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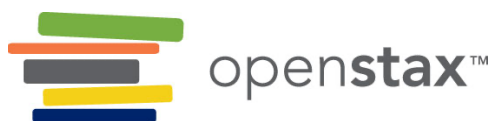
Astronomy 2e

SENIOR CONTRIBUTING AUTHORS

ANDREW FRAKNOI, FROMM INSTITUTE, UNIVERSITY OF SAN FRANCISCO

DAVID MORRISON, NASA (EMERITUS) AND SETI INSTITUTE

SIDNEY C. WOLFF, NOIRLAB (EMERITA)



OpenStax

Rice University
6100 Main Street MS-375
Houston, Texas 77005

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HARDCOVER BOOK ISBN-13
B&W PAPERBACK BOOK ISBN-13
DIGITAL VERSION ISBN-13
ORIGINAL PUBLICATION YEAR
2 3 4 5 6 7 8 9 10 RS 24 22

978-1-711470-57-3
978-1-711470-56-6
978-1-951693-50-3
2022

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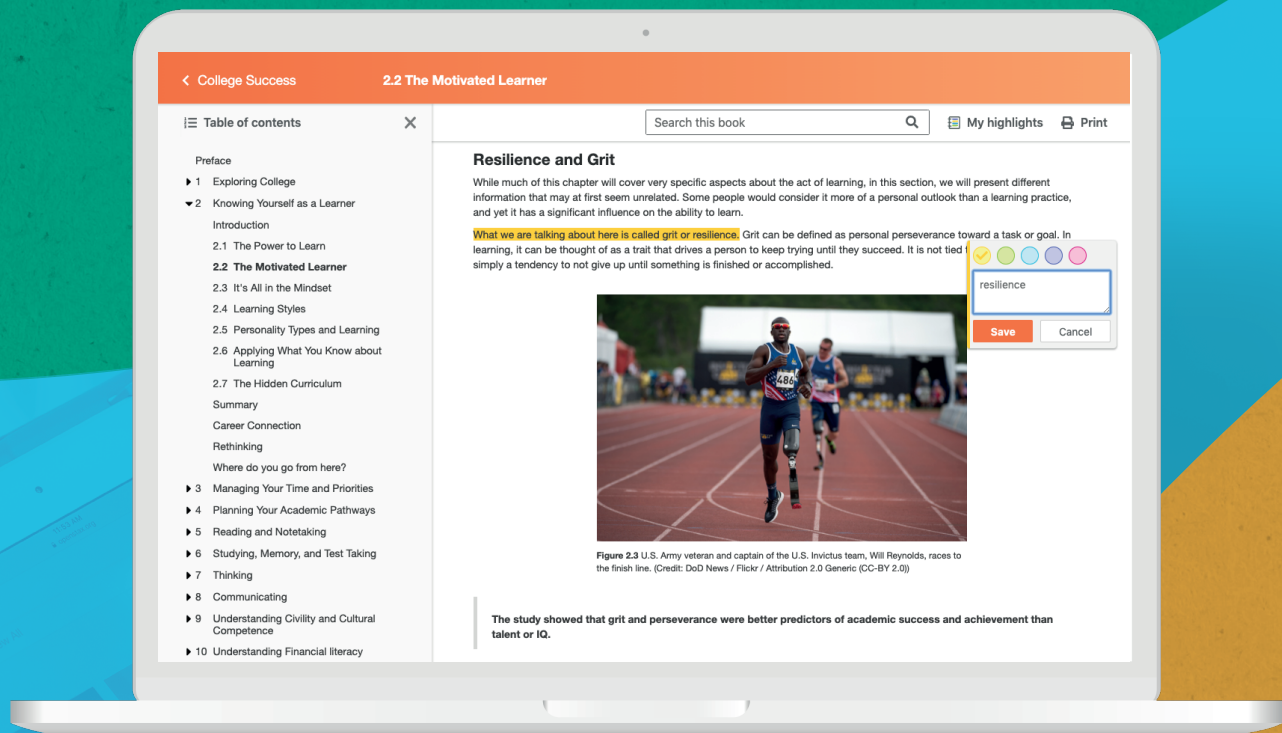
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Preface

Welcome to *Astronomy 2e*, an OpenStax resource. This textbook was written to increase student access to high-quality learning materials, maintaining highest standards of academic rigor at little to no cost.

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OpenStax is a nonprofit based at Rice University, and it's our mission to improve student access to education. Our first openly licensed college textbook was published in 2012 and our library has since scaled to over 50 books for college and AP[®] courses used by hundreds of thousands of students. OpenStax Tutor, our low-cost personalized learning tool, is being used in college courses throughout the country. Through our partnerships with philanthropic foundations and our alliance with other educational resource organizations, OpenStax is breaking down the most common barriers to learning and empowering students and instructors to succeed.

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Format

You can access this textbook for free in web view or PDF through OpenStax.org, and for a low cost in print.

About *Astronomy 2e*

Astronomy 2e is written in clear non-technical language, with the occasional touch of humor and a wide range of clarifying illustrations. It has many analogies drawn from everyday life to help non-science majors appreciate, on their own terms, what our modern exploration of the universe is revealing. The book can be used for either a one-semester or two-semester introductory course (bear in mind, you can customize your version and include only those chapters or sections you will be teaching.) It is made available free of charge in electronic form (and low cost in printed form) to students around the world.

Coverage and scope

Astronomy 2e was written by its three senior authors (see below) and was updated, reviewed, and vetted by a wide range of astronomers and astronomy educators in a strong community effort. It is designed to meet scope and sequence requirements of introductory astronomy courses nationwide.

Chapter 1: Science and the Universe: A Brief Tour
Chapter 2: Observing the Sky: The Birth of Astronomy
Chapter 3: Orbits and Gravity
Chapter 4: Earth, Moon, and Sky
Chapter 5: Radiation and Spectra
Chapter 6: Astronomical Instruments
Chapter 7: Other Worlds: An Introduction to the Solar System
Chapter 8: Earth as a Planet
Chapter 9: Cratered Worlds
Chapter 10: Earthlike Planets: Venus and Mars
Chapter 11: The Giant Planets
Chapter 12: Rings, Moons, and Pluto
Chapter 13: Comets and Asteroids: Debris of the Solar System
Chapter 14: Cosmic Samples and the Origin of the Solar System
Chapter 15: The Sun: A Garden-Variety Star
Chapter 16: The Sun: A Nuclear Powerhouse
Chapter 17: Analyzing Starlight
Chapter 18: The Stars: A Celestial Census
Chapter 19: Celestial Distances
Chapter 20: Between the Stars: Gas and Dust in Space
Chapter 21: The Birth of Stars and the Discovery of Planets outside the Solar System
Chapter 22: Stars from Adolescence to Old Age
Chapter 23: The Death of Stars
Chapter 24: Black Holes and Curved Spacetime
Chapter 25: The Milky Way Galaxy
Chapter 26: Galaxies
Chapter 27: Active Galaxies, Quasars, and Supermassive Black Holes
Chapter 28: The Evolution and Distribution of Galaxies
Chapter 29: The Big Bang
Chapter 30: Life in the Universe
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Appendix B: Astronomy Websites, Pictures, and Apps
Appendix C: Scientific Notation
Appendix D: Units Used in Science
Appendix E: Some Useful Constants for Astronomy
Appendix F: Physical and Orbital Data for the Planets
Appendix G: Selected Moons of the Planets
Appendix H: Upcoming Total Eclipses
Appendix I: The Nearest Stars, Brown Dwarfs, and White Dwarfs
Appendix J: The Brightest Twenty Stars
Appendix K: The Chemical Elements
Appendix L: The Constellations
Appendix M: Star Charts and Sky Event Resources

Currency and accuracy

Astronomy 2e has information and images from the LIGO and VIRGO gravitational-wave detectors, the Perseverance/Ingenuity mission to Mars, the Juno mission to Jupiter, and many other recent projects in astronomy. The discussion of exoplanets has been updated with recent information—indicating not just individual examples, but trends in what sorts of planets seem to be most common. Black holes receive their own chapter, and the role of supermassive black holes in active galaxies and galaxy evolution is clearly

explained. Chapters have been reviewed by subject-matter experts for accuracy and currency.

Flexibility

Because there are many different ways to teach introductory astronomy, we have made the text as flexible as we could. Math examples are shown in separate sections throughout, so that you can leave out the math or require it as you deem best. Each section of a chapter treats a different aspect of the topic being covered; a number of sections could be omitted in shorter overview courses and can be included where you need more depth. And, as we have already discussed, you can customize the book in a variety of ways that have never been possible in traditional textbooks.

Student-centered focus

This book is written to help students understand the big picture rather than get lost in random factoids to memorize. The language is accessible and inviting. Helpful diagrams and summary tables review and encapsulate the ideas being covered. Each chapter contains interactive group activities you can assign to help students work in teams and pool their knowledge.

Interactive online resources

Interesting “Links to Learning” are scattered throughout the chapters, which direct students to online animations, short videos, or enrichment readings to enhance their learning. Also, the resources listed at the end of each chapter include links to websites and other useful educational videos.

Feature boxes that help students think outside the box

A variety of feature boxes within the chapters connect astronomy to the students’ other subjects and humanize the face of astronomy by highlighting the lives of the men and women who have been key to its progress. Besides the math examples that we’ve already mentioned, the boxes include:

Making Connections. This feature connects the chapter topic to students’ experiences with other fields, from poetry to engineering, popular culture, and natural disasters.

Voyagers in Astronomy. This feature presents brief and engaging biographies of the people behind historically significant discoveries, as well as emerging research.

Astronomy Basics. This feature explains basic science concepts that we often (incorrectly) assume students know from earlier classes.

Seeing for Yourself. This feature provides practical ways that students can make astronomical observations on their own.

End-of-chapter materials to extend students’ learning

Chapter Summaries. Summaries give the gist of each section for easy review.

For Further Exploration. This section offers a list of suggested articles, websites, and videos so students can delve into topics of interest, whether for their own learning, for homework, extra credit, or papers.

Review Questions. Review questions allow students to show you (or themselves) how well they understood the chapter.

Thought Questions. Thought questions help students assess their learning by asking for critical reflection on principles or ideas in the chapter.

