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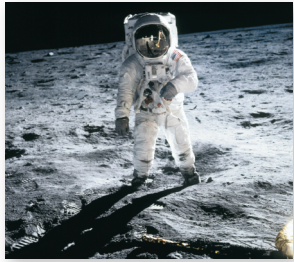
THE COSMIC
PERSPECTIVE

FUNDAMENTALS

third edition



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We humans have gazed into the sky for countless generations. We have wondered how our lives are connected to the Sun, Moon, planets, and stars that adorn the heavens. Today, through the science of astronomy, we know that these connections go far deeper than our ancestors ever imagined. This book focuses on the story of modern astronomy and the new perspective—the *cosmic perspective*—that astronomy gives us on ourselves and our planet.

Who Is This Book For?

The Cosmic Perspective Fundamentals is designed to support one-term college courses in introductory astronomy—particularly those in which instructors couple the text with Mastering™ Astronomy to create an active or collaborative learning environment. No prior background in astronomy or physics is assumed, making *The Cosmic Perspective Fundamentals* suitable for both high school courses and college courses for nonscience majors. *The Cosmic Perspective Fundamentals* differs from our more comprehensive texts (*The Cosmic Perspective* and *The Essential Cosmic Perspective*) in covering a smaller set of topics and therefore being much shorter in length, but it is built upon the same “big picture” approach to astronomy and uses the same pedagogical principles.

New to This Edition

Many new discoveries have been made in astronomy during the four years since publication of the second edition of *The Cosmic Perspective Fundamentals*, leading to many changes in this third edition. Indeed, the changes are too many to list here, but those who used the second edition will notice significant updates to almost every chapter in the book, primarily as a result of the many new astronomical discoveries that have occurred in recent years, including results from missions such as *New Horizons*, *Rosetta*, *Dawn*, *Curiosity*, *MAVEN*, *Cassini*, *Juno*, and more; the first direct detections of gravitational waves; and major advances in our understanding of extrasolar planets.

Topical Selection

A briefer, focused text must necessarily cover fewer topics. We have carefully selected those topics using the following four criteria:

- **Importance.** We surveyed a large number of professors to identify the topics considered of greatest importance in a college-level astronomy course, in order to ensure that the most fundamental concepts are covered in this text. Most astronomy courses begin with topics such as the scale of the universe, seasons, and phases of the Moon and then progress to study of the planets, stars, galaxies, and cosmology. Our selected topics have been organized in a similar fashion. The fifteen chapters are designed so that they can be covered in a typical semester at a rate of approximately one chapter per week.

- **Active learning.** Educational research has shown that students learn scientific concepts best by actively solving conceptual problems, both individually and in collaboration with other students. We have emphasized topics that are well suited to active learning, and each chapter includes **Think About It** critical thinking questions for in-class discussion and **See It for Yourself** hands-on activities to further promote active learning. These in-text features are reinforced by a variety of active learning resources on the Mastering Astronomy website.
- **Engagement.** Most students in a college astronomy course are there to satisfy a general education requirement, but the subject is sufficiently interesting that it should be possible to choose topics that students will find highly engaging—and that they will therefore be willing to work hard to learn.
- **Process of science.** We believe that the primary purpose of a general education requirement in science is to ensure that students learn about science itself. Throughout the book, we have chosen topics that illustrate important aspects of the process of science, and each chapter concludes with a section called **The Process of Science in Action**, which presents a case study of how the process of science has helped (or is currently helping) to provide greater insight into key topics in astronomy.

Book Structure

To facilitate student learning, we have created a simple pedagogical structure used in each of the book’s fifteen chapters:

- Each chapter begins with an opening page that includes a brief overview of the chapter content and a clear set of **Learning Goals** associated with the chapter. Each Learning Goal is phrased as a question to engage students as they read.
- Each chapter consists of three sections. The first two sections focus on the key topics of the chapter; the third section builds on the ideas from the first two sections, but focuses on **The Process of Science in Action**.
- Each section is written to address the Learning Goal questions from the chapter-opening page.
- Each chapter concludes with a **visual summary** that provides a concise review of the answers to the Learning Goal questions.
- The summary is followed by a 12-question **Quick Quiz** and a set of **short-answer, essay, and quantitative questions**.

Additional features of the book include the following:

- **Tools of Science** boxes, which present a brief overview of key tools that astronomers use, including theories, equations, observational techniques, and technology. Each chapter includes one Tools of Science box related to the chapter content.

- **Common Misconceptions** boxes, which address popularly held but incorrect ideas about topics in the text
- **Annotated Figures and Photos**, which act like the voice of an instructor, walking students through the key ideas presented in complex figures, photos, and graphs
- **Cosmic Context Figures**, which combine text and illustrations into accessible and coherent two-page visual summaries that will help improve student understanding of essential topics

Mastering Astronomy—A New Paradigm in Astronomy Teaching

What is the single most important factor in student success in astronomy? Both research and common sense reveal the same answer: *study time*. No matter how good the teacher or how good the textbook, students learn only when they spend adequate time studying. Unfortunately, limitations on resources for grading have prevented most instructors from assigning much homework despite its obvious benefits to student learning. And limitations on help and office hours have made it difficult for students to make sure they use self-study time effectively. That, in a nutshell, is why we created Mastering Astronomy. For students, it provides personalized learning designed to coach them *individually*—responding to their errors with specific, targeted feedback and providing optional hints for those who need additional guidance. For professors, Mastering Astronomy provides the unprecedented ability to automatically monitor and record students' step-by-step work and evaluate the effectiveness of assignments and exams.

All students registered for Mastering Astronomy receive full access to the Study Area. Key resources available in the Study Area include the following:

- A large set of prelecture videos, narrated figures, and interactive figures that will help students understand key concepts from the textbook
- A set of self-study tools, including a Quick Quiz for each chapter and interactive self-guided tutorials that go into depth on topics that some students find particularly challenging
- A downloadable set of group activities
- Additional videos covering basic math skills, as well as selected videos of the authors speaking to the public
- And much more, including a media workbook, Starry Night activities, World Wide Telescope tours, and even access to a full e-text of *The Cosmic Perspective Fundamentals*

Instructors have access to many additional resources, including a large Item Library featuring more than 250 assignable tutorials, organized by chapter, that include guidance for understanding key concepts, assessments based on the large set of prelecture videos, ranking tasks, sorting tasks, and more. There is also a set of Math Review tutorials to help students who need work on topics including scientific notation, working with units, metric units, and problem-solving skills.

Finally, please note that nearly all the content available at the Mastering Astronomy site for *The Cosmic Perspective Fundamentals* has been written or co-written by the textbook authors. This means that you can count on consistency between the textbook and web resources, with both emphasizing the same concepts and using the same terminology and the same pedagogical approaches. This type of consistency ensures that students will be able to study in the most efficient way possible.

Acknowledgments

A textbook may carry author names, but it is the result of hard work by a long list of committed individuals, as well as many reviewers. We could not possibly list everyone who has helped, but we would especially like to thank our editorial team at Pearson, our production team at Lifland et al., and the more than 100 professors who have reviewed our texts in depth, providing valuable feedback; a list of these professors can be found in *The Cosmic Perspective*, ninth edition.

Jeff Bennett
Megan Donahue
Nick Schneider
Mark Voit

About the Authors



Jeffrey Bennett, a recipient of the American Institute of Physics Science Communication Award, holds a B.A. in biophysics (UC San Diego) and an M.S. and Ph.D. in astrophysics (University of Colorado). He specializes in science and math education and has taught at every level from preschool through graduate school. Career highlights include serving 2 years as a visiting senior scientist

at NASA headquarters, where he developed programs to build stronger links between research and education, proposing and helping to develop the Voyage scale model solar system on the National Mall (Washington, DC) and developing the free app *Totality by Big Kid Science* to help people learn about total solar eclipses. He is the lead author of textbooks in astronomy, astrobiology, mathematics, and statistics and of critically acclaimed books for the public including *Beyond UFOs* (Princeton University Press), *Math for Life* (Big Kid Science), *What Is Relativity?* (Columbia University Press), *On Teaching Science* (Big Kid Science), and *A Global Warming Primer* (Big Kid Science). He is also the author of six science picture books for children, titled *Max Goes to the Moon*, *Max Goes to Mars*, *Max Goes to Jupiter*, *Max Goes to the Space Station*, *The Wizard Who Saved the World*, and *I, Humanity*; all six have been launched to the International Space Station and read aloud by astronauts for NASA's Story Time From Space program. His personal website is www.jeffreybennett.com.



Megan Donahue is a full professor in the Department of Physics and Astronomy at Michigan State University (MSU), a Fellow of the American Physical Society and of the American Association for the Advancement of Science, and President of the American Astronomical Society (2018–2020). Her research focuses on using x-ray, UV, infrared, and visible light to study gal-

axies and clusters of galaxies: their contents—dark matter, hot gas, galaxies, active galactic nuclei—and what they reveal about the contents of the universe and how galaxies form and evolve. She grew up on a farm in Nebraska and received an S.B. in physics from MIT, where she began her research career as an x-ray astronomer. She has a Ph.D. in astrophysics from the University of Colorado. Her Ph.D. thesis on theory and optical observations of intergalactic and intra-cluster gas won the 1993 Robert Trumpler Award from the Astronomical Society for the Pacific for an outstanding astrophysics doctoral dissertation in North America. She continued postdoctoral research as a Carnegie Fellow at Carnegie Observatories in Pasadena, California, and later as an STScI Institute Fellow at Space Telescope. Megan was a staff astronomer at the Space Telescope Science Institute until 2003, when she joined the MSU faculty. She is also actively involved in advising national and international astronomical facilities and NASA, including planning future NASA missions. Megan is married to Mark

Voit, and they collaborate on many projects, including this textbook, over 70 peer-reviewed astrophysics papers, and the nurturing of their children, Michaela, Sebastian, and Angela. Megan has run three full marathons, including Boston. These days she runs trails with friends, orienteers, and plays piano and bass guitar for fun and no profit.



Nicholas Schneider is a full professor in the Department of Astrophysical and Planetary Sciences at the University of Colorado and a researcher in the Laboratory for Atmospheric and Space Physics. He received his B.A. in physics and astronomy from Dartmouth College in 1979 and his Ph.D. in planetary science from the University of Arizona in 1988. His research interests include planetary atmospheres and planetary astronomy. One research focus is the odd case of Jupiter's moon Io. Another is the mystery of Mars's lost atmosphere, which he is helping to answer by leading the Imaging UV Spectrograph team on NASA's *MAVEN* mission now orbiting Mars. Nick enjoys teaching at all levels and is active in efforts to improve undergraduate astronomy education. Over his career he has received the National Science Foundation's Presidential Young Investigator Award, the Boulder Faculty Assembly's Teaching Excellence Award, and NASA's Exceptional Scientific Achievement Medal. Off the job, Nick enjoys exploring the outdoors with his family and figuring out how things work.



Mark Voit is a full professor in the Department of Physics and Astronomy and Associate Dean for Undergraduate Studies at Michigan State University. He earned his A.B. in astrophysical sciences at Princeton University and his Ph.D. in astrophysics at the University of Colorado in 1990. He continued his studies at the California Institute of Technology, where he was a research fellow in theoretical astrophysics, and then moved on to Johns Hopkins University as a Hubble Fellow. Before going to Michigan State, Mark worked in the Office of Public Outreach at the Space Telescope, where he developed museum exhibitions about the Hubble Space Telescope and helped design NASA's award-winning HubbleSite. His research interests range from interstellar processes in our own galaxy to the clustering of galaxies in the early universe, and he is a Fellow of the American Association for the Advancement of Science. He is married to coauthor Megan Donahue and cooks terrific meals for her and their three children. Mark likes getting outdoors whenever possible and particularly enjoys running, mountain biking, canoeing, orienteering, and adventure racing. He is also author of the popular book *Hubble Space Telescope: New Views of the Universe*.

