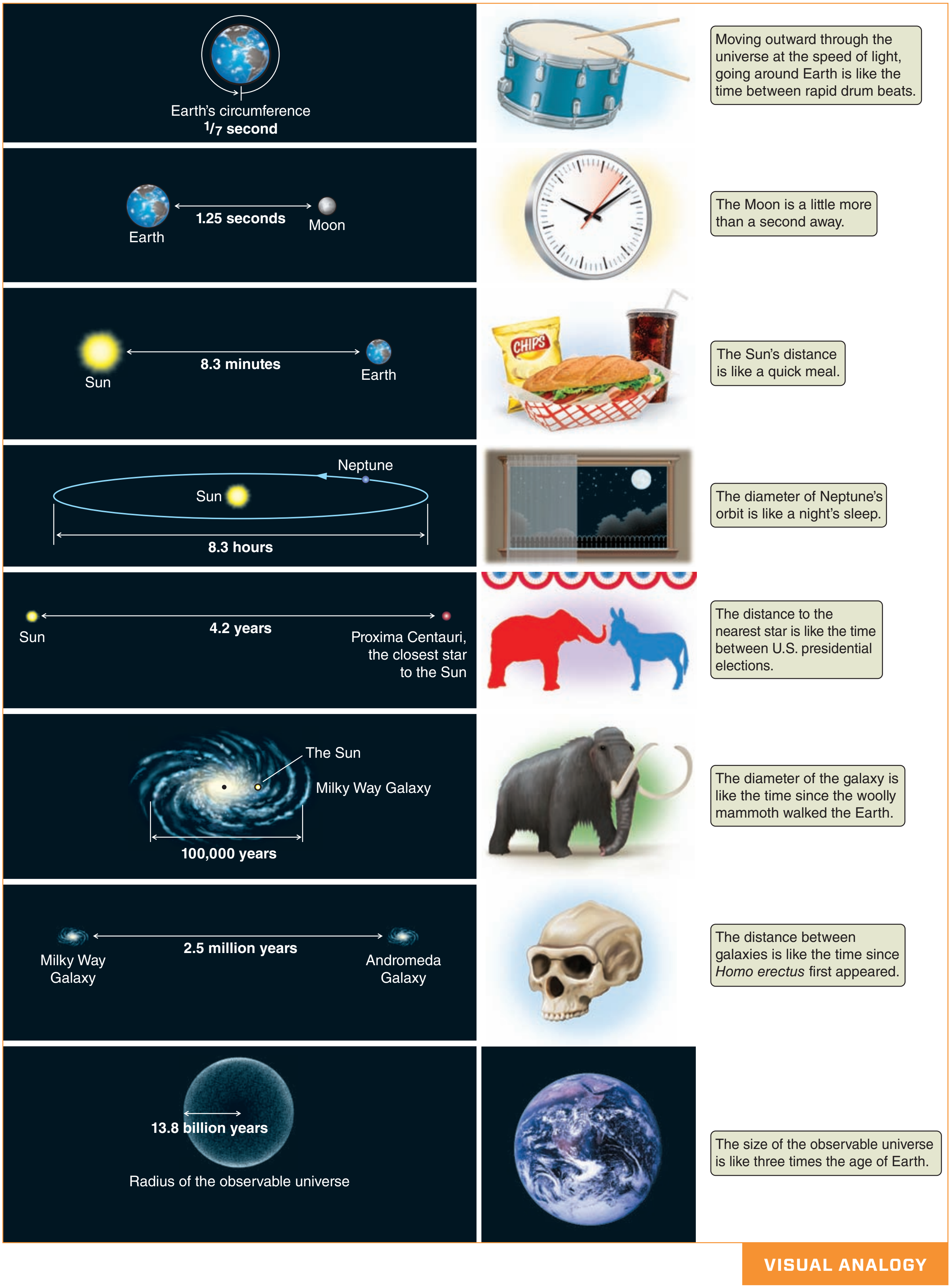


Figure 1.2 (a) The diameter of the Moon is about the same as the distance between New York, New York, and Ogden, Utah. (b) The size of Saturn, including the rings, is about 70 percent of the distance between Earth and the Moon.