Figuring For Yourself. Mathematical questions, using only basic algebra and arithmetic, allow students to apply the math principles given in the example boxes throughout the chapter.

Collaborative Group Activities. This section suggests ideas for group discussion, research, or reports.

Beautiful art program

Our comprehensive art program is designed to enhance students’ understanding of concepts through clear and effective illustrations, diagrams, and photographs. Here are a few examples.

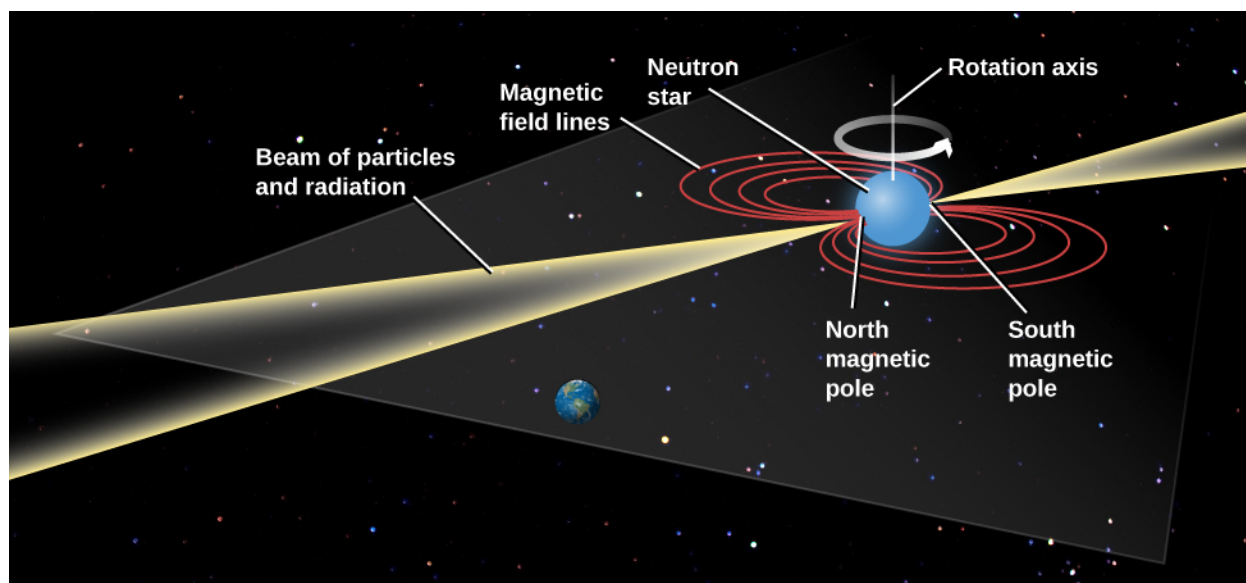


Figure 1 How a Pulsar Beam Sweeps over Earth.

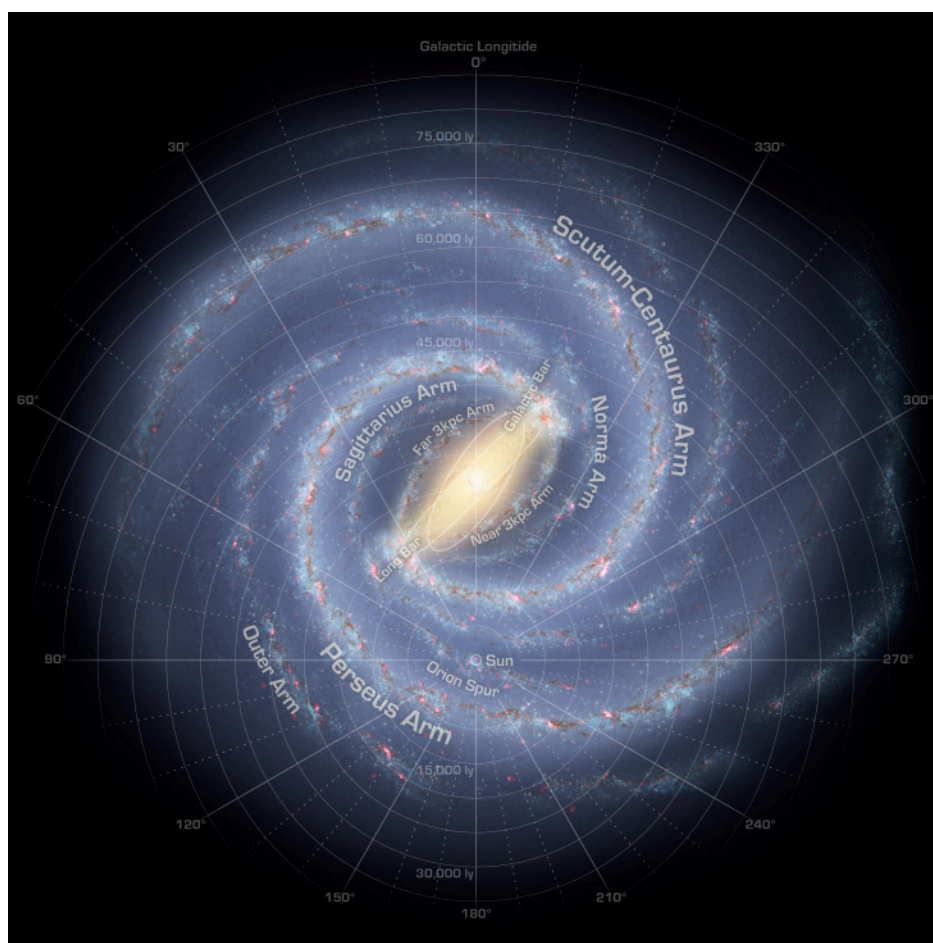


Figure 2 Structure of the Milky Way Galaxy.

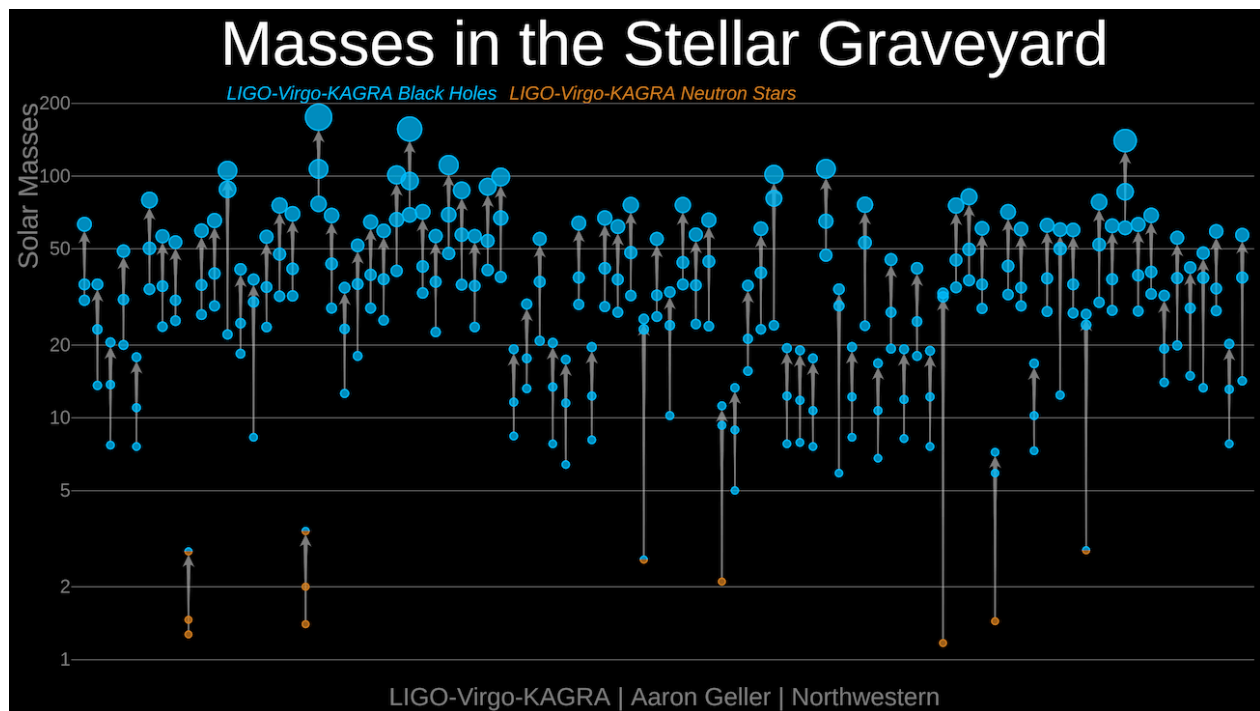


Figure 3 Masses in the Stellar Graveyard.



Figure 4 Pluto Close Up.

Answers to Questions in the Book

In order to allow instructors as much flexibility as possible, answers are provided only to instructors via the instructor resources. Due to the high variability of responses, answers to Collaborative Group Activities are not provided.

Additional resources

Student and instructor resources

We've compiled additional resources for both students and instructors, including Getting Started Guides, PowerPoint slides, and an instructor answer guide. Instructor resources require a verified instructor account, which you can apply for when you log in or create your account on OpenStax.org. Take advantage of these resources to supplement your OpenStax book.

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To reach the Community Hubs, visit https://www.oercommons.org/groups/openstax-astronomy/1283/?_hub_id=27 (https://www.oercommons.org/groups/openstax-astronomy/1283/?_hub_id=27).

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About the authors

Senior contributing authors



Figure 5 Senior contributing authors: Andrew Fraknoi (left), David Morrison (center), Sidney C. Wolff (right)

Andrew Fraknoi, Fromm Institute, University of San Francisco

Andrew Fraknoi retired as Chair of the Astronomy Department at Foothill College in 2017 and now teaches courses for older adults at the University of San Francisco and San Francisco State University. He served as the Executive Director of the Astronomical Society of the Pacific from 1978–1992. His work with the society included editing *Mercury Magazine*, the *Universe in the Classroom* newsletter, and *Astronomy Beat*. He is editor/co-author of *The Universe at Your Fingertips 2.0*, a collection of teaching activities, and co-author of

Solar Science, a book for middle-school teachers. He was also co-author of a syndicated newspaper column on astronomy, and appears regularly on local and national radio. With Sidney Wolff, he was founder of the refereed journal, *Astronomy Education Review*. In addition, he has organized six national symposia on teaching introductory astronomy, and for 10 years, has led the AAS Ambassadors workshops, training young astronomers to be better at outreach. He received the AAS Education Award, the Klumpke-Roberts Prize of the ASP, the Gemant Prize of the American Institute of Physics, and the Faraday Award of the NSTA.