How to Succeed in Your Astronomy Course

If Your Course Is	Times for Reading the Assigned Text (per week)	Times for Homework Assignments (per week)	Times for Review and Test Preparation (average per week)	Total Study Time (per week)
3 credits	2 to 4 hours	2 to 3 hours	2 hours	6 to 9 hours
4 credits	3 to 5 hours	2 to 4 hours	3 hours	8 to 12 hours
5 credits	3 to 5 hours	3 to 6 hours	4 hours	10 to 15 hours

The Key to Success: Study Time

The single most important key to success in any college course is to spend enough time studying. A general rule of thumb for college classes is that you should expect to study about 2 to 3 hours per week *outside* of class for each unit of credit. For example, based on this rule of thumb, a student taking 15 credit hours should expect to spend 30 to 45 hours each week studying outside of class. Combined with time in class, this works out to a total of 45 to 60 hours spent on academic work—not much more than the time a typical job requires, and you get to choose your own hours. Of course, if you are working or have family obligations while you attend school, you will need to budget your time carefully.

The table above gives rough guidelines for how you might divide your study time. If you find that you are spending fewer hours than these guidelines suggest, you can probably improve your grade by studying longer. If you are spending more hours than these guidelines suggest, you may be studying inefficiently; in that case, you should talk to your instructor about how to study more effectively.

Using This Book

Each chapter in this book is designed to make it easy for you to study effectively and efficiently. To get the most out of each chapter, you might wish to use the following study plan.

- A textbook is not a novel, and you'll learn best by reading the elements of this text in the following order:
 1. Start by reading the Learning Goals and the introductory paragraph at the beginning of the chapter so that you'll know what you are trying to learn.
 2. Get an overview of key concepts by studying the illustrations and their captions and annotations. The illustrations highlight most major concepts, so this "illustrations first" strategy gives you an opportunity to survey the concepts before you read about them in depth. You will find the two-page Cosmic Context figures especially useful.
 3. Read the chapter narrative, trying the Think About It questions and the See It for Yourself activities as you go along, but save the boxed features (Common Misconceptions, Tools of Science) to read later. As you read, make notes on the pages to remind yourself of ideas you'll want to review later. Take notes as you read, but avoid using a highlight pen

(or a highlighting tool if you are using an e-book), which makes it too easy to highlight mindlessly.

4. After reading the chapter once, go back through and read the boxed features.
 5. Review the Summary of Key Concepts, ideally by trying to answer the Learning Goal questions for yourself before reading the given answers.
- After completing the reading as outlined above, test your understanding with the end-of-chapter exercises. A good way to begin is to make sure you can answer all of the Quick Quiz questions; if you don't know an answer, look back through the chapter until you figure it out.
 - Further build your understanding by making use of the videos, quizzes, and other resources available at Mastering Astronomy. These resources have been developed specifically to help you learn the most important ideas in your course, and they have been extensively tested to make sure they are effective. They really do work, and the only way you'll gain their benefits is by going to the website and using them.

General Strategies for Studying

- Budget your time effectively. Studying 1 or 2 hours each day is more effective, and far less painful, than studying all night before homework is due or before exams. *Note:* Research shows that it can be helpful to create a "personal contract" for your study time (or for any other personal commitment), in which you specify rewards you'll give yourself for success and penalties you'll assess for failings.
- Engage your brain. Learning is an active process, not a passive experience. Whether you are reading, listening to a lecture, or working on assignments, always make sure that your mind is actively engaged. If you find your mind drifting or find yourself falling asleep, make a conscious effort to revive yourself, or take a break if necessary.
- Don't miss class, and come prepared. Listening to lectures and participating in class activities and discussions is much more effective than reading someone else's notes or watching a video later. Active participation will help you retain what you are learning. Also, be sure to complete any assigned reading *before* the class in which it will be discussed. This is crucial, since class lectures and discussions are designed to reinforce key ideas from the reading.

- Take advantage of resources offered by your professor, whether it be email, office hours, review sessions, online chats, or other opportunities to talk to and get to know your professor. Most professors will go out of their way to help you learn in any way that they can.
- Start your homework early. The more time you allow yourself, the easier it is to get help if you need it. If a concept gives you trouble, do additional reading or studying beyond what has been assigned. And if you still have trouble, ask for help: You surely can find friends, peers, or teachers who will be glad to help you learn.
- Working together with friends can be valuable in helping you understand difficult concepts. However, be sure that you learn *with* your friends and do not become dependent on them.
- Don't try to multitask. Research shows that human beings simply are not good at multitasking: When we attempt it, we do more poorly at all of the individual tasks. And in case you think you are an exception, research has also shown that those people who believe they are best at multitasking are often the worst! So when it is time to study, turn off your electronic devices, find a quiet spot, and concentrate on your work. (If you *must* use a device to study, as with an e-book or online homework, turn off email, text, and other alerts so that they will not interrupt your concentration; some apps will do this for you.)

Preparing for Exams

- Rework problems and other assignments; try additional questions, including the online quizzes available at Mastering Astronomy, to be sure you understand the concepts. Study your performance on assignments, quizzes, or exams from earlier in the term.
- Study your notes from classes, and reread relevant sections in your textbook. Pay attention to what your instructor expects you to know for an exam.
- Study individually *before* joining a study group with friends. Study groups are effective only if every individual comes prepared to contribute.
- Don't stay up too late before an exam. Don't eat a big meal within an hour of the exam (thinking is more difficult when blood is being diverted to the digestive system).
- Try to relax before and during the exam. If you have studied effectively, you are capable of doing well. Staying relaxed will help you think clearly.

Presenting Homework and Writing Assignments

All work that you turn in should be of *collegiate quality*: neat and easy to read, well organized, and demonstrating mastery of the subject matter. Future employers and teachers will expect this quality of work. Moreover, although submitting homework of collegiate quality requires “extra” effort, it serves two important purposes directly related to learning:

1. The effort you expend in clearly explaining your work solidifies your learning. Writing (or typing) triggers different areas of your

brain than reading, listening, or speaking. As a result, writing something down will reinforce your learning of a concept, even when you think you already understand it.

2. By making your work clear and self-contained (that is, making it a document that you can read without referring to the questions in the text), you will have a much more useful study guide when you review for a quiz or exam.

The following guidelines will help ensure that your assignments meet the standards of collegiate quality:

- Always use proper grammar, proper sentence and paragraph structure, and proper spelling. Do not use texting shorthand, and don't become over-reliant on spell checkers, which may miss “too two three mistakes, to.”
- All answers and other writing should be fully self-contained. A good test is to imagine that a friend is reading your work and to ask yourself whether the friend would understand exactly what you are trying to say. It is also helpful to read your work out loud to yourself, making sure that it sounds clear and coherent.
- In problems that require calculation:
 1. Be sure to *show your work* clearly so that both you and your instructor can follow the process you used to obtain an answer. Also, use standard mathematical symbols, rather than “calculator-ese.” For example, show multiplication with the \times symbol (not with an asterisk), and write 10^5 , not 10^5 or $10E5$.
 2. *Word problems should have word answers.* That is, after you have completed any necessary calculations, make sure that any problem stated in words is answered with one or more *complete sentences* that describe the point of the problem and the meaning of your solution.
 3. *Units are crucial.* If your answer has units, be sure they are stated clearly. For example, if you are asked to calculate a distance, be sure you state whether your answer is in miles, kilometers, or some other distance unit.
 4. Express your word answers in a way that would be *meaningful* to most people. For example, most people would find it more meaningful if you expressed a result of 720 hours as 1 month. Similarly, if a precise calculation yields an answer of 9,745,600 years, it may be more meaningfully expressed in words as “nearly 10 million years.”
- Include illustrations whenever they help explain your answer, and make sure your illustrations are neat and clear. For example, if you graph by hand, use a ruler to make straight lines. If you use software to make illustrations, be careful not to make them overly cluttered with unnecessary features.
- If you study with friends, be sure that you turn in your own work stated in your own words—you should avoid anything that might give even the *appearance* of possible academic dishonesty.

A Modern View of the Universe

1



This Hubble Space Telescope photo shows a piece of the sky so small that you could block your view of it with a grain of sand held at arm's length. Yet the photo shows an almost unimaginable expanse of both space and time: Nearly every object within it is a galaxy containing billions of stars, most likely orbited by planets, and some of the smaller smudges are galaxies so far away that their light has taken more than 12 billion years to reach us. A major goal of this book is to help you understand what you see in this photograph. We'll begin with a brief survey of our modern, scientific view of the universe.

LEARNING GOALS

1.1 The Scale of the Universe

- ◆ What is our place in the universe?
- ◆ How big is the universe?

1.2 The History of the Universe

- ◆ How did we come to be?
- ◆ How do our lifetimes compare to the age of the universe?



THE PROCESS OF SCIENCE IN ACTION

1.3 Defining Planets

- ◆ What is a planet?

1.1 The Scale of the Universe

For most of human history, our ancestors imagined Earth to be stationary at the center of a relatively small universe. This idea made sense at a time when understanding was built upon everyday experience. After all, we cannot feel the constant motion of Earth as it rotates on its axis and orbits the Sun, and if you observe the sky you'll see that the Sun, Moon, planets, and stars all appear to revolve around us each day. Nevertheless, we now know that Earth is a planet orbiting a rather average star in a rather typical galaxy, and that our universe is filled with far greater wonders than our ancestors ever imagined.

◆ What is our place in the universe?

Before we can discuss the universe and its great wonders, we first need to develop a general sense of our place within it. We can do this by thinking about what we might call our “cosmic address,” illustrated in Figure 1.1.

Our Cosmic Address Earth is a *planet* in our **solar system**, which consists of the Sun, the planets and their moons, and countless smaller objects that include rocky *asteroids* and icy *comets*. Keep in mind that our Sun is a *star*, just like the stars we see in our night sky.

Our solar system belongs to the huge, disk-shaped collection of stars called the **Milky Way Galaxy**. A **galaxy** is a great island of stars in space, all held together by gravity and orbiting a common center. The Milky Way is a relatively large galaxy, containing more than 100 billion stars, and we think that most of these stars are orbited by planets. Our solar system is located a little over halfway from the galactic center to the edge of the galactic disk.

Billions of other galaxies are scattered throughout space. Some galaxies are fairly isolated, but most are found in groups. Our Milky Way, for example, is one of the two largest among more than 70 galaxies (most relatively small) in the **Local Group**. Groups of galaxies with many more large members are often called **galaxy clusters**.

On a very large scale, galaxies and galaxy clusters appear to be arranged in giant chains and sheets with huge voids between them; the background of Figure 1.1 represents this large-scale structure. The regions in which galaxies and galaxy clusters are most tightly packed are called **superclusters**, which are essentially clusters of galaxy clusters. Our Local Group is located in the outskirts of the Local Supercluster (also called *Laniakea*, Hawaiian for “immense heaven”).

think about it Some people think that our tiny physical size in the vast universe makes us insignificant. Others think that our ability to learn about the wonders of the universe gives us significance despite our small size. What do *you* think?

Together, all these structures make up our **universe**. In other words, the universe is the sum total of all matter and energy, encompassing the superclusters and voids and everything within them.

