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Astro-nomy

Astronomy

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OpenStax provides free, peer-reviewed, openly licensed textbooks for introductory college and Advanced Placement® courses and low-cost, personalized courseware that helps students learn. A nonprofit ed tech initiative based at Rice University, we're committed to helping students access the tools they need to complete their courses and meet their educational goals.

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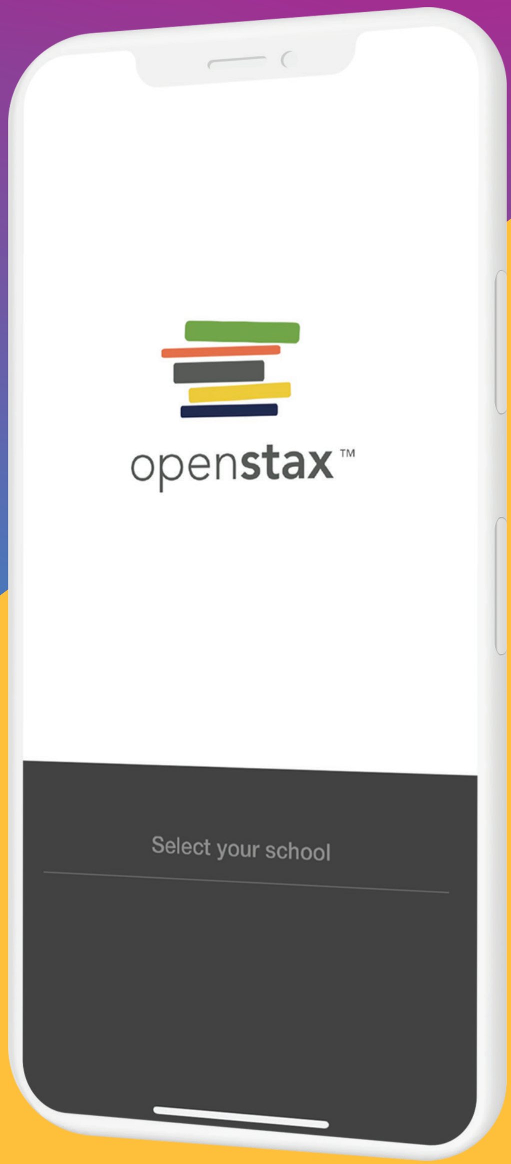
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TABLE OF CONTENTS

PREFACE

Welcome to *Astronomy*, 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.

About OpenStax

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 25 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.

About OpenStax resources

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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*

Astronomy 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. If you have ever thrown up your hands in despair over the spiraling cost of astronomy textbooks, you owe your students a good look at this one.

Coverage and scope

Astronomy was written, updated, and reviewed by a broad 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

Currency and accuracy

Astronomy has information and images from the New Horizons exploration of Pluto, the discovery of gravitational waves, the Rosetta Mission to Comet C-G, 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.