David Morrison, NASA (Emeritus) and SETI Institute

David Morrison received his PhD in astronomy from Harvard, where he was one of Carl Sagan's graduate students. He is a founder of the field of astrobiology and is known for research on small bodies in the solar system (Asteroid 2410 Morrison is named for him). He spent his early career at University of Hawaii's Institute for Astronomy, where he was Director of the IRTF at Maunakea Observatory. Morrison has held senior NASA positions including Director of Space Research at Ames Research Center, Chief of the Space Science Division, and founding Director of the Lunar Science Institute. He's been on science teams for the Voyager, Galileo, and Kepler missions, and he received NASA Outstanding Leadership Medals and Exceptional Achievement Medal. His contributions to public understanding of science have been recognized by education prizes from the Astronomical Society of the Pacific, the American Astronomical Society, and NASA. Committed to the struggle against pseudoscience, he serves as Contributing Editor of *Skeptical Inquirer*.

Sidney C. Wolff, NOIRLab (Emerita)

After receiving her PhD from the UC Berkeley, Dr. Wolff was involved with the astronomical development of Maunakea. In 1984, she became the Director of Kitt Peak National Observatory, and was director of National Optical Astronomy Observatory. She led the design and development phases of the Gemini Observatory and the Rubin Observatory. Most recently, she has worked on plans for user support for the next generation of large ground-based telescopes. Dr. Wolff has published over ninety refereed papers on star formation and stellar atmospheres. She has served as President of the AAS and the ASP. Her book, *The Boundless Universe: Astronomy in the New Age of Discovery*, won the 2016 IPPY (Independent Publisher Book Awards) Silver Medal in Science.

All three senior contributing authors have received the Education Prize of the American Astronomical Society and have had an asteroid named after them by the International Astronomical Union. They have worked together on a series of astronomy textbooks over the past two decades.

Contributing authors

John Beck, Stanford University

Susan D. Benecchi, Planetary Science Institute

John Bochanski, Rider University

Howard Bond, Pennsylvania State University, Emeritus, Space Telescope Science Institute

Jennifer Carson, Occidental College

Bryan Dunne, University of Illinois at Urbana-Champaign

Martin Elvis, Harvard-Smithsonian Center for Astrophysics

Debra Fischer, Yale University

Heidi Hammel, Association of Universities for Research in Astronomy

Tori Hoehler, NASA Ames Research Center

Douglas Ingram, Texas Christian University

Steven Kawaler, Iowa State University

Lloyd Knox, University of California, Davis

Mark Krumholz, Australian National University

James Lowenthal, Smith College

Geoff Mathews, Foothill College

Siobahn Morgan, University of Northern Iowa

Daniel Perley, California Institute of Technology
Claire Raftery, National Solar Observatory
Deborah Scherrer, retired, Stanford University
Phillip Scherrer, Stanford University
Sanjoy Som, Blue Marble Space Institute of Science, NASA Ames Research Center
Wes Tobin, Indiana University East
William H. Waller, retired, Tufts University, Rockport (MA) Public Schools
Todd Young, Wayne State College

Reviewers

Elisabeth R. Adams, Planetary Science Institute
Alfred N. Alaniz, San Antonio College
Charles Allison, Texas A&M University–Kingsville
Douglas Arion, Carthage College
Timothy Barker, Wheaton College
Marshall Bartlett, The Hockaday School
Charles Benesh, Wesleyan College
Gerald B. Cleaver, Baylor University
Kristi Concannon, King's College
Anthony Crider, Elon University
Scott Engle, Villanova University
Matthew Fillingim, University of California, Berkeley
Robert Fisher, University of Massachusetts, Dartmouth
Carrie Fitzgerald, Montgomery College
Christopher Fuse, Rollins College
Shila Garg, Emeritus, The College of Wooster
Richard Gelderman, Western Kentucky University
Lee Hartman, University of Michigan
Beth Hufnagel, Anne Arundel Community College
Francine Jackson, Brown University
Joseph Jensen, Utah Valley University
John Kielkopf, University of Louisville
James C. Lombardi, Jr., Allegheny College
Amy Lovell, Agnes Scott College
Charles Niederriter, Gustavus Adolphus College
Richard Olenick, University of Dallas
Matthew Olmstead, King's College
Zoran Pazameta, Eastern Connecticut State University
David Quesada, Saint Thomas University
Valerie A. Rapson, Dudley Observatory
Joseph Ribaud, Utica College
Dean Richardson, Xavier University of Louisiana
Andrew Rivers, Northwestern University
Marc Sher, College of William & Mary
Christopher Sirola, University of Southern Mississippi
Ran Sivron, Baker University
J. Allyn Smith, Austin Peay State University
Jason Smolinski, Calvin College
Michele Thornley, Bucknell University
Richard Webb, Union College

Terry Willis, Chesapeake College

David Wood, San Antonio College

Jeremy Wood, Hazard Community and Technical College

Jared Workman, Colorado Mesa University

Kaisa E. Young, Nicholls State University

Science and the Universe: A Brief Tour

Figure 1.1 Distant Galaxies. These two interacting islands of stars (galaxies) are so far away that their light takes hundreds of millions of years to reach us on Earth (photographed with the Hubble Space Telescope). (credit: modification of work by NASA, ESA, the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration, and K. Noll (STScI))

Chapter Outline

- 1.1 The Nature of Astronomy
- 1.2 The Nature of Science
- 1.3 The Laws of Nature
- 1.4 Numbers in Astronomy
- 1.5 Consequences of Light Travel Time
- 1.6 A Tour of the Universe
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Introduction

We invite you to come along on a series of voyages to explore the universe as astronomers understand it today. Beyond Earth are vast and magnificent realms full of objects that have no counterpart on our home planet. Nevertheless, we hope to show you that the evolution of the universe has been directly responsible for your presence on Earth today.

Along your journey, you will encounter:

- a canyon system so large that, on Earth, it would stretch from Los Angeles to Washington, DC ([Figure 1.2](#)).

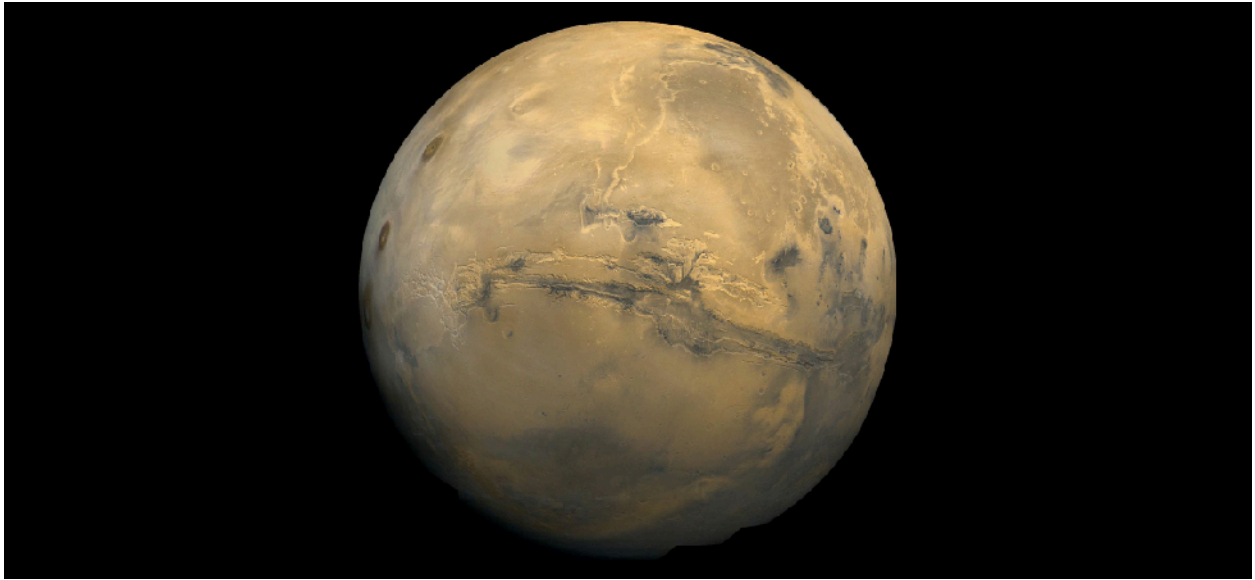


Figure 1.2 Mars Mosaic. This image of Mars is centered on the Valles Marineris (Mariner Valley) complex of canyons, which is as long as the United States is wide. (credit: modification of work by NASA)

- a crater and other evidence on Earth that tell us that the dinosaurs (and many other creatures) died because of a cosmic collision.
- a tiny moon whose gravity is so weak that one good throw from its surface could put a baseball into orbit.
- a collapsed star so dense that to duplicate its interior we would have to squeeze every human being on Earth into a single raindrop.
- exploding stars whose violent end could wipe clean all of the life-forms on a planet orbiting a neighboring star ([Figure 1.3](#)).
- a “cannibal galaxy” that has already consumed a number of its smaller galaxy neighbors and is not yet finished finding new victims.
- a radio echo that is the faint but unmistakable signal of the creation event for our universe.