Astronomical Distance Measurements The labels in Figure 1.1 give approximate sizes for the various structures in kilometers (recall that 1 kilometer \approx 0.6 mile), but many distances in astronomy are so large that kilometers are not the most convenient unit. Instead, we often use two other units:

- One **astronomical unit (AU)** is Earth's average distance from the Sun, which is about 150 million kilometers (93 million miles). We commonly describe distances within our solar system in AU.

Our Cosmic Address

▼ **FIGURE 1.1**

These paintings show key levels of structure in our universe; for a more detailed view, see the "You Are Here in Space" foldout diagram in the front of the book.

Universe

approx. size: 10^{21} km \approx 100 million ly

Local Supercluster

approx. size: 3×10^{19} km \approx 3 million ly

Local Group

approx. size:
 10^{18} km \approx 100,000 ly

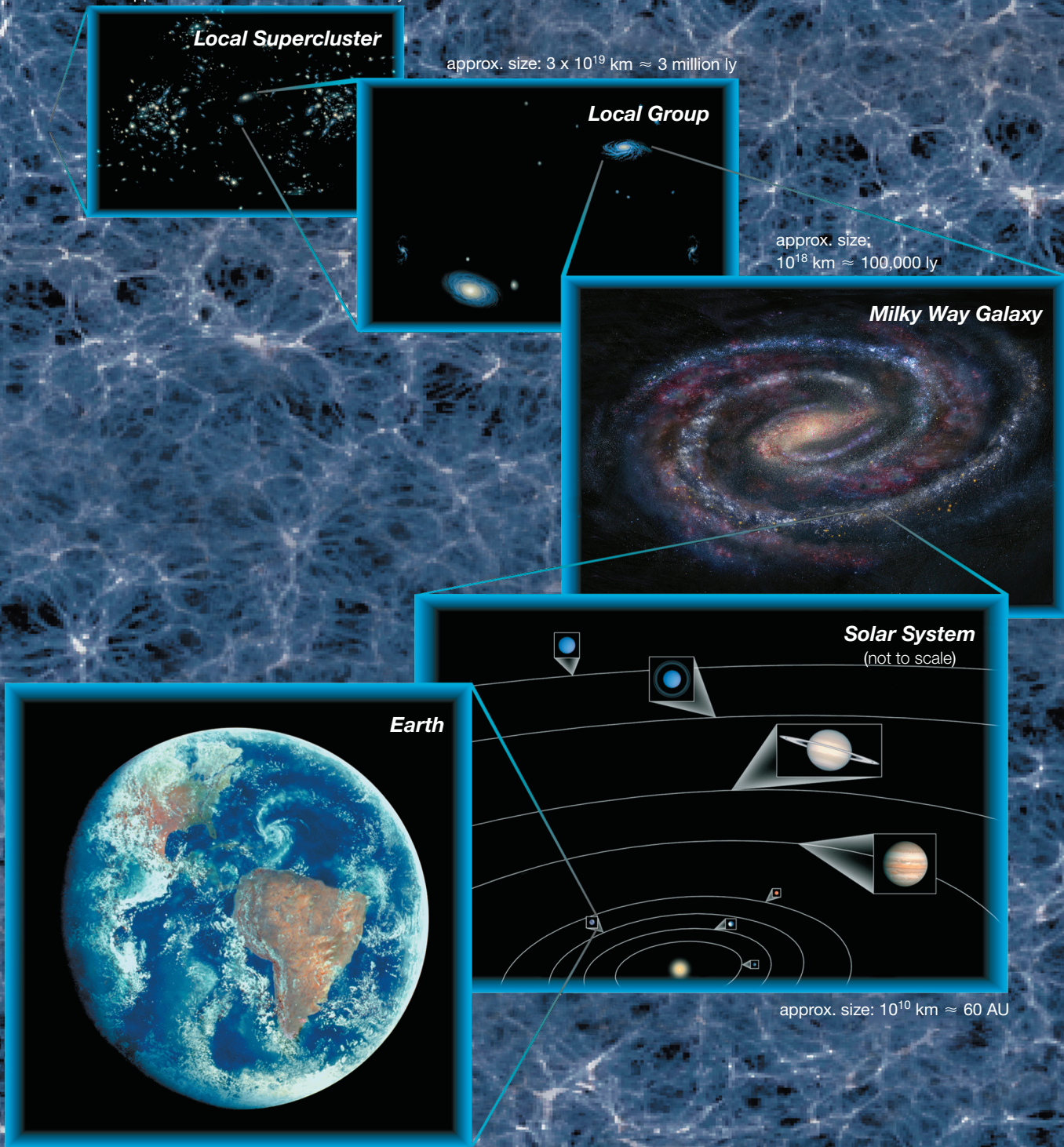
Milky Way Galaxy

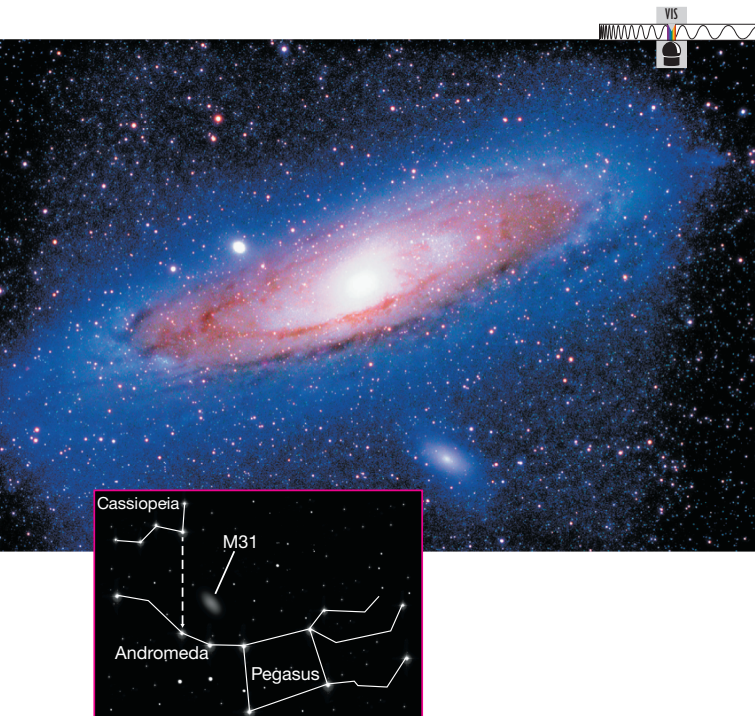
Solar System
(not to scale)

Earth

approx. size: 10^{10} km \approx 60 AU

approx. size: 10^4 km





▲ FIGURE 1.2

The Andromeda Galaxy (also known as M31). When we look at this galaxy, we see light that traveled through space for 2.5 million years. The inset shows the galaxy's location in the constellation Andromeda.

- One **light-year (ly)** is the *distance* that light can travel in 1 year, which is about 10 trillion kilometers (see Tools of Science, page 10). We generally use light-years to describe the distances of stars and galaxies.

Looking Back in Time Light-years are a unit of distance, but they are related to the time it takes light to travel through space. Consider Sirius, the brightest star in the night sky, which is located about 8 light-years away. Because it takes light 8 years to travel this distance, we see Sirius not as it is today, but rather as it was 8 years ago. The star Betelgeuse, a bright red star in the constellation Orion, is about 600 light-years away, which means we see it as it was about 600 years ago. If Betelgeuse exploded in the past 600 years or so (a possibility we'll discuss in Chapter 9), we would not yet know it, because the light from the explosion would not yet have reached us.

The general idea that light takes time to travel through space leads to a remarkable fact: **The farther away we look in distance, the further back we look in time.** The effect is dramatic for large distances. The Andromeda Galaxy (Figure 1.2) is about 2.5 million light-years away, which means we see it as it looked about 2.5 million years ago. We see more distant galaxies as they were even further in the past.

It's also amazing to realize that any "snapshot" of a distant galaxy is a picture of both space and time. For example, because the Andromeda Galaxy is about 100,000 light-years in diameter, the light we see from the far side of the galaxy must have left on its journey to us some 100,000 years before the light from the near side. Figure 1.2 therefore shows different parts of the galaxy spread over a time period of 100,000 years. When we study the universe, it is impossible to separate space and time.

see it for yourself

The glow from the central region of the Andromeda Galaxy is faintly visible to the naked eye and easy to see with binoculars. Use a star chart to find it in the night sky, and remember that you are seeing light that spent 2.5 million years in space before reaching your eyes. If students on a planet in the Andromeda Galaxy were looking at the Milky Way right now, what would they see? Could they know that we exist here on Earth?

The Observable Universe As we'll discuss in Section 1.2, the measured age of the universe is about 14 billion years. This fact, combined with the fact that looking deep into space means looking far back in time, places a limit on the portion of the universe that we can see, even in principle.

Figure 1.3 shows the idea. If we look at a galaxy that is 7 billion light-years away, we see it as it looked 7 billion years ago*—which means we see it as it was when the universe was half its current age. If we look at a galaxy that is 12 billion light-years away (like the most distant ones in the Hubble Space Telescope photo on page 1), we see it as it was 12 billion years ago, when the universe was only 2 billion years old. And if we tried to look beyond 14 billion light-years, we'd be looking to a time more than 14 billion years ago—which is before the universe existed and therefore means that there is nothing to see. This distance of 14 billion light-years therefore marks the boundary (or *horizon*) of our **observable universe**—the portion of the entire universe that we can potentially observe. Note that this fact does not put any limit on the size of the *entire* universe, which may be far larger than our observable universe. We simply have no hope of seeing or studying anything beyond the bounds of our observable universe.

*As we'll discuss in Chapter 12, distances to faraway galaxies in an expanding universe can be described in more than one way; distances like those given here are based on the time it has taken a galaxy's light to reach us (called the *lookback time*).

common misconceptions

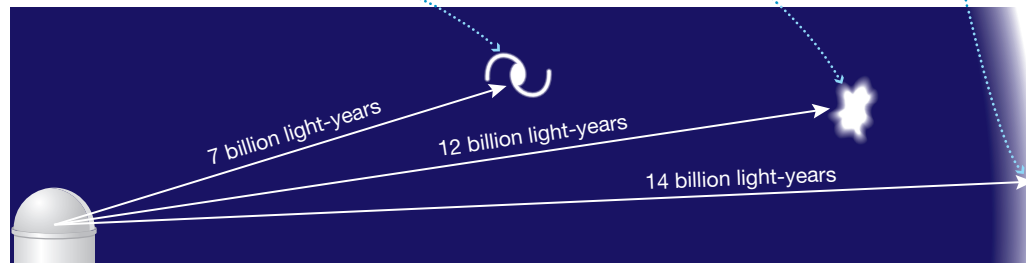
The Meaning of a Light-Year

Maybe you've heard people say things like "It will take me light-years to finish this homework!" But that statement doesn't make sense, because light-years are a unit of *distance*, not time. If you are unsure whether the term *light-year* is being used correctly, try testing the statement by using the fact that 1 light-year is about 10 trillion kilometers, or 6 trillion miles. The statement then becomes "It will take me 6 trillion miles to finish this homework," which clearly does not make sense.

Far: We see a galaxy 7 billion light-years away as it was 7 billion years ago—when the universe was half its current age of 14 billion years.

Farther: We see a galaxy 12 billion light-years away as it was 12 billion years ago—when the universe was only about 2 billion years old.

The limit of our observable universe: Light from nearly 14 billion light-years away shows the universe as it looked shortly after the Big Bang, before galaxies existed.



Beyond the observable universe: We cannot see anything farther than 14 billion light-years away, because light has not had enough time to reach us.

▲ **FIGURE 1.3** 

The farther away we look in space, the further back we look in time. The age of the universe therefore puts a limit on the size of the *observable* universe—the portion of the entire universe that we could observe in principle.

basic astronomical objects, units, and motions

This box summarizes key definitions used throughout this book.