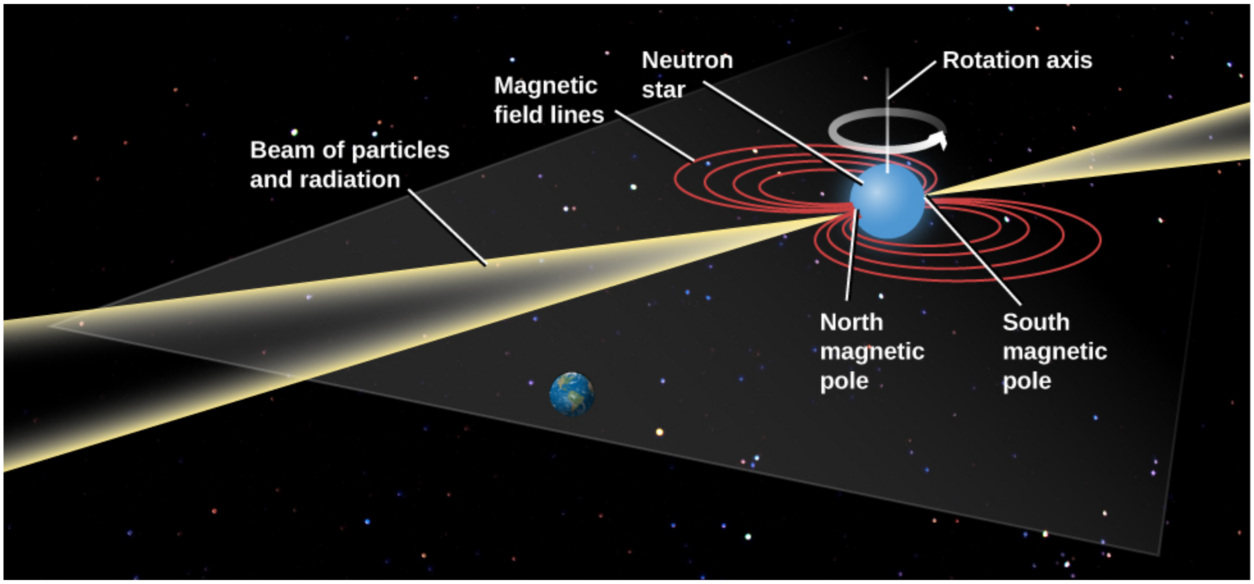

Figure 1 How a Pulsar Beam Sweeps over Earth.

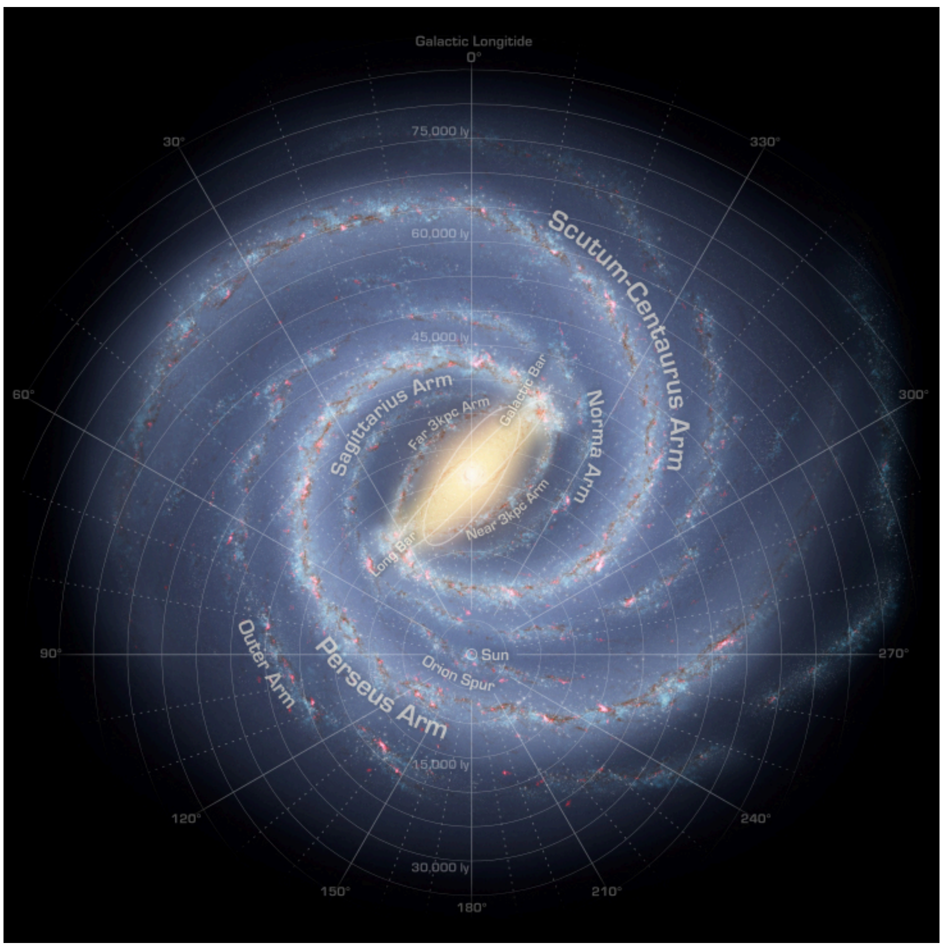

Figure 2 Structure of the Milky Way Galaxy.