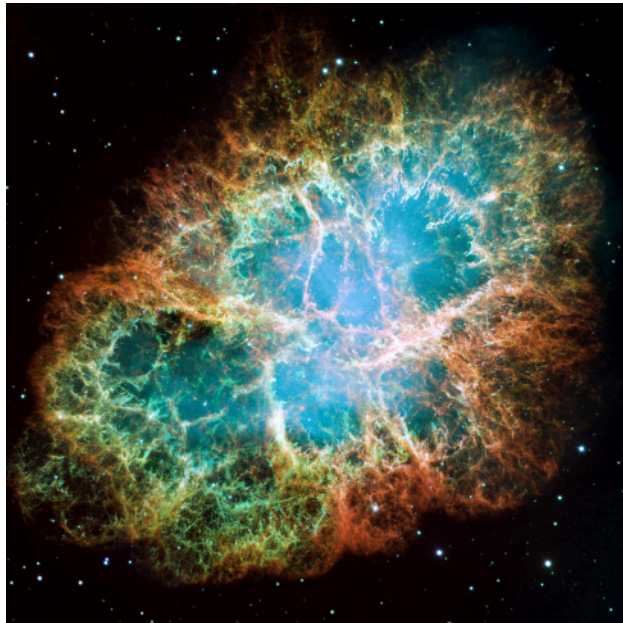


Figure 1.3 Stellar Corpse. We observe the remains of a star that was seen to explode in our skies in 1054 (and was, briefly, bright enough to be visible during the daytime). Today, the remnant is called the Crab Nebula and its central region is seen here. Such exploding stars are crucial to the development of life in the universe. (credit: NASA, ESA, J. Hester (Arizona State University))

Such discoveries are what make astronomy such an exciting field for scientists and many others—but you will

explore much more than just the objects in our universe and the latest discoveries about them. We will pay equal attention to the *process* by which we have come to understand the realms beyond Earth and the tools we use to increase that understanding.

We gather information about the cosmos from the messages the universe sends our way. Because the stars are the fundamental building blocks of the universe, decoding the message of starlight has been a central challenge and triumph of modern astronomy. By the time you have finished reading this text, you will know a bit about how to read that message and how to understand what it is telling us.

1.1 The Nature of Astronomy

Astronomy is defined as the study of the objects that lie beyond our planet Earth and the processes by which these objects interact with one another. We will see, though, that it is much more. It is also humanity's attempt to organize what we learn into a clear history of the universe, from the instant of its birth in the Big Bang to the present moment. Throughout this book, we emphasize that science is a *progress report*—one that changes constantly as new techniques and instruments allow us to probe the universe more deeply.

In considering the history of the universe, we will see again and again that the cosmos *evolves*; it changes in profound ways over long periods of time. For example, the universe made the carbon, the calcium, and the oxygen necessary to construct something as interesting and complicated as you. Today, many billions of years later, the universe has evolved into a more hospitable place for life. Tracing the evolutionary processes that continue to shape the universe is one of the most important (and satisfying) parts of modern astronomy.

1.2 The Nature of Science

The ultimate judge in science is always what nature itself reveals based on observations, experiments, models, and testing. Science is not merely a body of knowledge, but a *method* by which we attempt to understand nature and how it behaves. This method begins with many observations over a period of time. From the trends found through observations, scientists can *model* the particular phenomena we want to understand. Such models are always approximations of nature, subject to further testing.

As a concrete astronomical example, ancient astronomers constructed a model (partly from observations and partly from philosophical beliefs) that Earth was the center of the universe and everything moved around it in circular orbits. At first, our available observations of the Sun, Moon, and planets did fit this model; however, after further observations, the model had to be updated by adding circle after circle to represent the movements of the planets around Earth at the center. As the centuries passed and improved instruments were developed for keeping track of objects in the sky, the old model (even with a huge number of circles) could no longer explain all the observed facts. As we will see in the chapter on [Observing the Sky: The Birth of Astronomy](#), a new model, with the Sun at the center, fit the experimental evidence better. After a period of philosophical struggle, it became accepted as our view of the universe.

When they are first proposed, new models or ideas are sometimes called *hypotheses*. You may think there can be no new hypotheses in a science such as astronomy—that everything important has already been learned. Nothing could be further from the truth. Throughout this textbook you will find discussions of recent, and occasionally still controversial, hypotheses in astronomy. For example, the significance that the huge chunks of rock and ice that hit Earth have for life on Earth itself is still debated. And while the evidence is strong that vast quantities of invisible “dark energy” make up the bulk of the universe, scientists have no convincing explanation for what the dark energy actually is. Resolving these issues will require difficult observations done at the forefront of our technology, and all such hypotheses need further testing before we incorporate them fully into our standard astronomical models.

This last point is crucial: a hypothesis must be a proposed explanation that can be *tested*. The most

straightforward approach to such testing in science is to perform an experiment. If the experiment is conducted properly, its results either will agree with the predictions of the hypothesis or they will contradict it. If the experimental result is truly inconsistent with the hypothesis, a scientist must discard the hypothesis and try to develop an alternative. If the experimental result agrees with predictions, this does not necessarily prove that the hypothesis is absolutely correct; perhaps later experiments will contradict crucial parts of the hypothesis. But, the more experiments that agree with the hypothesis, the more likely we are to accept the hypothesis as a useful description of nature.

One way to think about this is to consider a scientist who was born and lives on an island where only black sheep live. Day after day the scientist encounters black sheep only, so he or she hypothesizes that all sheep are black. Although every observed sheep adds confidence to the hypothesis, the scientist only has to visit the mainland and observe one white sheep to prove the hypothesis wrong.

When you read about experiments, you probably have a mental picture of a scientist in a laboratory conducting tests or taking careful measurements. This is certainly the case for a biologist or a chemist, but what can astronomers do when our laboratory is the universe? It's impossible to put a group of stars into a test tube or to order another comet from a scientific supply company.

As a result, astronomy is sometimes called an *observational* science; we often make our tests by observing many samples of the kind of object we want to study and noting carefully how different samples vary. New instruments and technology can let us look at astronomical objects from new perspectives and in greater detail. Our hypotheses are then judged in the light of this new information, and they pass or fail in the same way we would evaluate the result of a laboratory experiment.

Much of astronomy is also a *historical* science—meaning that what we observe has already happened in the universe and we can do nothing to change it. In the same way, a geologist cannot alter what has happened to our planet, and a paleontologist cannot bring an ancient animal back to life. While this can make astronomy challenging, it also gives us fascinating opportunities to discover the secrets of our cosmic past.

You might compare an astronomer to a detective trying to solve a crime that occurred before the detective arrived at the scene. There is lots of evidence, but both the detective and the scientist must sift through and organize the evidence to test various hypotheses about what actually happened. And there is another way in which the scientist is like a detective: they both must prove their case. The detective must convince the district attorney, the judge, and perhaps ultimately the jury that his hypothesis is correct. Similarly, the scientist must convince colleagues, editors of journals, and ultimately a broad cross-section of other scientists that her hypothesis is provisionally correct. In both cases, one can only ask for evidence “beyond a reasonable doubt.” And sometimes new evidence will force both the detective and the scientist to revise their last hypothesis.

This self-correcting aspect of science sets it off from most human activities. Scientists spend a great deal of time questioning and challenging one another, which is why applications for project funding—as well as reports for publication in academic journals—go through an extensive process of *peer review*, which is a careful examination by other scientists in the same field. In science (after formal education and training), everyone is encouraged to improve upon experiments and to challenge any and all hypotheses. New scientists know that one of the best ways to advance their careers is to find a weakness in our current understanding of something and to correct it with a new or modified hypothesis.

This is one of the reasons science has made such dramatic progress. An undergraduate science major today knows more about science and math than did Sir Isaac Newton, one of the most renowned scientists who ever lived. Even in this introductory astronomy course, you will learn about objects and processes that no one a few generations ago even dreamed existed.

1.3 The Laws of Nature

Over centuries scientists have extracted various *scientific laws* from countless observations, hypotheses, and experiments. These scientific laws are, in a sense, the “rules” of the game that nature plays. One remarkable discovery about nature—one that underlies everything you will read about in this text—is that the same laws apply everywhere in the universe. The rules that determine the motion of stars so far away that your eye cannot see them are the same laws that determine the arc of a baseball after a batter has hit it out of the park.

Note that without the existence of such universal laws, we could not make much headway in astronomy. If each pocket of the universe had different rules, we would have little chance of interpreting what happened in other “neighborhoods.” But, the consistency of the laws of nature gives us enormous power to understand distant objects without traveling to them and learning the local laws. In the same way, if every region of a country had completely different laws, it would be very difficult to carry out commerce or even to understand the behavior of people in those different regions. A consistent set of laws, though, allows us to apply what we learn or practice in one state to any other state.

This is not to say that our current scientific models and laws cannot change. New experiments and observations can lead to new, more sophisticated models—models that can include new phenomena and laws about their behavior. The general theory of relativity proposed by Albert Einstein is a perfect example of such a transformation that took place about a century ago; it led us to predict, and eventually to observe, a strange new class of objects that astronomers call *black holes*. Only the patient process of observing nature ever more carefully and precisely can demonstrate the validity of such new scientific models.

One important problem in describing scientific models has to do with the limitations of language. When we try to describe complex phenomena in everyday terms, the words themselves may not be adequate to do the job. For example, you may have heard the structure of the atom likened to a miniature solar system. While some aspects of our modern model of the atom do remind us of planetary orbits, many other of its aspects are fundamentally different.

This problem is the reason scientists often prefer to describe their models using equations rather than words. In this book, which is designed to introduce the field of astronomy, we use mainly words to discuss what scientists have learned. We avoid complex math, but if this course piques your interest and you go on in science, more and more of your studies will involve the precise language of mathematics.

1.4 Numbers in Astronomy

In astronomy we deal with distances on a scale you may never have thought about before, with numbers larger than any you may have encountered. We adopt two approaches that make dealing with astronomical numbers a little bit easier. First, we use a system for writing large and small numbers called *scientific notation* (or sometimes *powers-of-ten notation*). This system is very appealing because it eliminates the many zeros that can seem overwhelming to the reader. In scientific notation, if you want to write a number such as 500,000,000, you express it as 5×10^8 . The small raised number after the 10, called an *exponent*, keeps track of the number of places we had to move the decimal point to the left to convert 500,000,000 to 5. If you are encountering this system for the first time or would like a refresher, we suggest you look at [Appendix C](#) and [Example 1.1](#) for more information. The second way we try to keep numbers simple is to use a consistent set of units—the metric International System of Units, or SI (from the French *Système International d’Unités*). The metric system is summarized in [Appendix D](#) (see [Example 1.2](#)).

LINK TO LEARNING



Watch this [brief PBS animation \(https://openstax.org/l/30scinotation\)](https://openstax.org/l/30scinotation) that explains how scientific notation works and why it's useful.