Basic Astronomical Objects

star A large, glowing ball of gas that generates heat and light through nuclear fusion in its core. Our Sun is a star.

planet A moderately large object that orbits a star and shines primarily by reflecting light from its star. According to the current definition, an object can be considered a planet only if (1) orbits a star, (2) is large enough for its own gravity to make it round, and (3) has cleared most other objects from its orbital path. An object that meets the first two criteria but not the third, like Pluto, is designated a **dwarf planet**.

moon (or **satellite**) An object that orbits a planet. The term *satellite* is also used more generally to refer to any object orbiting another object.

asteroid A relatively small and rocky object that orbits a star.

comet A relatively small and ice-rich object that orbits a star.

small solar system body An asteroid, comet, or other object that orbits a star but is too small to qualify as a planet or dwarf planet.

Collections of Astronomical Objects

solar system The Sun and all the material that orbits it, including the planets, dwarf planets, and small solar system bodies. Although the term *solar system* technically refers only to our own star system (*solar* means “of the Sun”), it is often applied to other star systems as well.

star system A star (sometimes more than one star) and any planets and other materials that orbit it.

galaxy A great island of stars in space, all held together by gravity and orbiting a common center, with a total mass equivalent to millions, billions, or even trillions of stars.

cluster of galaxies (or **group of galaxies**) A collection of galaxies bound together by gravity. Small collections (up to a few dozen galaxies) are generally called *groups*, while larger collections are called *clusters*.

supercluster A gigantic region of space where many individual galaxies and many groups and clusters of galaxies are packed more closely together than elsewhere in the universe.

universe (or **cosmos**) The sum total of all matter and energy—that is, all galaxies and everything between them.

observable universe The portion of the entire universe that can be seen from Earth, at least in principle. The observable universe is probably only a tiny portion of the entire universe.

Astronomical Distance Units

astronomical unit (AU) The average distance between Earth and the Sun, which is about 150 million kilometers. More technically, 1 AU is the length of the semimajor axis of Earth’s orbit.

light-year (ly) The distance that light can travel in 1 year, which is about 9.46 trillion kilometers.

Terms Relating to Motion

rotation The spinning of an object around its axis. For example, Earth rotates once each day around its axis, which is an imaginary line connecting the North and South Poles.

orbit (or **revolution**) The orbital motion of one object around another due to gravity. For example, Earth orbits around the Sun once each year.

expansion (of the universe) The increase in the average distance between galaxies as time progresses.

about 15 meters (16.5 yards) from the grapefruit-sized Sun, which means you can picture Earth's orbit as a circle of radius 15 meters around a grapefruit.

Perhaps the most striking feature of our solar system when we view it to scale is its emptiness. The Voyage model shows the planets along a straight path, so we'd need to draw each planet's orbit around the model Sun to show the full extent of our planetary system. Fitting all these orbits would require an area measuring more than a kilometer on a side—an area equivalent to more than 300 football fields arranged in a grid. Spread over this large area, only the grapefruit-size Sun, the planets, and a few moons would be big enough to see. The rest of the area would look virtually empty (that's why we call it *space!*).

Seeing our solar system to scale also helps put space exploration into perspective. The Moon, the only other world on which humans have ever stepped (Figure 1.6), lies only about 4 centimeters ($1\frac{1}{2}$ inches) from Earth in the Voyage model. On this scale, the palm of your hand can cover the entire region of the universe in which humans have so far traveled. The trip to Mars is more than 150 times as far as the trip to the Moon, even when Mars is on the same side of its orbit as Earth. And while you can walk from Earth to Pluto in just a few minutes on the Voyage scale, the *New Horizons* spacecraft, which flew past Pluto in 2015, took more than 9 years to make the real journey, despite traveling at a speed nearly 100 times that of a commercial jet.

Distance to Stars If you visit the Voyage model in Washington, D.C., you need to walk only about 600 meters to go from the Sun to Pluto. How much farther would you have to walk to reach the next star on this scale?

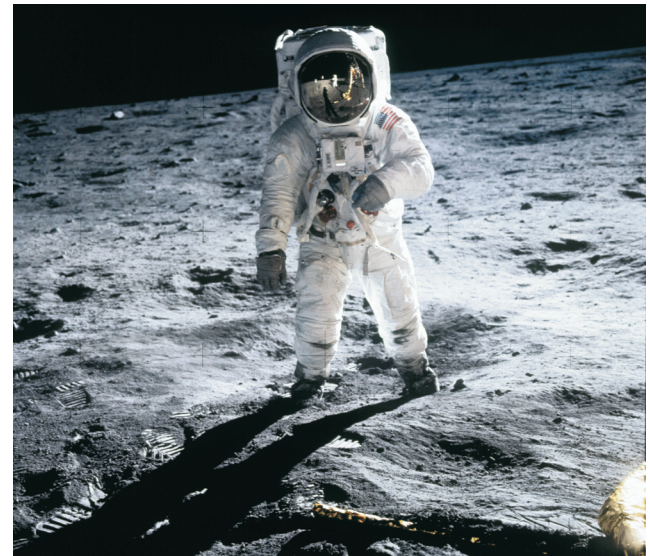
Amazingly, you would need to walk to California. If this answer seems hard to believe, you can check it for yourself. A light-year is about 10 trillion kilometers, which becomes 1000 kilometers on the 1-to-10-billion scale (because $10 \text{ trillion} \div 10 \text{ billion} = 1000$). The nearest star system to our own, a three-star system called Alpha Centauri (Figure 1.7), is about 4.4 light-years away. That distance is about 4400 kilometers (2700 miles) on the 1-to-10-billion scale, roughly equivalent to the distance across the United States.

The tremendous distances to the stars give us some perspective on the technological challenge of astronomy. For example, because the largest star of the Alpha Centauri system is roughly the same size and brightness as our Sun, viewing it in the night sky is somewhat like being in Washington, D.C., and seeing a very bright grapefruit in San Francisco (neglecting the problems introduced by the curvature of the Earth). It may seem remarkable that we can see this star at all, but the blackness of the night sky allows the naked eye to see it as a faint dot of light. It looks much brighter through powerful telescopes, but we still cannot see features of the star's surface.

Now, consider the difficulty of detecting *planets* orbiting nearby stars, which is equivalent to looking from Washington, D.C., and trying to find ball points or marbles orbiting grapefruits in California or beyond. When you consider this challenge, it is all the more amazing to realize that we now have technology capable of finding such planets [Section 7.1].

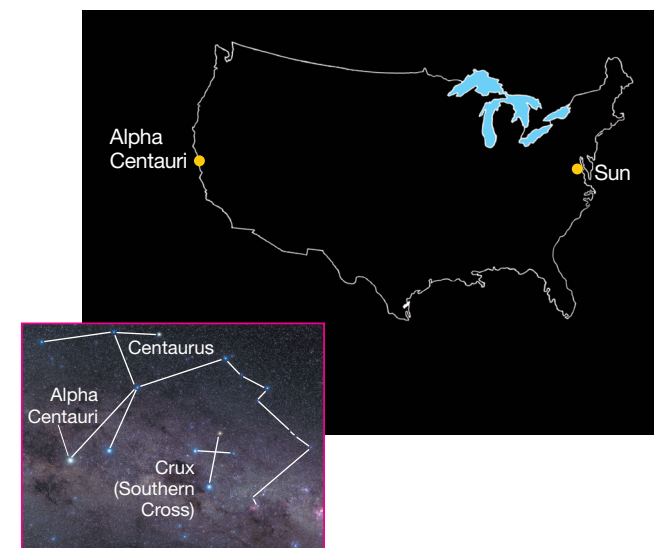
The vast distances to the stars also offer a sobering lesson about interstellar travel. Although science fiction shows like *Star Trek* and *Star Wars* make such travel look easy, the reality is far different. Consider the *Voyager 2* spacecraft. Launched in 1977, *Voyager 2* flew by Jupiter in 1979, Saturn in 1981, Uranus in 1986, and Neptune in 1989. It is now bound for the stars at a speed of close to 50,000 kilometers per hour—about 100 times as fast as a speeding bullet. But even at this speed, *Voyager 2* would take about 100,000 years to reach Alpha Centauri if it were headed in that direction (which it's not). Convenient interstellar travel remains well beyond our present technology.

The Size of the Milky Way Galaxy We must change our scale to visualize the galaxy, because very few stars would even fit on Earth with the 1-to-10-billion



▲ **FIGURE 1.6**

This famous photograph from the first Moon landing (*Apollo 11* in July 1969) shows astronaut Buzz Aldrin, with Neil Armstrong reflected in his visor. Armstrong was the first to step onto the Moon's surface, saying, "That's one small step for a man, one giant leap for mankind." (When asked why this photo became so iconic, Aldrin replied, "Location, location, location!")



▲ **FIGURE 1.7**

On the same 1-to-10-billion scale on which you can walk from the Sun to Pluto in just a few minutes, you'd need to cross the United States to reach Alpha Centauri, the nearest other star system. The inset shows the location and appearance of Alpha Centauri among the constellations.



▲ **FIGURE 1.8**

This painting shows the Milky Way Galaxy on a scale where its diameter is the length of a football field. On this scale, stars are microscopic and the distance between our solar system and Alpha Centauri is only 4.4 millimeters. There are so many stars in our galaxy that it would take thousands of years just to count them out loud.



▲ **FIGURE 1.9**

The number of stars in the observable universe is comparable to the number of grains of dry sand on all the beaches on Earth.

scale we used to visualize the solar system. Let's therefore reduce our scale by another factor of 1 billion (making it a scale of 1 to 10^{19}).

On this new scale, each light-year becomes 1 millimeter, and the 100,000-light-year diameter of the Milky Way Galaxy becomes 100 meters, or about the length of a football field. Visualize a football field with a scale model of our galaxy centered over midfield (Figure 1.8). Our entire solar system is a microscopic dot located around the 20-yard line. The 4.4-light-year separation between our solar system and Alpha Centauri becomes just 4.4 millimeters on this scale—smaller than the width of your little finger. If you stood at the position of our solar system in this model, millions of star systems would lie within reach of your arms.

Another way to put the galaxy into perspective is to consider its number of stars—more than 100 billion. Imagine that tonight you are having difficulty falling asleep (perhaps because you are contemplating the scale of the universe). Instead of counting sheep, you decide to count stars. If you are able to count about one star each second, how long would it take you to count 100 billion stars in the Milky Way? Clearly, the answer is 100 billion (10^{11}) seconds, but how long is that? Amazingly, 100 billion seconds is more than 3000 years. (You can confirm this by dividing 100 billion by the number of seconds in 1 year.) You would need thousands of years just to *count* the stars in the Milky Way Galaxy, and this assumes you never take a break—no sleeping, no eating, and absolutely no dying!

The Observable Universe As incredible as the scale of our galaxy may seem, the Milky Way is only one of more than 100 billion large galaxies in the observable universe. Just as it would take thousands of years to count the stars in the Milky Way, it would take thousands of years to count all these galaxies.

Think for a moment about the total number of stars in all these galaxies. If we assume 100 billion galaxies and 100 billion stars per galaxy, the total number of stars in the observable universe is roughly $100 \text{ billion} \times 100 \text{ billion}$, or 10,000,000,000,000,000,000 (10^{22}). How big is this number? Visit a beach. Run your hands through the fine-grained sand. Imagine counting each tiny grain of sand as it slips through your fingers. Then imagine counting every grain of sand on the beach and continuing to count *every* grain of dry sand on *every* beach on Earth. If you could actually complete this task, you would find that the number of grains of sand was comparable to the number of stars in the observable universe (Figure 1.9).

think about it

Contemplate the incredible numbers of stars in our galaxy and in the universe, and the fact that each star is a potential sun for a system of planets. How does this perspective affect your thoughts about the possibilities for finding life—or intelligent life—beyond Earth? Explain.