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



Moving outward through the universe at the speed of light, going around Earth is like the time between rapid drum beats.

The Moon is a little more than a second away.

The Sun's distance is like a quick meal.

The diameter of Neptune's orbit is like a night's sleep.

The distance to the nearest star is like the time between U.S. presidential elections.

The diameter of the galaxy is like the time since the woolly mammoth walked the Earth.

The distance between galaxies is like the time since *Homo erectus* first appeared.

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

VISUAL ANALOGY

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.

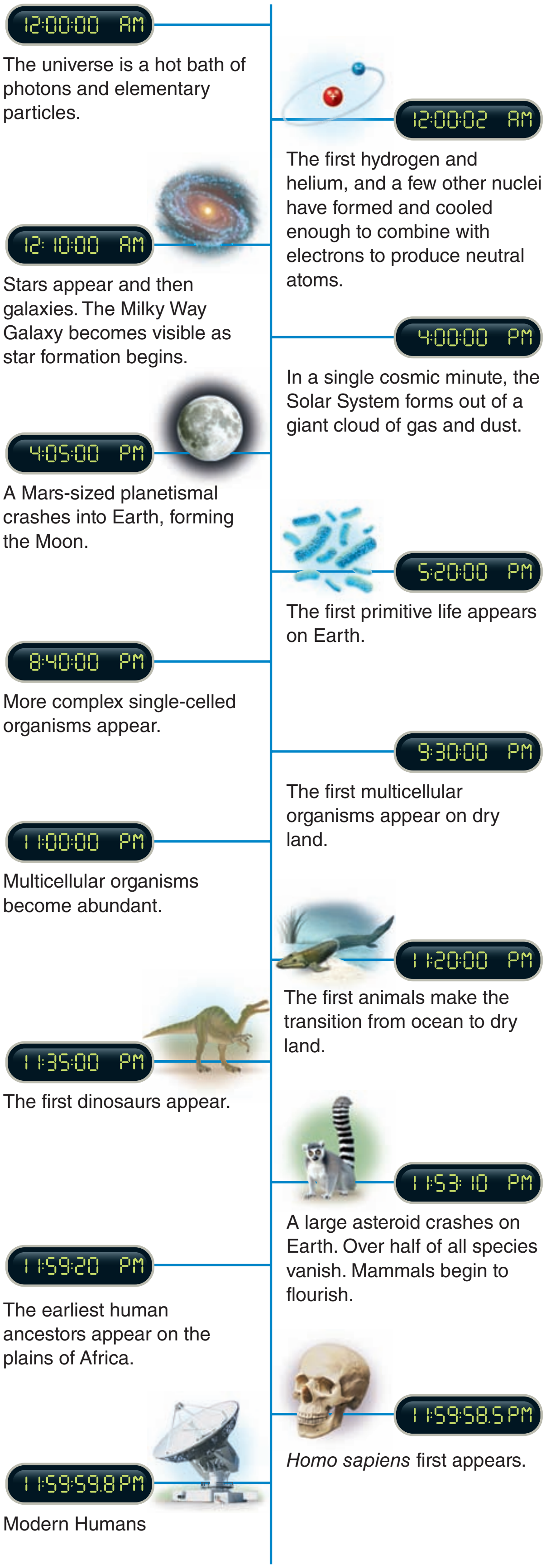


Figure 1.4 This cosmic timeline presents the history of the universe as a 24-hour day.

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.

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.