A common unit astronomers use to describe distances in the universe is a light-year, which is the distance light travels during one year. Because light always travels at the same speed, and because its speed turns out to be the fastest possible speed in the universe, it makes a good standard for keeping track of distances. You might be confused because a “light-year” seems to imply that we are measuring time, but this mix-up of time and distance is common in everyday life as well. For example, when your friend asks where the movie theater is located, you might say “about 20 minutes from downtown.”

So, how many kilometers are there in a light-year? Light travels at the amazing pace of 3×10^5 kilometers per second (km/s), which makes a light-year 9.46×10^{12} kilometers. You might think that such a large unit would reach the nearest star easily, but the stars are far more remote than our imaginations might lead us to believe. Even the nearest star (other than the Sun) is 4.25 light-years away—more than 40 trillion kilometers. Other stars visible to the unaided eye are hundreds to thousands of light-years away ([Figure 1.4](#)).



Figure 1.4 Orion Nebula. This beautiful cloud of cosmic raw material (gas and dust from which new stars and planets are being made) called the Orion Nebula is about 1400 light-years away. That's a distance of roughly 1.34×10^{16} kilometers—a pretty big number. The gas and dust in this region are illuminated by the intense light from a few extremely energetic adolescent stars. (credit: NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team)

EXAMPLE 1.1

Scientific Notation

In 2015, the richest human being on our planet had a net worth of \$79.2 billion. Some might say this is an astronomical sum of money. Express this amount in scientific notation.

Solution

\$79.2 billion can be written \$79,200,000,000. Expressed in scientific notation it becomes 7.92×10^{10}

EXAMPLE 1.2**Getting Familiar with a Light-Year**

How many kilometers are there in a light-year?

Solution

Light travels 3×10^5 km in 1 s. So, let's calculate how far it goes in a year:

- There are 60 (6×10^1) s in 1 min, and 6×10^1 min in 1 h.
- Multiply these together and you find that there are 3.6×10^3 s/h.
- Thus, light covers 3×10^5 km/s $\times 3.6 \times 10^3$ s/h = 1.08×10^9 km/h.
- There are 24 or 2.4×10^1 h in a day, and 365.25 (3.65×10^2) days in 1 y.
- The product of these two numbers is 8.77×10^3 h/y.
- Multiplying this by 1.08×10^9 km/h gives 9.46×10^{12} km/light-year.

That's almost 10,000,000,000,000 km that light covers in a year. To help you imagine how long this distance is, we'll mention that a string 1 light-year long could fit around the circumference of Earth 236 million times.

1.5 Consequences of Light Travel Time

There is another reason the speed of light is such a natural unit of distance for astronomers. Information about the universe comes to us almost exclusively through various forms of light, and all such light travels at the speed of light—that is, 1 light-year every year. This sets a limit on how quickly we can learn about events in the universe. If a star is 100 light-years away, the light we see from it tonight left that star 100 years ago and is just now arriving in our neighborhood. The soonest we can learn about any changes in that star is 100 years after the fact. For a star 500 light-years away, the light we detect tonight left 500 years ago and is carrying 500-year-old news.

Because many of us are accustomed to instant news from the Internet, some might find this frustrating.

"You mean, when I see that star up there," you ask, "I won't know what's actually happening there for another 500 years?"

But this isn't the most helpful way to think about the situation. For astronomers, *now* is when the light reaches us here on Earth. There is no way for us to know anything about that star (or other object) until its light reaches us.

But what at first may seem a great frustration is actually a tremendous benefit in disguise. If astronomers really want to piece together what has happened in the universe since its beginning, they must find evidence about each epoch (or period of time) of the past. Where can we find evidence today about cosmic events that occurred billions of years ago?

The delay in the arrival of light provides an answer to this question. The farther out in space we look, the longer the light has taken to get here, and the longer ago it left its place of origin. By looking billions of light-years out into space, astronomers are actually seeing billions of years into the past. In this way, we can

reconstruct the history of the cosmos and get a sense of how it has evolved over time.

This is one reason why astronomers strive to build telescopes that can collect more and more of the faint light in the universe. The more light we collect, the fainter the objects we can observe. On average, fainter objects are farther away and can, therefore, tell us about periods of time even deeper in the past. Instruments such as the Hubble Space Telescope ([Figure 1.5](#)) and the Very Large Telescope in Chile (which you will learn about in the chapter on [Astronomical Instruments](#)), are giving astronomers views of deep space and deep time better than any we have had before.



Figure 1.5 Telescope in Orbit. The Hubble Space Telescope, shown here in orbit around Earth, is one of many astronomical instruments in space. (credit: modification of work by European Space Agency)

1.6 A Tour of the Universe

We can now take a brief introductory tour of the universe as astronomers understand it today to get acquainted with the types of objects and distances you will encounter throughout the text. We begin at home with Earth, a nearly spherical planet about 13,000 kilometers in diameter ([Figure 1.6](#)). A space traveler entering our planetary system would easily distinguish Earth from the other planets in our solar system by the large amount of liquid water that covers some two thirds of its crust. If the traveler had equipment to receive radio or television signals, or came close enough to see the lights of our cities at night, she would soon find signs that this watery planet has sentient life.



Figure 1.6 Humanity's Home Base. This image shows the Western hemisphere as viewed from space 35,400 kilometers (about 22,000 miles) above Earth. Data about the land surface from one satellite was combined with another satellite's data about the clouds to create the image. (credit: modification of work by R. Stockli, A. Nelson, F. Hasler, NASA/ GSFC/ NOAA/ USGS)

Our nearest astronomical neighbor is Earth's satellite, commonly called the *Moon*. [Figure 1.7](#) shows Earth and the Moon drawn to scale on the same diagram. Notice how small we have to make these bodies to fit them on the page with the right scale. The Moon's distance from Earth is about 30 times Earth's diameter, or approximately 384,000 kilometers, and it takes about a month for the Moon to revolve around Earth. The Moon's diameter is 3476 kilometers, about one fourth the size of Earth.

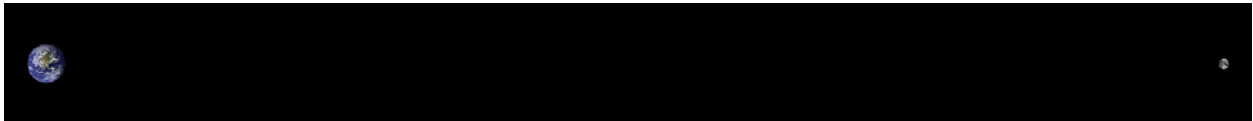


Figure 1.7 Earth and Moon, Drawn to Scale. This image shows Earth and the Moon shown to scale for both size and distance. (credit: modification of work by NASA)

Light (or radio waves) takes 1.3 seconds to travel between Earth and the Moon. If you've seen videos of the Apollo flights to the Moon, you may recall that there was a delay of about 3 seconds between the time Mission Control asked a question and the time the astronauts responded. This was not because the astronauts were thinking slowly, but rather because it took the radio waves almost 3 seconds to make the round trip.

Earth revolves around our star, the Sun, which is about 150 million kilometers away—approximately 400 times as far away from us as the Moon. We call the average Earth–Sun distance an *astronomical unit* (AU) because, in the early days of astronomy, it was the most important measuring standard. Light takes slightly more than 8 minutes to travel 1 astronomical unit, which means the latest news we receive from the Sun is always 8 minutes old. The diameter of the Sun is about 1.5 million kilometers; Earth could fit comfortably inside one of the minor eruptions that occurs on the surface of our star. If the Sun were reduced to the size of a basketball, Earth would be a small apple seed about 30 meters from the ball.

It takes Earth 1 year (3×10^7 seconds) to go around the Sun at our distance; to make it around, we must travel at approximately 110,000 kilometers per hour. (If you, like many students, still prefer miles to kilometers, you might find the following trick helpful. To convert kilometers to miles, just multiply kilometers by 0.6. Thus, 110,000 kilometers per hour becomes 66,000 miles per hour.) Because gravity holds us firmly to Earth and there is no resistance to Earth's motion in the vacuum of space, we participate in this extremely fast-moving trip without being aware of it day to day.

Earth is only one of eight planets that revolve around the Sun. These planets, along with their moons and swarms of smaller bodies such as dwarf planets, make up the solar system ([Figure 1.8](#)). A planet is defined as a body of significant size that orbits a star and does not produce its own light. (If a large body consistently produces its own light, it is then called a *star*.) Later in the book this definition will be modified a bit, but it is perfectly fine for now as you begin your voyage.

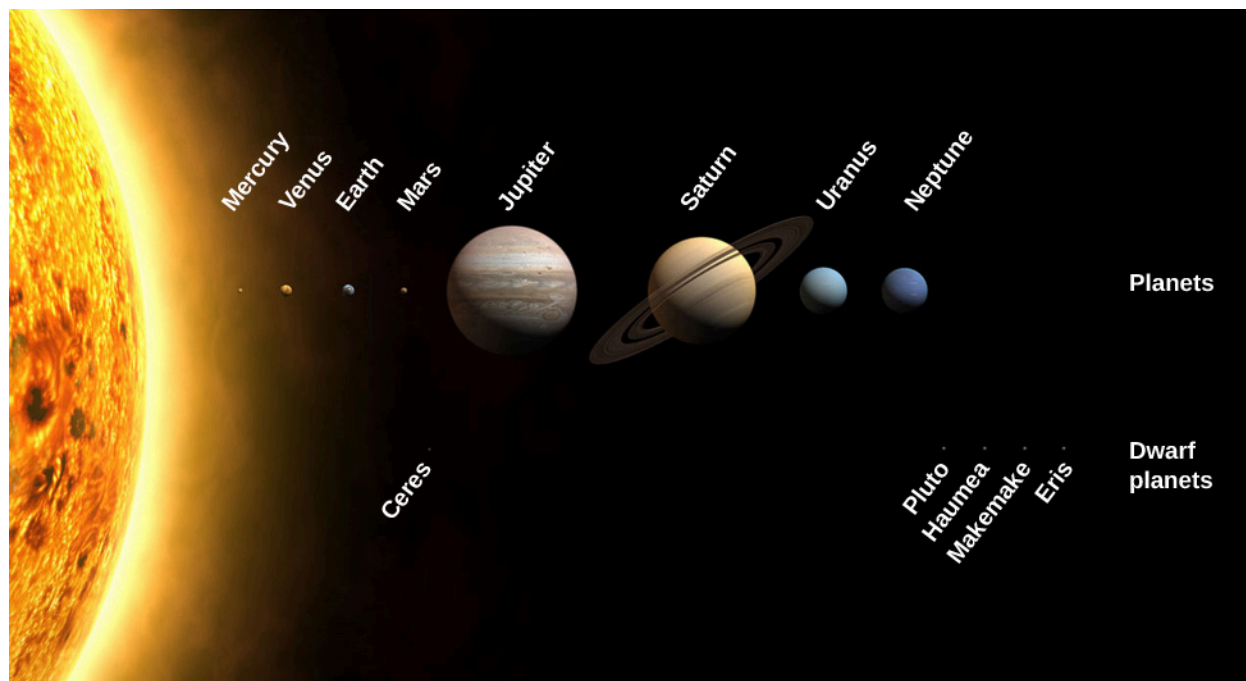


Figure 1.8 Our Solar Family. The Sun, the planets, and some dwarf planets are shown with their sizes drawn to scale. The orbits of the planets are much more widely separated than shown in this drawing. Notice the size of Earth compared to the giant planets. (credit: modification of work by NASA)