1.2 The History of the Universe

Our universe is vast not only in space, but also in time. In this section, we will briefly discuss the history of the universe as we understand it today.

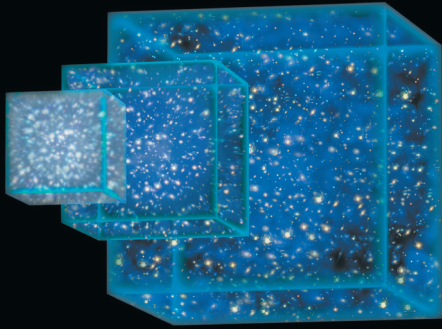
◆ How did we come to be?

Figure 1.10 summarizes the history of the universe according to modern science. Let's start at the upper left of the figure, and discuss the key events and what they mean.

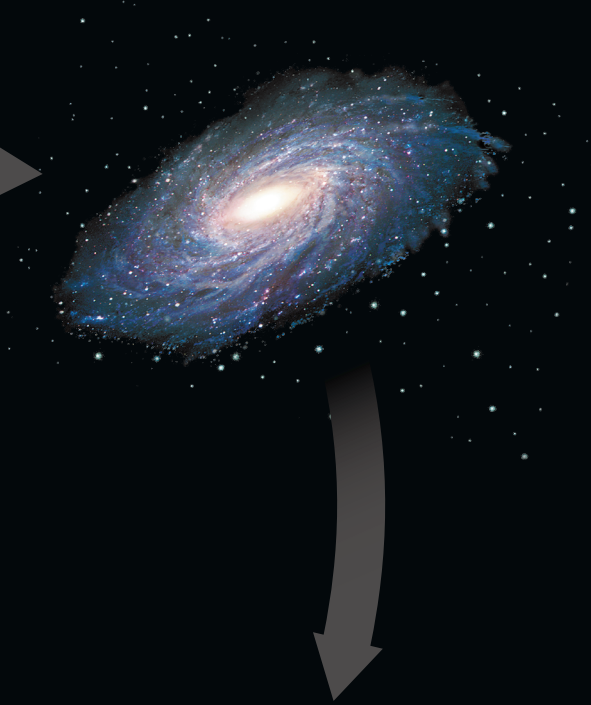
Our Cosmic Origins

▼ FIGURE 1.10

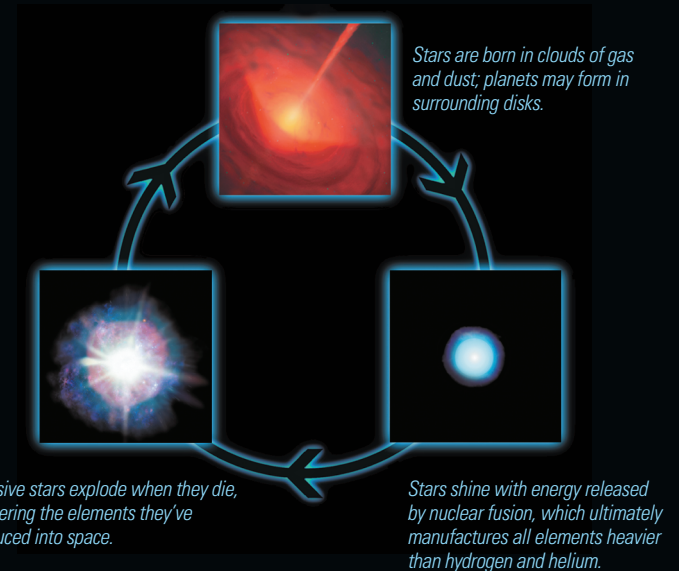
Birth of the Universe: The expansion of the universe began with the hot and dense Big Bang. The cubes show how one region of the universe has expanded with time. The universe continues to expand, but on smaller scales gravity has pulled matter together to make galaxies.



Galaxies as Cosmic Recycling Plants: The early universe contained only two chemical elements: hydrogen and helium. All other elements were made by stars and recycled from one stellar generation to the next within galaxies like our Milky Way.



Earth and Life: By the time our solar system was born, 4½ billion years ago, about 2% of the original hydrogen and helium had been converted into heavier elements. We are therefore “star stuff,” because we and our planet are made from elements manufactured in stars that lived and died long ago.



Life Cycles of Stars: Many generations of stars have lived and died in the Milky Way.

common misconceptions

Confusing Very Different Things

Most people are familiar with the terms *solar system* and *galaxy*, but few realize how incredibly different they are. Our solar system is a single star system, while our galaxy is a collection of more than 100 billion star systems—so many that it would take thousands of years just to count them. Moreover, if you look at the sizes in Figure 1.1, you'll see that our galaxy is about 100 million times larger in diameter than our solar system. So be careful; numerically speaking, mixing up *solar system* and *galaxy* is a gigantic mistake!

The Big Bang, Expansion, and the Age of the Universe Telescopic observations of distant galaxies show that the entire universe is *expanding*, meaning that average distances between galaxies are increasing with time. This fact implies that galaxies must have been closer together in the past, and if we go back far enough, we must reach the point at which the expansion began. We call this beginning the **Big Bang**, and scientists use the observed rate of expansion to calculate that it occurred about 14 billion years ago. The three cubes in the upper left corner of Figure 1.10 represent the expansion of a small piece of the entire universe through time.

The universe as a whole has continued to expand ever since the Big Bang, but on smaller scales the force of gravity has drawn matter together. Structures such as galaxies and galaxy clusters occupy regions where gravity has won out against the overall expansion. That is, while the universe as a whole continues to expand, individual galaxies and galaxy clusters (and objects within them such as stars and planets) do *not* expand. This idea is also illustrated by the three cubes in Figure 1.10. Notice that as the cube as a whole grew larger, the matter within it clumped into galaxies and galaxy clusters. Most galaxies, including our own Milky Way, formed within a few billion years after the Big Bang.

tools of science

Doing the Math

Mathematics is one of the most important tools of science, because it allows scientists to make precise, numerical predictions that can be tested through observations or experiments. These types of tests make it possible for us to gain confidence in scientific ideas. That is why the development of science and mathematics has often gone hand in hand. For example, Sir Isaac Newton developed the mathematics of calculus so that he could do the calculations necessary to test his theory of gravity, and Einstein used new mathematical ideas to work out the details of his general theory of relativity. Fortunately, you don't have to be a Newton or an Einstein to benefit from mathematics in science. Calculations using only multiplication and division can still provide important insights into scientific ideas. Let's look at a few examples.

EXAMPLE 1: How far is a light-year?

Solution: A light-year (ly) is the distance that light can travel in one year; recall that light travels at the *speed of light*, which is 300,000 km/s. Just as we can find the distance that a car travels in 2 hours by multiplying the car's speed by 2 hours, we can find a light-year by multiplying the speed of light by 1 year. Because we are given the speed of light in kilometers per second, we must carry out the multiplication while converting 1 year into seconds (see Appendix C for a review of unit conversions). The result is

$$\begin{aligned} 1 \text{ ly} &= \left(300,000 \frac{\text{km}}{\text{s}} \right) \times (1 \text{ yr}) \\ &= \left(300,000 \frac{\text{km}}{\text{s}} \right) \times \left(1 \text{ yr} \times 365 \frac{\text{day}}{\text{yr}} \times 24 \frac{\text{hr}}{\text{day}} \times 60 \frac{\text{min}}{\text{hr}} \times 60 \frac{\text{s}}{\text{min}} \right) \\ &= 9,460,000,000,000 \text{ km} \end{aligned}$$

That is, 1 light-year is equivalent to 9.46 trillion kilometers, which is easier to remember as almost 10 trillion kilometers.

EXAMPLE 2: How big is the Sun on the 1-to-10-billion scale?

Solution: The Sun's actual radius is 695,000 km, which we express in scientific notation as 6.95×10^5 km. (See Appendix C to review powers of 10

and scientific notation.) To find the Sun's radius on the 1-to-10-billion scale, we divide its actual radius by 10 billion, or 10^{10} :

$$\begin{aligned} \text{scaled radius} &= \frac{\text{actual radius}}{10^{10}} \\ &= \frac{6.95 \times 10^5 \text{ km}}{10^{10}} \\ &= 6.95 \times 10^{(5-10)} \text{ km} \\ &= 6.95 \times 10^{-5} \text{ km} \end{aligned}$$

This answer is easier to interpret if we convert it to centimeters, which we can do by recalling that there are 1000 ($= 10^3$) meters in a kilometer and 100 ($= 10^2$) centimeters in a meter:

$$6.95 \times 10^{-5} \text{ km} \times \frac{10^3 \text{ m}}{1 \text{ km}} \times \frac{10^2 \text{ cm}}{1 \text{ m}} = 6.95 \text{ cm}$$

On the 1-to-10-billion scale, the Sun is just under 7 centimeters in radius, or 14 centimeters in diameter.

EXAMPLE 3: How fast is Earth orbiting the Sun?

Solution: Earth completes one orbit in 1 year, so we can find its average orbital speed by dividing the circumference of its orbit by 1 year. Earth's orbit is nearly circular with a radius of 1 AU ($= 1.5 \times 10^8$ km); the circumference of a circle is given by the formula $2\pi \times \text{radius}$. If we want the speed to come out in units of km/hr, we divide this circumference by 1 year converted to hours, as follows:

$$\begin{aligned} \text{orbital speed} &= \frac{\text{orbital circumference}}{1 \text{ yr}} \\ &= \frac{2 \times \pi \times (1.5 \times 10^8 \text{ km})}{1 \text{ yr} \times \frac{365 \text{ day}}{\text{yr}} \times \frac{24 \text{ hr}}{\text{day}}} \\ &\approx 107,000 \text{ km/hr} \end{aligned}$$

Earth's average speed as it orbits the Sun is more than 100,000 km/hr.

Stellar Lives and Galactic Recycling Within galaxies like the Milky Way, gravity drives the collapse of clouds of gas and dust to form stars and planets. Stars are not living organisms, but they nonetheless go through “life cycles.” A star is born when gravity compresses the material in a cloud to the point at which the center becomes dense enough and hot enough to generate energy by **nuclear fusion**, the process in which lightweight atomic nuclei smash together and stick (or fuse) to make heavier nuclei. The star “lives” as long as it can shine with energy from fusion, and “dies” when it exhausts its usable fuel.

In its final death throes, a star blows much of its content back out into space. The most massive stars die in titanic explosions called *supernovae*. The returned matter mixes with other matter floating between the stars in the galaxy, eventually becoming part of new clouds of gas and dust from which new generations of stars can be born. Galaxies therefore function as cosmic recycling plants, recycling material expelled from dying stars into new generations of stars and planets. This cycle is illustrated in the lower right of Figure 1.10. Our own solar system is a product of many generations of such recycling.

Star Stuff The recycling of stellar material is connected to our existence in an even deeper way. By studying stars of different ages, we have learned that the early universe contained only the simplest chemical elements: hydrogen and helium (and a trace of lithium). We and Earth are made primarily of other elements, such as carbon, nitrogen, oxygen, and iron. Where did these other elements come from? Evidence shows that they were manufactured by stars, some through the nuclear fusion that makes stars shine and most others through nuclear reactions accompanying the explosions that end stellar lives.