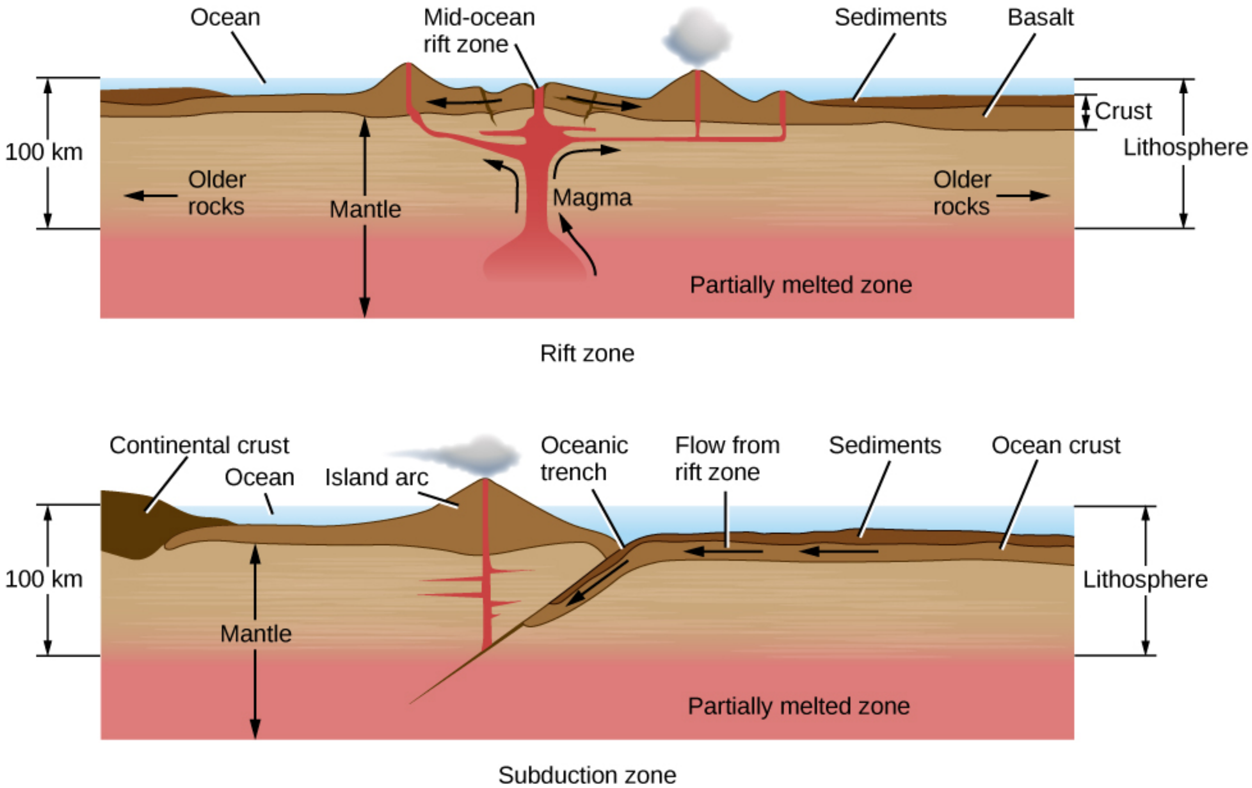

Figure 3 Two Aspects of Plate Tectonics.

Figure 4 Pluto Close Up.

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.

Community Hubs

OpenStax partners with the Institute for the Study of Knowledge Management in Education (ISKME) to offer Community Hubs on OER Commons – a platform for instructors to share community-created resources that support OpenStax books, free of charge. Through our Community Hubs, instructors can upload their own materials or download resources to use in their own courses, including additional ancillaries, teaching material, multimedia, and relevant course content. We encourage instructors to join the hubs for the subjects most relevant to your teaching and research as an opportunity both to enrich your courses and to engage with other faculty.

To reach the Community Hubs, visit **https://www.oercommons.org/hubs/OpenStax (https://www.oercommons.org/hubs/OpenStax)** .