We are able to see the nearby planets in our skies only because they reflect the light of our local star, the Sun. If the planets were much farther away, the tiny amount of light they reflect would usually not be visible to us. The planets we have so far discovered orbiting other stars were found from the pull their gravity exerts on their parent stars, or from the light they block from their stars when they pass in front of them. We can't see most of these planets directly, although a few are now being imaged directly.

The Sun is our local star, and all the other stars are also enormous balls of glowing gas that generate vast amounts of energy by nuclear reactions deep within. We will discuss the processes that cause stars to shine in more detail later in the book. The other stars look faint only because they are so very far away. If we continue our basketball analogy, Proxima Centauri, the nearest star beyond the Sun, which is 4.25 light-years away, would be almost 7000 kilometers from the basketball.

When you look up at a star-filled sky on a clear night, all the stars visible to the unaided eye are part of a single collection of stars we call the *Milky Way Galaxy*, or simply the *Galaxy*. (When referring to the Milky Way, we capitalize *Galaxy*; when talking about other galaxies of stars, we use lowercase *galaxy*.) The Sun is one of hundreds of billions of stars that make up the Galaxy; its extent, as we will see, staggers the human imagination. Within a sphere 10 light-years in radius centered on the Sun, we find roughly ten stars. Within a sphere 100 light-years in radius, there are roughly 10,000 (10^4) stars—far too many to count or name—but we have still traversed only a tiny part of the Milky Way Galaxy. Within a 1000-light-year sphere, we find some ten million (10^7) stars; within a sphere of 100,000 light-years, we finally encompass the entire Milky Way Galaxy.

Our Galaxy looks like a giant disk with a small ball in the middle. If we could move outside our Galaxy and look down on the disk of the Milky Way from above, it would probably resemble the galaxy in [Figure 1.9](#), with its spiral structure outlined by the blue light of hot adolescent stars.



Figure 1.9 Spiral Galaxy. This galaxy of billions of stars, called by its catalog number NGC 1073, is thought to be similar to our own Milky Way Galaxy. Here we see the giant wheel-shaped system with a bar of stars across its middle. (credit: NASA, ESA)

The Sun is somewhat less than 30,000 light-years from the center of the Galaxy, in a location with nothing much to distinguish it. From our position inside the Milky Way Galaxy, we cannot see through to its far rim (at least not with ordinary light) because the space between the stars is not completely empty. It contains a sparse distribution of gas (mostly the simplest element, hydrogen) intermixed with tiny solid particles that we call *interstellar dust*. This gas and dust collect into enormous clouds in many places in the Galaxy, becoming the raw material for future generations of stars. [Figure 1.10](#) shows an image of the disk of the Galaxy as seen from our vantage point.



Figure 1.10 Milky Way Galaxy. Because we are inside the Milky Way Galaxy, we see its disk in cross-section flung across the sky like a great milky white avenue of stars with dark “rifts” of dust. In this dramatic image, part of it is seen above Trona Pinnacles in the California desert. (credit: Ian Norman)

Typically, the interstellar material is so extremely sparse that the space between stars is a much better vacuum than anything we can produce in terrestrial laboratories. Yet, the dust in space, building up over thousands of light-years, can block the light of more distant stars. Like the distant buildings that disappear from our view on a smoggy day in Los Angeles, the more distant regions of the Milky Way cannot be seen behind the layers of interstellar smog. Luckily, astronomers have found that stars and raw material shine with various forms of light, some of which do penetrate the smog, and so we have been able to develop a pretty good map of the Galaxy.

Recent observations, however, have also revealed a rather surprising and disturbing fact. There appears to be more—much more—to the Galaxy than meets the eye (or the telescope). From various investigations, we have evidence that much of our Galaxy is made of material we cannot currently observe directly with our instruments. We therefore call this component of the Galaxy *dark matter*. We know the dark matter is there by the pull its gravity exerts on the stars and raw material we can observe, but what this dark matter is made of and how much of it exists remain a mystery. Furthermore, this dark matter is not confined to our Galaxy; it appears to be an important part of other star groupings as well.

By the way, not all stars live by themselves, as the Sun does. Many are born in double or triple systems with two, three, or more stars revolving about each other. Because the stars influence each other in such close systems, multiple stars allow us to measure characteristics that we cannot discern from observing single stars. In a number of places, enough stars have formed together that we recognized them as star clusters ([Figure 1.11](#)). Some of the largest of the star clusters that astronomers have cataloged contain hundreds of thousands of stars and take up volumes of space hundreds of light-years across.

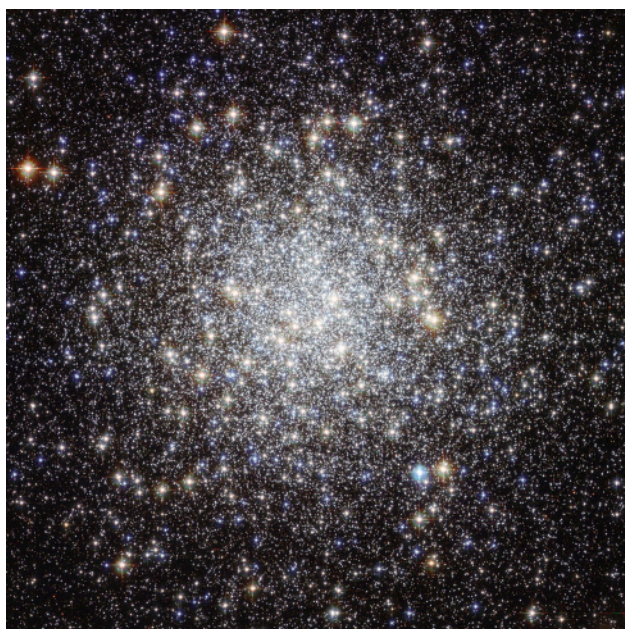


Figure 1.11 Star Cluster. This large star cluster is known by its catalog number, M9. It contains some 250,000 stars and is seen more clearly from space using the Hubble Space Telescope. It is located roughly 25,000 light-years away. (credit: NASA, ESA)

You may hear stars referred to as “eternal,” but in fact no star can last forever. Since the “business” of stars is making energy, and energy production requires some sort of fuel to be used up, eventually all stars run out of fuel. This news should not cause you to panic, though, because our Sun still has at least 5 or 6 billion years to go. Ultimately, the Sun and all stars will die, and it is in their death throes that some of the most intriguing and important processes of the universe are revealed. For example, we now know that many of the atoms in our bodies were once inside stars. These stars exploded at the ends of their lives, recycling their material back into the reservoir of the Galaxy. In this sense, all of us are literally made of recycled “star dust.”

1.7 The Universe on the Large Scale

In a very rough sense, you could think of the solar system as your house or apartment and the Galaxy as your town, made up of many houses and buildings. In the twentieth century, astronomers were able to show that, just as our world is made up of many, many towns, so the universe is made up of enormous numbers of galaxies. (We define the universe to be everything that exists that is accessible to our observations.) Galaxies stretch as far into space as our telescopes can see, many billions of them within the reach of modern instruments. When they were first discovered, some astronomers called galaxies *island universes*, and the term is aptly descriptive; galaxies do look like islands of stars in the vast, dark seas of intergalactic space.

The nearest galaxy, discovered in 1993, is a small one that lies 70,000 light-years from the Sun in the direction of the constellation Sagittarius, where the smog in our own Galaxy makes it especially difficult to discern. (A constellation, we should note, is one of the 88 sections into which astronomers divide the sky, each named after a prominent star pattern within it.) Beyond this Sagittarius dwarf galaxy lie two other small galaxies, about 160,000 light-years away. First recorded by Magellan’s crew as he sailed around the world, these are called the *Magellanic Clouds* (Figure 1.12). All three of these small galaxies are satellites of the Milky Way Galaxy, interacting with it through the force of gravity. Ultimately, all three may even be swallowed by our much larger Galaxy, as other small galaxies have been over the course of cosmic time.



Figure 1.12 Neighbor Galaxies. This image shows both the Large Magellanic Cloud and the Small Magellanic Cloud above the telescopes of the Atacama Large Millimeter/Submillimeter Array (ALMA) in the Atacama Desert of northern Chile. (credit: ESO, C. Malin)

The nearest large galaxy is a spiral quite similar to our own, located in the constellation of Andromeda, and is thus called the Andromeda galaxy; it is also known by one of its catalog numbers, M31 ([Figure 1.13](#)). M31 is a little more than 2 million light-years away and, along with the Milky Way, is part of a small cluster of more than 50 galaxies referred to as the *Local Group*.