By the time our solar system formed, about $4\frac{1}{2}$ billion years ago, earlier generations of stars had already converted up to 2% of our galaxy’s original hydrogen and helium into heavier elements. Therefore, the cloud that gave birth to our solar system was made of roughly 98% hydrogen and helium and 2% other elements. This 2% may sound small, but it was more than enough to make the small rocky planets of our solar system, including Earth. On Earth, some of these elements became the raw ingredients of life, which ultimately blossomed into the great diversity of life on Earth today.

In summary, most of the material from which we and our planet are made was created inside stars that lived and died before the birth of our Sun. As astronomer Carl Sagan (1934–1996) said, we are “star stuff.”

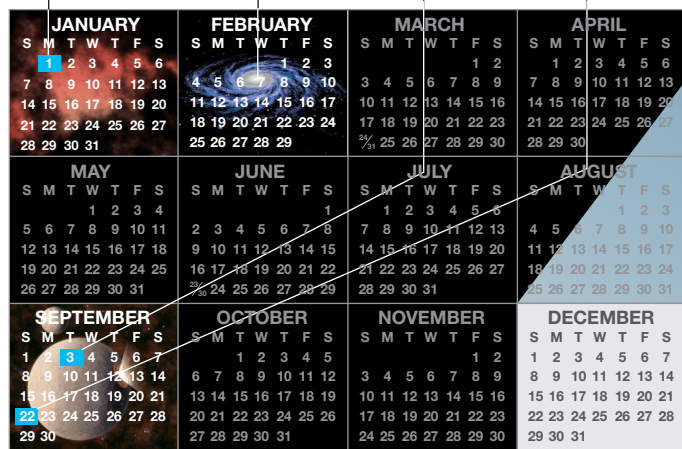
◆ How do our lifetimes compare to the age of the universe?

We can put the 14-billion-year age of the universe into perspective by imagining this time compressed into a single year, so each month represents a little more than 1 billion years. On this *cosmic calendar*, the Big Bang occurs at the first instant of January 1 and the present is the stroke of midnight on December 31 (Figure 1.11).

On this time scale, the Milky Way Galaxy probably formed in February. Many generations of stars lived and died in the subsequent cosmic months, enriching the galaxy with the “star stuff” from which we and our planet are made.

Our solar system and our planet did not form until early September on this scale, or $4\frac{1}{2}$ billion years ago in real time. By late September, life on Earth was flourishing. However, for most of Earth’s history, living organisms remained relatively primitive and microscopic. On the scale of the cosmic calendar, recognizable animals became prominent only in mid-December. Early dinosaurs appeared on the day after Christmas. Then, in a cosmic instant, the dinosaurs disappeared forever—probably because of the impact of an asteroid or a comet [Section 6.3]. In real time the death of the dinosaurs occurred some 65 million years ago, but on the cosmic calendar it was only yesterday. With the dinosaurs gone, small furry mammals

THE HISTORY OF THE UNIVERSE IN 1 YEAR

January 1:
The Big BangFebruary:
The Milky Way formsSeptember 3:
Earth formsSeptember 22:
Early life on EarthDecember 17:
Cambrian explosionDecember 26:
Rise of the dinosaursDecember 30:
Extinction of
the dinosaurs

▲ FIGURE 1.11

The cosmic calendar compresses the 14-billion-year history of the universe into 1 year, so that each month represents a little more than 1 billion years. (Adapted from the cosmic calendar created by Carl Sagan. For a more detailed version, see the “You Are Here in Time” foldout diagram in the front of the book.)

inherited Earth. Some 60 million years later, or at around 9 P.M. on December 31 of the cosmic calendar, early hominids (human ancestors) began to walk upright.

Perhaps the most astonishing thing about the cosmic calendar is that the entire history of human civilization falls into just the last half-minute. The ancient Egyptians built the pyramids only about 11 seconds ago on this scale. About 1 second ago, Kepler and Galileo proved that Earth orbits the Sun rather than vice versa. The average college student was born about 0.05 second ago, around 11:59:59.95 P.M. on the cosmic calendar. On the scale of cosmic time, the human species is the youngest of infants, and a human lifetime is a mere blink of an eye.

think about it Study the more detailed cosmic calendar found on the foldout in the front of this book. How does an understanding of the scale of time affect your view of human civilization? Explain.



THE PROCESS OF SCIENCE IN ACTION

1.3 Defining Planets

One of the goals of this book is to help you learn more about science in general as you study the science of astronomy. We will therefore conclude each chapter with a case study that illustrates the process of science in action. Here, we look at the process of scientific classification, focusing on the challenge of defining the seemingly simple term *planet*.

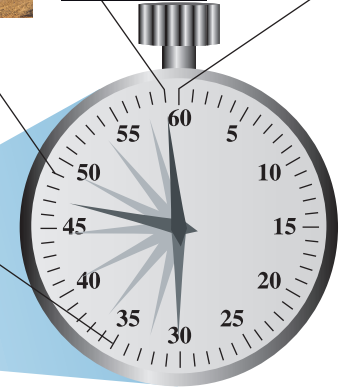
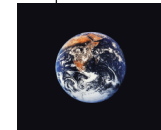
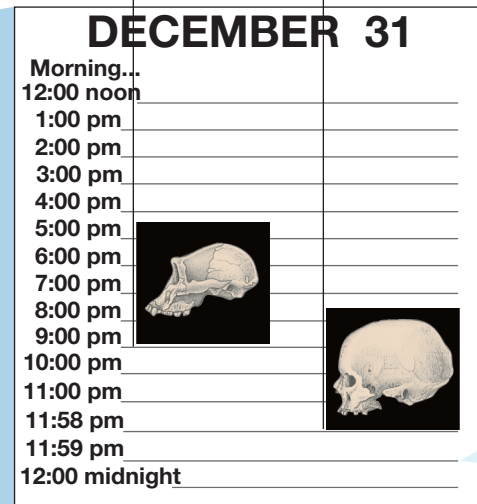
Science begins with observations of the world around us, and after observing we often try to classify the objects we find. Scientific classification helps us organize our thinking and provides a common language for discussion. In this chapter, we have already classified objects into categories such as planets, stars, and galaxies. The box on page 5 provides basic definitions for these categories but does not explain *how* we came to classify objects in this way. The story behind the definition of *planet* provides an excellent example of how scientists classify objects and how scientific classification must adapt to new discoveries.

December 31:**9:00 pm:**

Early hominids evolve

11:58 pm:

Modern humans evolve

25 seconds ago:
Agriculture arises**11 seconds ago:**
Pyramids built**1 second ago:**Kepler and Galileo
show that Earth
orbits the Sun**Now**

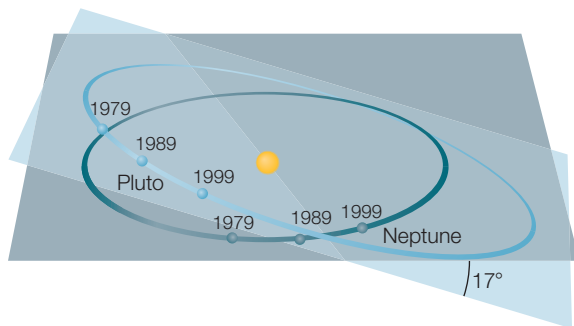
◆ What is a planet?

The difference between a star and a planet is not obvious from a casual glance at the night sky. In fact, the term *star* historically applied to almost any shining object in the night sky, including the planets and even the brief flashes of light known as “shooting stars” (or *meteors*), which we now know to be caused by comet dust entering Earth’s atmosphere. To the naked eye, the difference between stars and planets becomes clear only if you observe the sky over a period of many days or weeks: Stars remain fixed in the patterns of the constellations, while planets appear to move slowly among the constellations of stars [Section 2.3].

Planets as Wanderers The word *planet* comes from the Greek for “wanderer,” and in ancient times it applied to all objects that appear to move, or wander, among the constellations. The Sun and the Moon were counted as planets, because they move steadily through the constellations. Earth did *not* count as a planet, since it is not something we see in the sky and it was presumed to be stationary at the center of the universe. Ancient observers therefore recognized seven objects as planets: the Sun, the Moon, and the five planets that are easily visible to the naked eye (Mercury, Venus, Mars, Jupiter, and Saturn). The special status of these seven objects is still enshrined in the names of the seven days of the week. In English, only Sunday, “Moonday,” and “Saturday” are obvious, but if you know a romance language like Spanish you’ll be able to figure out the rest: Tuesday is Mars day (*martes*), Wednesday is Mercury day (*miércoles*), Thursday is Jupiter day (*jueves*), and Friday is Venus day (*viernes*).

This original definition of *planet* began to change about 400 years ago, when we learned that Earth is *not* the center of the universe but rather an object that orbits the Sun. The term *planet* then came to mean any object that orbits the Sun, which added Earth to the list of planets and removed the Sun and Moon (because the Moon orbits Earth). This definition successfully accommodated the planets Uranus and Neptune after their discoveries in 1781 and 1846, respectively, and it can also be easily adapted for planets around other stars.

A weakness of this definition became apparent as scientists began to discover asteroids, starting with the discovery of Ceres in 1801. Ceres was initially hailed



▲ FIGURE 1.12

Pluto's orbit is significantly elongated and tilted with respect to those of the other planets. Pluto even comes closer than Neptune to the Sun for 20 years in each 248-year orbit, as was the case between 1979 and 1999. There's no danger of a collision, however, because Neptune completes exactly three orbits for every two of Pluto's orbits.

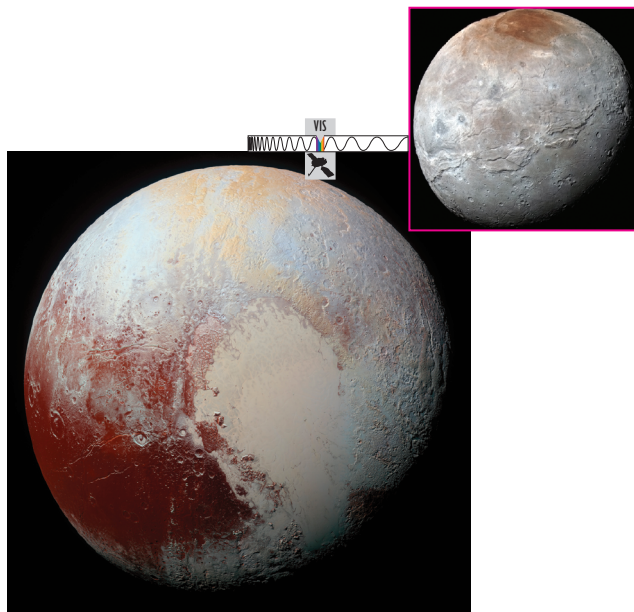
as a new “planet,” but as the number of known asteroids grew—and as we realized that asteroids were all much smaller than the traditional planets—scientists decided that these relatively small worlds should count only as “minor planets.” Today we refer to “minor planets” as asteroids or comets, depending on their composition, though larger ones, such as Ceres, also qualify as *dwarf planets*.

The Case of Pluto The most recent change in the definition of *planet* comes from the story of Pluto. Pluto was quickly given planetary status upon its discovery in 1930, partly because astronomers were actively searching for a planet but also because they initially overestimated its mass. Still, it was clear from the start that Pluto was a misfit among the known planets. Its 248-year orbit around the Sun is more elongated in shape than that of any other planet. Its orbit is also significantly tilted relative to the orbits of the other planets (Figure 1.12). It became even more of a misfit after astronomers pinned down its mass and composition: Pluto is only about $\frac{1}{25}$ as massive as Mercury, smallest of the first eight planets, and its ice-rich composition is more similar to that of a comet than to that of any of the other planets.