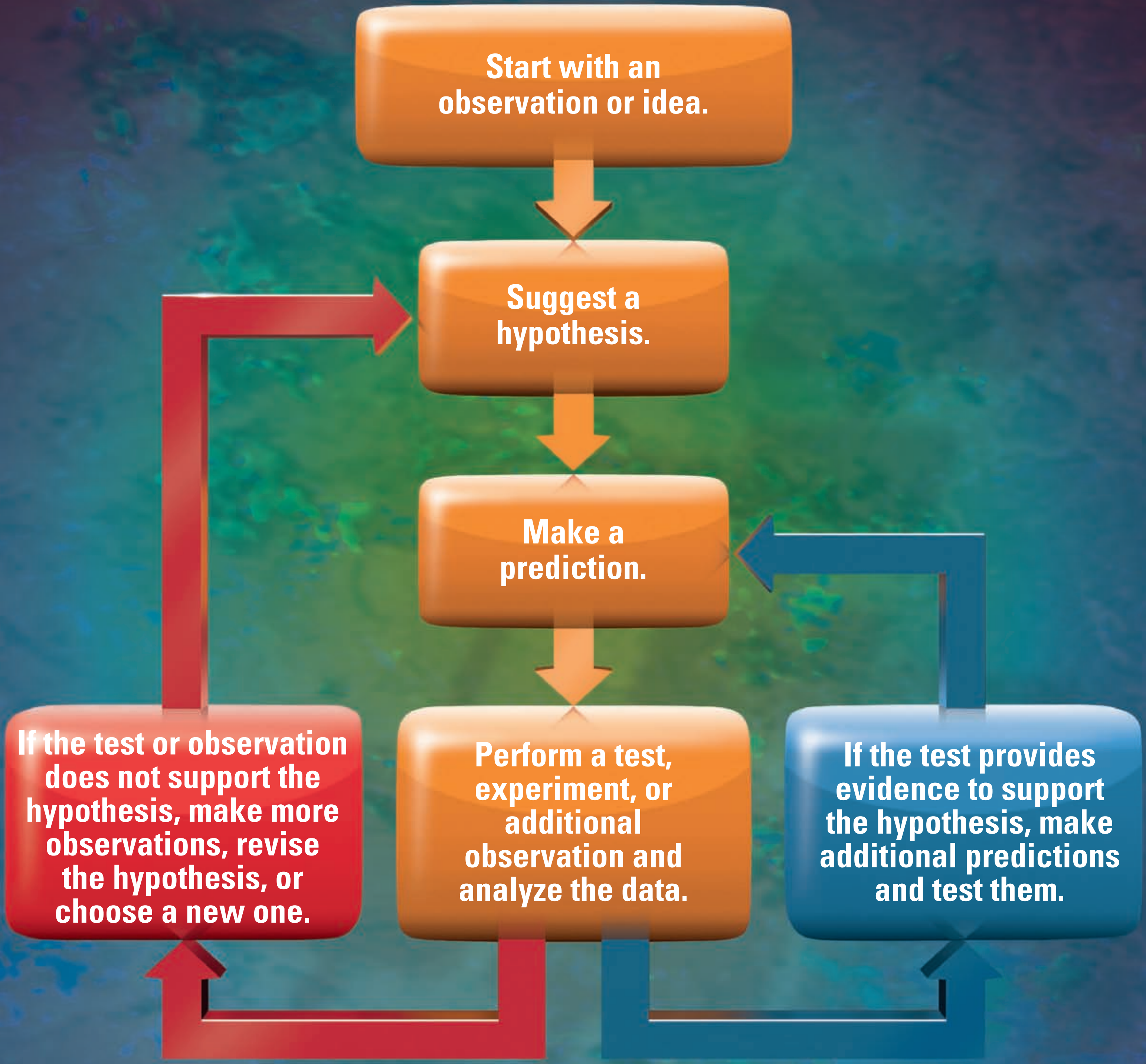
As shown in the **Process of Science Figure**, the scientific method follows a specific sequence. Scientists begin with an observation or idea, followed by careful analysis, followed by a hypothesis, followed by prediction, followed by further observations or experiments to test the prediction. A hypothesis 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.



Start with an observation or idea.

Suggest a hypothesis.

Make a prediction.

Perform a test, experiment, or additional observation and analyze the data.

If the test or observation does not support the hypothesis, make more observations, revise the hypothesis, or choose a new one.

If the test provides evidence to support the hypothesis, make additional predictions and test them.

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.