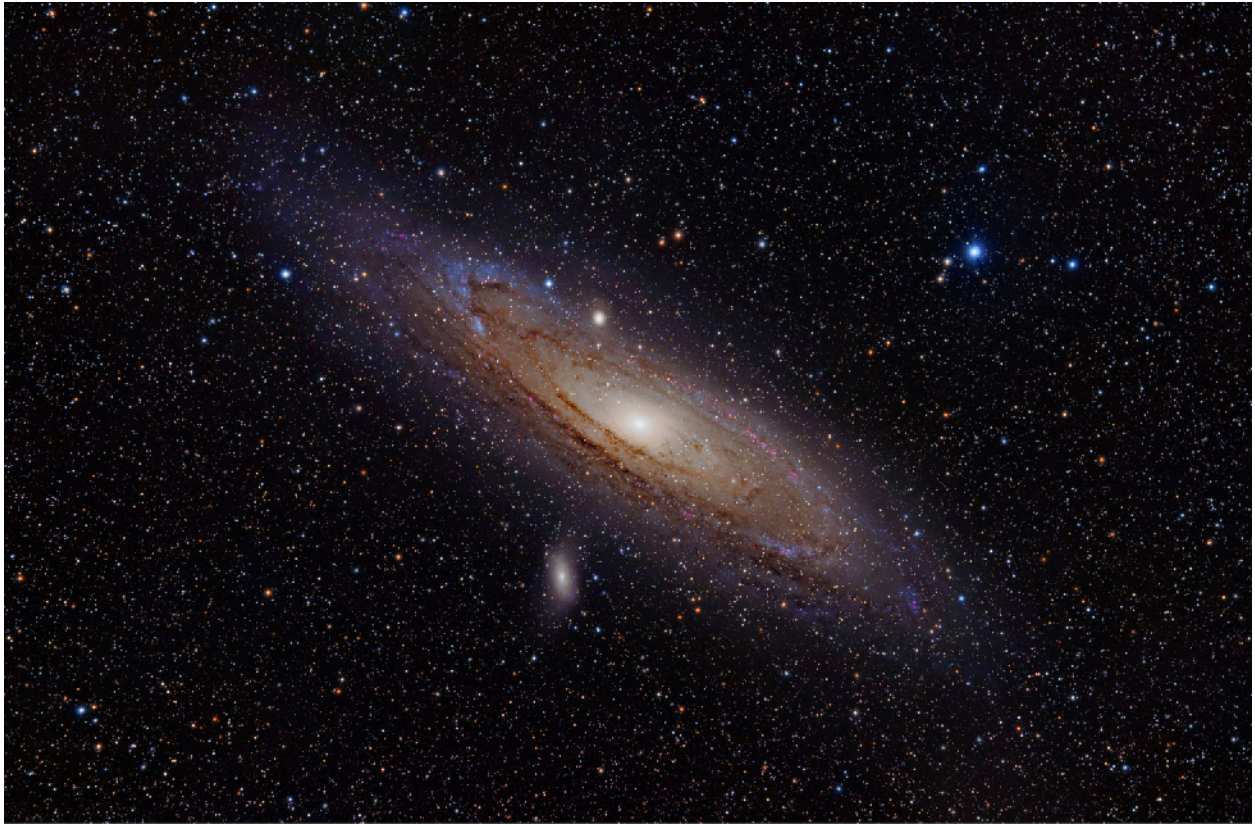


Figure 1.13 Closest Spiral Galaxy. The Andromeda galaxy (M31) is a spiral-shaped collection of stars similar to our own Milky Way. (credit: Adam Evans)

At distances of 10 to 15 million light-years, we find other small galaxy groups, and then at about 50 million light-years there are more impressive systems with thousands of member galaxies. We have discovered that galaxies occur mostly in clusters, both large and small ([Figure 1.14](#)).

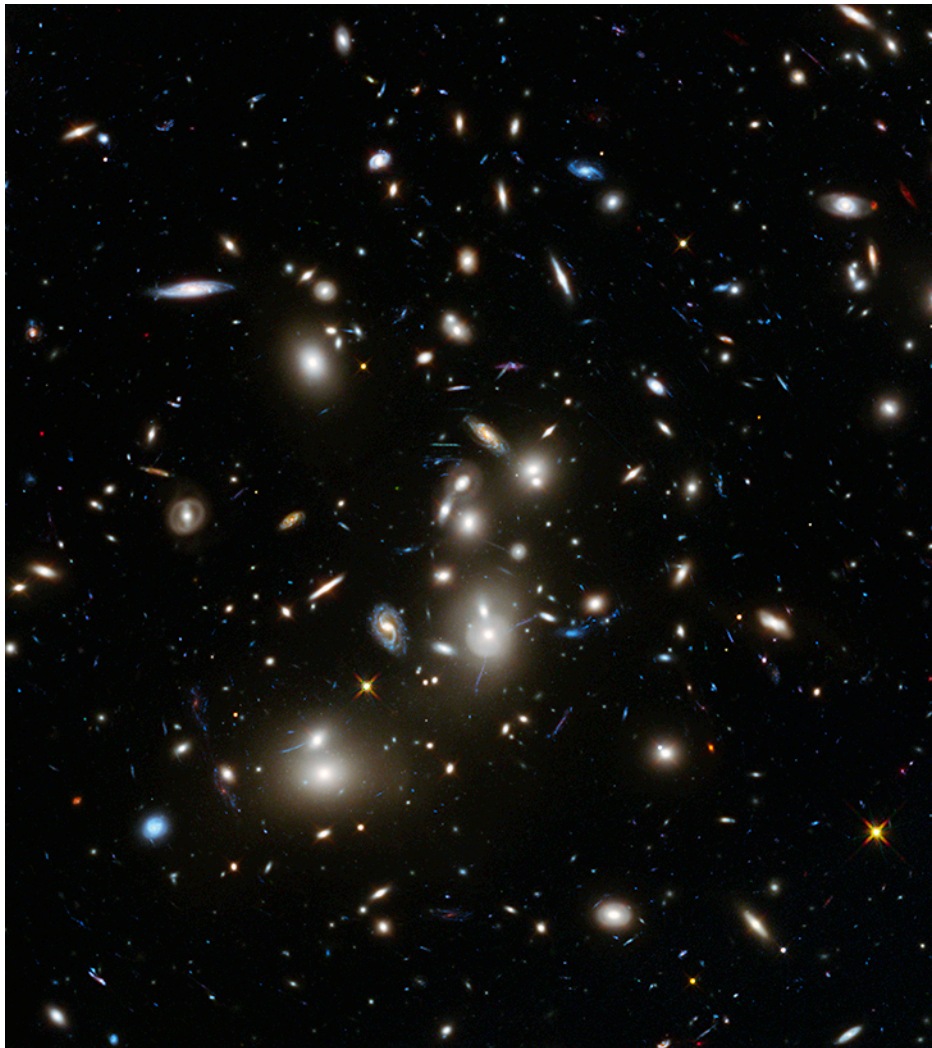


Figure 1.14 Cluster of Galaxies. This image shows part of a rich cluster of galaxies some 4 billion light-years away. Nicknamed Pandora's Cluster, the grouping consists of many galaxies, each with billions of stars in them. (credit: NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI))

Some of the clusters themselves form into larger groups called *superclusters*. The Local Group is part of a supercluster of galaxies, called the Virgo Supercluster, which stretches over a diameter of 110 million light-years. We are just beginning to explore the structure of the universe at these enormous scales and are already encountering some unexpected findings.

At even greater distances, where many ordinary galaxies are too dim to see, we find *quasars*. These are brilliant centers of galaxies, glowing with the light of an extraordinarily energetic process. The enormous energy of the quasars is produced by gas that is heated to a temperature of millions of degrees as it falls toward a massive black hole and swirls around it. The brilliance of quasars makes them the most distant beacons we can see in the dark oceans of space. They allow us to probe the universe 10 billion light-years away or more, and thus 10 billion years or more in the past.

With quasars we can see way back close to the Big Bang explosion that marks the beginning of time. Beyond the quasars and the most distant visible galaxies, we have detected the feeble glow of the explosion itself, filling the universe and thus coming to us from all directions in space. The discovery of this “afterglow of creation” is considered to be one of the most significant events in twentieth-century science, and we are still exploring the many things it has to tell us about the earliest times of the universe.

Measurements of the properties of galaxies and quasars in remote locations require large telescopes,

sophisticated light-amplifying devices, and painstaking labor. Every clear night, at observatories around the world, astronomers and students are at work on such mysteries as the birth of new stars and the large-scale structure of the universe, fitting their results into the tapestry of our understanding.

1.8 The Universe of the Very Small

The foregoing discussion has likely impressed on you that the universe is extraordinarily large and extraordinarily empty. On average, it is 10,000 times more empty than our Galaxy. Yet, as we have seen, even the Galaxy is mostly empty space. The air we breathe has about 10^{19} atoms in each cubic centimeter—and we usually think of air as empty space. In the interstellar gas of the Galaxy, there is about one atom in every cubic centimeter. Intergalactic space is filled so sparsely that to find one atom, on average, we must search through a cubic meter of space. Most of the universe is fantastically empty; places that are dense, such as the human body, are tremendously rare.

Even our most familiar solids are mostly space. If we could take apart such a solid, piece by piece, we would eventually reach the tiny molecules from which it is formed. Molecules are the smallest particles into which any matter can be divided while still retaining its chemical properties. A molecule of water (H_2O), for example, consists of two hydrogen atoms and one oxygen atom bonded together.

Molecules, in turn, are built of atoms, which are the smallest particles of an element that can still be identified as that element. For example, an atom of gold is the smallest possible piece of gold. Nearly 100 different kinds of atoms (elements) exist in nature. Most of them are rare, and only a handful account for more than 99% of everything with which we come in contact. The most abundant elements in the cosmos today are listed in [Table 1.1](#); think of this table as the “greatest hits” of the universe when it comes to elements. Note that the list includes the four elements most common in life on Earth—hydrogen, carbon, nitrogen, and oxygen.

The Cosmically Abundant Elements

Element ¹	Symbol	Number of Atoms per Million Hydrogen Atoms
Hydrogen	H	1,000,000
Helium	He	80,000
Carbon	C	450
Nitrogen	N	92
Oxygen	O	740
Neon	Ne	130
Magnesium	Mg	40
Silicon	Si	37

Table 1.1

¹ This list of elements is arranged in order of the atomic number, which is the number of protons in each nucleus.