Pluto's low mass, unusual orbit, and comet-like composition eventually began to cause controversy over its status as a planet. Scientists had known since the 1950s that many of the comets that we see in the inner solar system come from the same region of the solar system in which Pluto orbits (called the *Kuiper belt* [Section 4.1]). By the 1990s, advancing telescope technology had made it possible for astronomers to discover vast numbers of objects orbiting within the Kuiper belt, including some that were not much smaller than Pluto. Then, in 2005, astronomer Mike Brown announced the discovery of Eris, which is slightly more massive than Pluto. This discovery forced astronomers to consider the question of whether Eris and other objects similar in size to Pluto should count as planets.

Decisions on astronomical names and definitions are officially made by the International Astronomical Union (IAU), which is made up of astronomers from nations around the world. Members of the IAU considered numerous possible definitions of the term *planet*. One proposed definition would have applied the term to any object large enough for its own gravity to make it round. Proponents of this definition argued that it would make planetary status depend only on an object's intrinsic characteristics (as opposed to also including orbital properties), and that roundness is a good indicator of whether an object is large enough to have had any “planet-like” geological activity during its history; this latter idea was confirmed by the dramatic images of Pluto and its moon Charon obtained by the *New Horizons* spacecraft during its 2015 flyby (Figure 1.13). Those arguing against this definition pointed out that, in addition to significantly raising the official number of planets in our solar system, it would also have meant counting numerous large moons — including Earth's Moon — as planets.

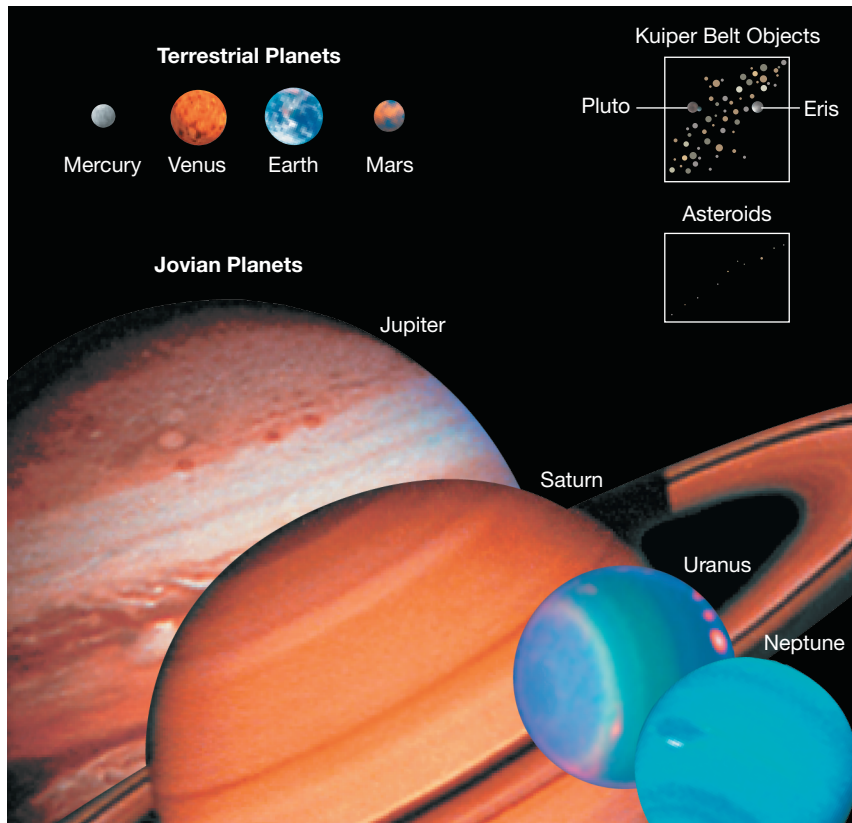
The definition that ultimately won out (in an IAU vote held in 2006) focused on both size and orbits, defining a planet as an object that (1) orbits a star (but is not itself a star),* (2) is massive enough for its own gravity to make it round, and (3) dominates its orbital region. This definition leaves out moons because they orbit planets rather than stars, and it leaves out Pluto and Eris because, although they orbit the Sun and are round, they share their orbital region with many similarly sized objects.



▲ FIGURE 1.13

Pluto and its largest moon, Charon (shown to scale), as seen by the *New Horizons* spacecraft during its 2015 flyby of them. As we'll discuss further in Chapter 6, the visible surface features offer clear evidence that both worlds have had interesting geological histories, and Pluto may have ongoing geological activity.

*The officially adopted definition refers only to objects orbiting *our Sun*, but astronomers have generally applied the definition in a way that also allows us to refer to “planets” orbiting other stars.



▲ **FIGURE 1.14** Relative sizes of various objects in the solar system. Notice that the eight planets divide clearly into two groups, known as the *jovian planets* (Jupiter, Saturn, Uranus, and Neptune) and the *terrestrial planets* (Mercury, Venus, Earth, and Mars). Pluto and Eris clearly belong to a group of much smaller but more numerous objects.

Future Challenges The adopted definition of *planet* still stirs some controversy, but it works well in dividing the objects of our solar system by size: Figure 1.14 shows that the eight planets clearly divide into two groups, while Pluto and Eris clearly belong to a different group. Nevertheless, the current definition is likely to face future challenges, including one that may arise fairly soon. Over the past few years, astronomers have discovered that many small objects in the outer solar system appear to be following an orbital pattern suggesting that they are being tugged on by the gravity of an undiscovered object at least several times as massive as Earth. As this book goes to press, astronomers are actively searching for such an object, which has been called “planet nine.” But note that, if it really exists, this object would likely be sharing the same general region of the solar system with many other ice-rich objects, which would mean it would not count as a planet under the current definition, despite its large size. And even if this object turns out not to exist in our solar system, we will probably find similar objects in other solar systems, forcing us once again to reconsider the definition of a planet.

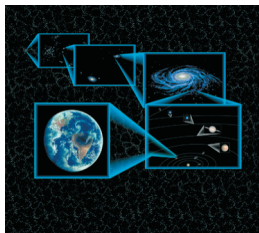
Perhaps the most important scientific idea to take away from this debate is that nature need not obey the classification systems we propose. Whether we call an object like Pluto a planet, a dwarf planet, or a large comet may affect the way we think about it, but it does not change what it actually is or our scientific interest in it. A key part of science is learning to adapt our own notions of organization to the underlying reality of nature. As we discover new things, we must sometimes change our definitions.

think about it How would *you* define “planet,” and why? Defend your choice.

summary of key concepts

1.1 The Scale of the Universe

◆ What is our place in the universe?



Earth is a planet orbiting the Sun. Our Sun is one of more than 100 billion stars in the **Milky Way Galaxy**. Our galaxy is one of more than 70 galaxies in the **Local Group**. The Local Group is one small part of the **Local Supercluster**, which is one small part of the **universe**.

◆ How big is the universe?

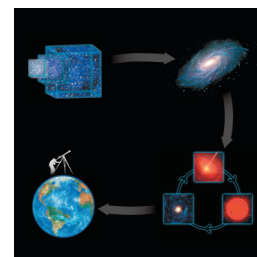


On a 1-to-10-billion scale, the Sun is the size of a grapefruit, Earth is a ball point about 15 meters away, and the nearest stars are thousands of kilometers away. Our galaxy has so many stars that it would take

thousands of years just to count them out loud. The **observable universe** contains more than 100 billion galaxies, and the total number of stars is comparable to the number of grains of dry sand on all the beaches on Earth.

1.2 The History of the Universe

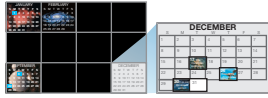
◆ How did we come to be?



The universe began in the **Big Bang** and has been expanding ever since, except in localized regions where gravity has caused matter to collapse into galaxies and stars. The Big Bang essentially produced only two chemical elements: hydrogen and helium. The rest have been produced by stars and recycled within galaxies

from one generation of stars to the next, which is why we are “star stuff.”

◆ How do our lifetimes compare to the age of the universe?



On a cosmic calendar that compresses the history of the universe into 1 year, human civilization is just a few seconds old, and a human lifetime lasts only a fraction of a second.



THE PROCESS OF SCIENCE IN ACTION

1.3 Defining Planets

◆ What is a planet?



The definition of the term *planet* has changed over time. It originally referred to objects that wandered among the constellations, but now applies to Earth and seven other objects in our solar system, while Pluto, Eris, and similar objects are classified as *dwarf planets*. The definition may yet change again, showing how scientific classification must adapt to new discoveries.

Investigations

For instructor-assigned homework and other learning materials, go to www.MasteringAstronomy.com.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning.

- Which of the following correctly lists our “cosmic address” from smallest to largest? (a) Earth, solar system, Milky Way Galaxy, Local Group, Local Supercluster, universe (b) Earth, solar system, Local Group, Local Supercluster, Milky Way Galaxy, universe (c) Earth, Milky Way Galaxy, solar system, Local Group, Local Supercluster, universe
- An *astronomical unit* is (a) any planet’s average distance from the Sun. (b) Earth’s average distance from the Sun. (c) any large astronomical distance.
- A *light-year* is (a) about 10 trillion kilometers. (b) the time it takes light to reach the nearest star. (c) the time it takes light to travel around the Sun.
- The star Betelgeuse is about 600 light-years away. If it explodes tonight, (a) we’ll know because it will be brighter than the full Moon. (b) we’ll know because debris from the explosion will rain down on us from space. (c) we won’t know about it until about 600 years from now.
- Could we see a galaxy that is 50 billion light-years away? (a) Yes, if we had a big enough telescope. (b) No, because it would be beyond the bounds of our observable universe. (c) No, because a galaxy could not possibly be that far away.
- If we represent the solar system on a scale that allows us to walk from the Sun to Pluto in a few minutes, then (a) the planets are the size of basketballs and the nearest stars are a few miles away. (b) the planets are marble size or smaller and the nearest stars are thousands of miles away. (c) the planets are microscopic and the stars are millions of miles away.
- The number of stars in the Milky Way Galaxy is roughly (a) 100,000. (b) 100 million. (c) 100 billion.
- When we say the universe is *expanding*, we mean that (a) everything in the universe is growing in size. (b) the average distance between galaxies is growing with time. (c) the universe is getting older.
- The *Big Bang* is the name astronomers give to (a) the explosion that occurs when a star dies. (b) the largest explosion ever observed. (c) the birth of the universe.
- We are “star stuff” in the sense that (a) we are made of elements that were produced in stars. (b) our bodies have the same chemical composition as stars. (c) we are born, live, and die, just like stars.
- The age of our solar system is about (a) $\frac{1}{2}$ of the age of the universe. (b) $\frac{3}{4}$ of the age of the universe. (c) the same as the age of the universe.
- The event that triggered the change in Pluto’s status from planet to dwarf planet was the discovery that (a) it is smaller than the planet Mercury. (b) it has a comet-like composition of ice and rock. (c) it is not the most massive object in its region of the solar system.

Short-Answer/Essay Questions

Explain all answers clearly, using complete sentences and proper essay structure if needed. An asterisk (*) designates a quantitative problem, for which you should show all your work.