Element ¹	Symbol	Number of Atoms per Million Hydrogen Atoms
Sulfur	S	19
Iron	Fe	32

Table 1.1

All atoms consist of a central, positively charged nucleus surrounded by negatively charged electrons. The bulk of the matter in each atom is found in the nucleus, which consists of positive protons and electrically neutral neutrons all bound tightly together in a very small space. Each element is defined by the number of protons in its atoms. Thus, any atom with 6 protons in its nucleus is called *carbon*, any with 50 protons is called *tin*, and any with 70 protons is called *ytterbium*. (For a list of the elements, see [Appendix K](#).)

The distance from an atomic nucleus to its electrons is typically 100,000 times the size of the nucleus itself. This is why we say that even solid matter is mostly space. The typical atom is far emptier than the solar system out to Neptune. (The distance from Earth to the Sun, for example, is only 100 times the size of the Sun.) This is one reason atoms are not like miniature solar systems.

Remarkably, physicists have discovered that everything that happens in the universe, from the smallest atomic nucleus to the largest superclusters of galaxies, can be explained through the action of only four forces: gravity, electromagnetism (which combines the actions of electricity and magnetism), and two forces that act at the nuclear level. The fact that there are four forces (and not a million, or just one) has puzzled physicists and astronomers for many years and has led to a quest for a unified picture of nature.

LINK TO LEARNING



To construct an atom, particle by particle, check out this [guided animation \(https://openstax.org//30buildanatom\)](https://openstax.org//30buildanatom) for building an atom.

1.9 A Conclusion and a Beginning

If you are new to astronomy, you have probably reached the end of our brief tour in this chapter with mixed emotions. On the one hand, you may be fascinated by some of the new ideas you've read about and you may be eager to learn more. On the other hand, you may be feeling a bit overwhelmed by the number of topics we have covered, and the number of new words and ideas we have introduced. Learning astronomy is a little like learning a new language: at first it seems there are so many new expressions that you'll never master them all, but with practice, you soon develop facility with them.

At this point you may also feel a bit small and insignificant, dwarfed by the cosmic scales of distance and time. But, there is another way to look at what you have learned from our first glimpses of the cosmos. Let us consider the history of the universe from the Big Bang to today and compress it, for easy reference, into a single year. (We have borrowed this idea from Carl Sagan's 1977 Pulitzer Prize-winning book, *The Dragons of Eden*.)

On this scale, the Big Bang happened at the first moment of January 1, and this moment, when you are reading this chapter would be the end of the very last second of December 31. When did other events in the development of the universe happen in this "cosmic year?" Our solar system formed around September 10,

and the oldest rocks we can date on Earth go back to the third week in September ([Figure 1.15](#)).

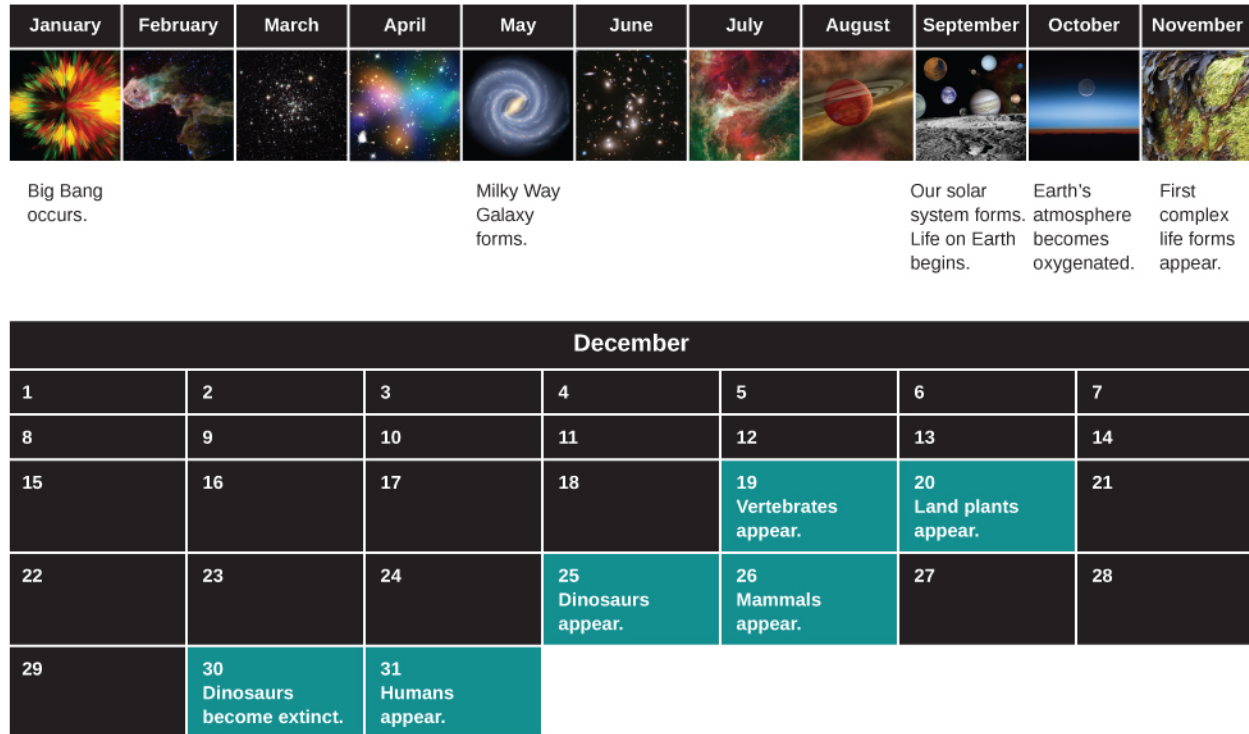


Figure 1.15 Charting Cosmic Time. On a cosmic calendar, where the time since the Big Bang is compressed into 1 year, creatures we would call human do not emerge on the scene until the evening of December 31. (credit: February: modification of work by NASA, JPL-Caltech, W. Reach (SSC/Caltech); March: modification of work by ESA, Hubble and NASA, Acknowledgement: Giles Chapdelaine; April: modification of work by NASA, ESA, CFHT, CXO, M.J. Jee (University of California, Davis), A. Mahdavi (San Francisco State University); May: modification of work by NASA, JPL-Caltech; June: modification of work by NASA/ESA; July: modification of work by NASA, JPL-Caltech, Harvard-Smithsonian; August: modification of work by NASA, JPL-Caltech, R. Hurt (SSC-Caltech); September: modification of work by NASA; October: modification of work by NASA; November: modification of work by Dénes Emőke)

Where does the origin of human beings fall during the course of this cosmic year? The answer turns out to be the evening of December 31. The invention of the alphabet doesn't occur until the fiftieth second of 11:59 p.m. on December 31. And the beginnings of modern astronomy are a mere fraction of a second before the New Year. Seen in a cosmic context, the amount of time we have had to study the stars is minute, and our success in piecing together as much of the story as we have is remarkable.

Certainly our attempts to understand the universe are not complete. As new technologies and new ideas allow us to gather more and better data about the cosmos, our present picture of astronomy will very likely undergo many changes. Still, as you read our current progress report on the exploration of the universe, take a few minutes every once in a while just to savor how much you have already learned.



For Further Exploration

Articles

Bakich, M., et al. "101 Cosmic Objects You Must See." *Astronomy* (January 2022): 6.

Talcott, R. "30 Years of Hubble's Greatest Hits." *Astronomy* (March 2020): 18.

Books

Miller, Ron, and William Hartmann. *The Grand Tour: A Traveler's Guide to the Solar System*. 3rd ed. Workman, 2005. This volume for beginners is a colorfully illustrated voyage among the planets.

Sagan, Carl. *Cosmos*. Ballantine, 2013 [1980]. This tome presents a classic overview of astronomy by an astronomer who had a true gift for explaining things clearly. (You can also check out Sagan's television series *Cosmos: A Personal Voyage* and Neil DeGrasse Tyson's current series *Cosmos: A Spacetime Odyssey*.)

Tyson, Neil DeGrasse, and Don Goldsmith. *Origins: Fourteen Billion Years of Cosmic Evolution*. Norton, 2004. This book provides a guided tour through the beginnings of the universe, galaxies, stars, planets, and life.

Websites

If you enjoyed the beautiful images in this chapter (and there are many more fabulous photos to come in other chapters), you may want to know where you can obtain and download such pictures for your own enjoyment. (Many astronomy images are from government-supported instruments or projects, paid for by tax dollars, and therefore are free of copyright laws.) Here are three resources we especially like:

- Astronomy Picture of the Day: apod.nasa.gov/apod/astropix.html (<https://apod.nasa.gov/apod/astropix.html>). Two space scientists scour the internet and select one beautiful astronomy image to feature each day. Their archives range widely, from images of planets and nebulae to rockets and space instruments; they also have many photos of the night sky. The search function (see the menu on the bottom of the page) works quite well for finding something specific among the many years' worth of daily images.
- Hubble Space Telescope Images: <https://www.spacetelescope.org/images/> (<https://www.spacetelescope.org/images/>) or James Webb Space Telescope Images: <https://esawebb.org/images> (<https://esawebb.org/images>). Here you can browse some of the remarkable images from these two space telescopes, select a particular subject in the menu boxes, or search for the name of an object that intrigues you in this book.
- National Aeronautics and Space Administration's (NASA's) Planetary Photojournal: photojournal.jpl.nasa.gov (<https://photojournal.jpl.nasa.gov>). This site features thousands of images from NASA planetary exploration, with captions of varied length. You can select images by world, feature name, date, or catalog number, and download images in a number of popular formats. Use the Photojournal Search option on the menu at the top of the homepage to access ways to search their archives.

See [Appendix B](#) for more sources of astronomical images.

Videos

Powers of Ten: www.youtube.com/watch?v=0fKBhvDjuy0 (<https://www.youtube.com/watch?v=0fKBhvDjuy0>). This classic short video is a much earlier version of Powers of Ten, narrated by Philip Morrison (9:00).

The Known Universe: www.youtube.com/watch?v=17jymDn0W6U (<https://www.youtube.com/watch?v=17jymDn0W6U>). This video tour from the American Museum of Natural History has realistic animation, music, and captions (6:30).

Wanderers: apod.nasa.gov/apod/ap141208.html (<https://apod.nasa.gov/apod/ap141208.html>). This video provides a tour of the solar system, with narrative by Carl Sagan, imagining other worlds with dramatically

realistic paintings (3:50).