- Our Cosmic Origins*. Write one to three paragraphs summarizing why we could not be here if the universe did not contain both stars and galaxies.
- Alien Technology*. Some people believe that Earth is regularly visited by aliens who travel here from other star systems. For this to be true, how much more advanced than our own technology would the alien space travel technology have to be? Write one to two paragraphs to give a sense of the technological difference. (*Hint*: The ideas of scale in this chapter can help you contrast the distance the aliens would have to travel with the distances we currently are capable of traveling.)
- Looking for Evidence*. In this first chapter, we have discussed the scientific story of the universe but have not yet discussed most of the evidence that backs it up. Choose one idea from this chapter—such as the idea that there are billions of galaxies, that the universe was born in the Big Bang, or that we are “star stuff”—and briefly discuss the type of evidence you would like to see before accepting the idea. (*Hint*: It’s okay to look ahead in the book to see the evidence presented in later chapters.)
- The Value of Classification*. Section 1.3 discussed difficulties that can arise with attempts to define scientific classifications precisely, such as those that occur with the term *planet*. Make a bullet list of pros and cons (at least three of each) of having classification schemes. Then write a one-paragraph summary stating your opinion of the value (or lack of value) of scientific classification.
- The Cosmic Perspective*. Write a one-page essay describing how the ideas presented in this chapter affect your perspectives on your own life and on human civilization.
- *18. *Light-Minute*. Just as a light-year is the distance that light can travel in 1 year, a light-minute is the distance that light can travel in 1 minute. What is a light-minute in kilometers?
- *19. *Sunlight*. Use the speed of light and the Earth–Sun distance of 1 AU to calculate how long it takes light to travel from the Sun to Earth.
- *20. *Cosmic Calendar*. The cosmic calendar condenses the 14-billion-year history of the universe into 1 year. How long does 1 second represent on the cosmic calendar?
- *21. *Saturn vs. the Milky Way*. Photos of Saturn with its rings can look so similar to photos of galaxies that children often think they are similar objects, but of course galaxies are far larger. About how many times larger in diameter is the Milky Way Galaxy than Saturn’s rings? (*Data*: Saturn’s rings are 270,000 km in diameter; the Milky Way is 100,000 light-years in diameter.)
- *22. *Galactic Rotation*. Our solar system is located about 27,000 light-years from the galactic center and orbits the center once every 230 million years. How fast are we traveling around the galaxy, in km/hr?



This time-exposure photo, taken at Arches National Park in Utah, shows how the entire sky seems to circle daily around a point above Earth's North Pole (or South Pole, for the Southern Hemisphere). Stars far to the north, like those visible within the arch, complete their entire circles above the northern horizon. Other stars—along with the Sun, Moon, and planets—follow circles that cross the horizon, which is why they rise in the east and set in the west each day. This daily circling of the sky explains why most of our ancestors assumed that the universe revolved around Earth. Today, we know that it is actually Earth's daily rotation that makes the sky appear to turn. How did we learn this fact? Through careful study of other, more subtle patterns of change in the sky, including the patterns we will study in this chapter.

LEARNING GOALS

2.1 Understanding the Seasons

- ◆ What causes the seasons?
- ◆ Why do the constellations we see depend on the time of year?

2.2 Understanding the Moon

- ◆ Why do we see phases of the Moon?
- ◆ What causes eclipses?



THE PROCESS OF SCIENCE IN ACTION

2.3 The Puzzle of Planetary Motion

- ◆ Why did the ancient Greeks reject the real explanation for planetary motion?

2.1 Understanding the Seasons

We're all familiar with seasonal changes, such as longer and warmer days in summer and shorter and cooler days in winter. But *why* do the seasons occur? We'll explore the answer in this section.

◆ What causes the seasons?

Seasons are a result of the way the tilt of Earth's axis causes sunlight to fall differently on Earth at different times of year. To understand exactly how this works, we'll first look at how Earth's rotation produces the apparent daily path of the Sun through the sky, then examine how Earth's axis tilt and orbit cause this path to change over the course of each year.

The Sun's Daily Path

The general pattern of the Sun's daily path through the sky is fairly simple: Unless you live within the Arctic or Antarctic circle, the Sun always rises somewhere in the east, reaches its highest point around noon, then sets somewhere in the west. Ancient people assumed that the Sun actually circled Earth each day, but we now know that its daily motion arises from Earth's rotation. Just as the world seems to circle around you if you spin in place, the Sun seems to go around us on our rotating planet. However, while the general pattern is always the same, the Sun's precise path through the sky varies with the seasons.

To describe the Sun's daily path more clearly, we need to define a few key reference points in the sky (Figure 2.1). The boundary between Earth and sky defines the **horizon**. The point directly overhead is the **zenith**. The **meridian** is an imaginary half-circle stretching from the horizon due south, through the zenith, to the horizon due north. We can pinpoint the position of any object in the sky by stating its *direction* along the horizon (sometimes expressed as *azimuth*) and its *altitude* above the horizon.

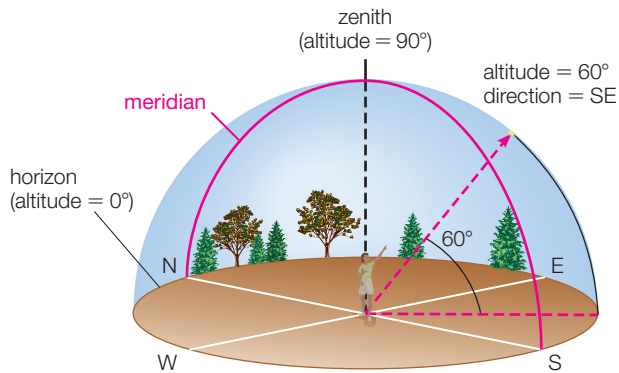
Figure 2.2 shows how the Sun's daily path differs at different times of year for a typical Northern Hemisphere location. Notice that the Sun's path is long and high in summer, with the Sun rising well north of due east and setting well north of due west. In winter, the Sun's path is short and low, as it rises well south of due east and sets well south of due west. Notice also that the Sun *never* passes directly overhead at this latitude. The Sun can reach the zenith only for locations within the *tropics*, meaning locations on Earth that are between latitudes of $23\frac{1}{2}^{\circ}\text{N}$ and $23\frac{1}{2}^{\circ}\text{S}$.

▶ The Reason for Seasons

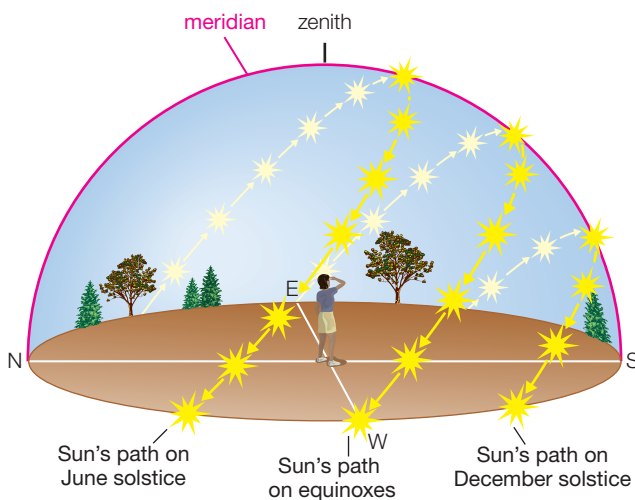
The Reason for Seasons

The causes of these seasonal changes in the Sun's path are summarized in the four steps of Figure 2.3 (pp. 20–21). Step 1 illustrates how Earth's rotation axis is tilted with respect to its orbit. Notice that the axis remains pointed in the same direction in space (toward the North Star, Polaris) throughout the year. As a result, the orientation of the axis *relative to the Sun* changes over the course of each orbit: The Northern Hemisphere is tipped toward the Sun in June and away from the Sun in December, while the reverse is true for the Southern Hemisphere. That is why the two hemispheres experience opposite seasons.

Step 2 shows Earth in June, when the axis tilt causes sunlight to strike the Northern Hemisphere at a steeper angle and the Southern Hemisphere at a shallower angle. The steeper sunlight angle makes it summer in the Northern Hemisphere, for two reasons. First, as shown in the zoom-out, the steeper angle means more concentrated sunlight, which tends to make it warmer. Second, if you visualize



▲ **FIGURE 2.1** From any place on Earth, the local sky looks like a dome (hemisphere). This diagram shows key reference points in the local sky. It also shows how we can describe any position in the local sky by its altitude and direction.



▲ **FIGURE 2.2** This diagram shows the Sun's path in different seasons for a Northern Hemisphere location (latitude 40°N). The precise paths are different for other latitudes.

what happens as Earth rotates each day, you'll see that the steeper angle also means the Sun follows a longer and higher path through the sky (the path shown for June in Figure 2.2), giving the Northern Hemisphere more hours of daylight during which it is warmed by the Sun. The opposite is true for the Southern Hemisphere at this time: The shallower sunlight angle makes it winter there, because sunlight is less concentrated and the Sun follows a shorter, lower path through the sky.

The sunlight angle gradually changes as Earth orbits the Sun. At the opposite side of Earth's orbit, Step 4 shows that it has become winter for the Northern Hemisphere and summer for the Southern Hemisphere. In between these two extremes, Step 3 shows that both hemispheres are illuminated equally in March and September. It is therefore spring for the hemisphere that is on the way from winter to summer, and fall for the hemisphere on the way from summer to winter.

The key point is this: Seasons occur because of the combination of Earth's axis tilt and its orbit around the Sun. If Earth did not have an axis tilt, we would not have seasons.

think about it Jupiter has an axis tilt of about 3° , small enough to be insignificant. Saturn has an axis tilt of about 27° , slightly greater than that of Earth. Both planets have nearly circular orbits around the Sun. Do you expect Jupiter to have seasons? Do you expect Saturn to have seasons? Explain.

Solstices and Equinoxes To help us mark the changing seasons, we define four special moments in the year, each of which corresponds to one of the four special positions in Earth's orbit shown in Figure 2.3.

- The **June solstice**, called the *summer solstice* in the Northern Hemisphere, occurs around June 21 and is the moment when the Northern Hemisphere is tipped most directly toward the Sun and receives the most direct sunlight.
- The **December solstice**, called the *winter solstice* in the Northern Hemisphere, occurs around December 21 and is the moment when the Northern Hemisphere receives the least direct sunlight.
- The **March equinox**, called the *spring* (or *vernal*) *equinox* in the Northern Hemisphere, occurs around March 21 and is the moment when the Northern Hemisphere goes from being tipped slightly away from the Sun to being tipped slightly toward the Sun.
- The **September equinox**, called the *fall* (or *autumnal*) *equinox* in the Northern Hemisphere, occurs around September 22 and is the moment when the Northern Hemisphere first starts to be tipped away from the Sun.

The exact dates and times of the solstices and equinoxes can vary by up to a couple days from the dates given above, depending on where we are in the leap year cycle. Leap years add a day—February 29—to the calendar every fourth year, except century years that are *not* divisible by 400. (So the years 1700, 1800, and 1900 were not leap years, but the year 2000 was.) Leap days keep the calendar aligned with the seasons by making the average length of the calendar year match the true length of the year, which is very close to $365\frac{1}{4}$ days.

First Days of Seasons We usually say that each equinox or solstice marks the first day of a season. For example, the day of the June solstice is usually called the “first day of summer” in the Northern Hemisphere. Notice, however, that the Northern Hemisphere has its *maximum* tilt toward the Sun at this time. You might then wonder why we consider the summer solstice to be the beginning rather than the midpoint of summer.

The choice is somewhat arbitrary, but it makes sense in at least two ways. First, it was much easier for ancient people to identify the days on which the Sun reached extreme positions in the sky—such as when it reached its highest point

common misconceptions

The Cause of Seasons

Many people guess that seasons are caused by variations in Earth's distance from the Sun. But if this were true, the whole Earth would have summer or winter at the same time, and it doesn't: The seasons are opposite in the Northern and Southern Hemispheres. In fact, Earth's slightly varying orbital distance has virtually no effect on the weather. The real cause of seasons is Earth's axis tilt, which causes the two hemispheres to take turns being tipped toward the Sun over the course of each year.