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Andrew Fraknoi is Chair of the Astronomy Department at Foothill College and served as the Executive Director of the Astronomical Society of the Pacific from 1978–1992. His work with the society included editing *Mercury* Magazine, *Universe in the Classroom*, and *Astronomy Beat*. He's taught at San Francisco State University, Canada College, and the University of California Extension. 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 co-author of a syndicated newspaper column on astronomy, and appears regularly on local and national radio. With Sidney Wolff, he was founder of *Astronomy Education Review*. He serves on the Board of Trustees of the SETI Institute and on the Lick Observatory Council. In addition, he has organized six national symposia on teaching introductory astronomy. He received the Klumpke-Roberts Prize of the ASP, the Gemant Award of the American Institute of Physics, and the Faraday Award of the NSTA.

David Morrison, National Aeronautics and Space Administration
David Morrison is a Senior Scientist at NASA Ames Research Center. He 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. He spent 17 years at University of Hawaii's Institute for Astronomy and the Department of Physics and Astronomy. He was Director of the IRTF at Mauna Kea Observatory. Morrison has held senior NASA positions including Chief of the Ames Space Science Division and founding Director of the Lunar Science Institute. He's been on science teams for the Voyager, Galileo, and Kepler missions. Morrison received NASA Outstanding Leadership Medals and the NASA Exceptional Achievement Medal. He was awarded the AAS Carl Sagan medal and the ASP Klumpke-Roberts prize. Committed to the struggle against pseudoscience, he serves as Contributing Editor of *Skeptical Inquirer* and on the Advisory Council of the National Center for Science Education.

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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.

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1 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 (STScl/AURA)-ESA/Hubble Collaboration, and K. Noll (STScl))

Chapter Outline

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).

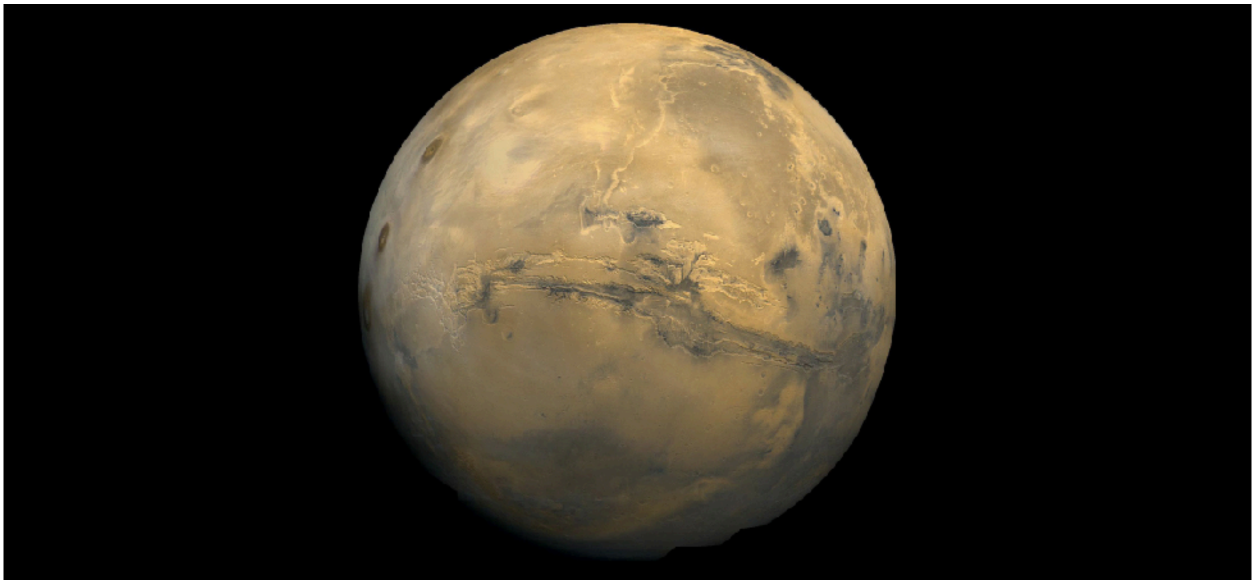


Figure 1.2 Mars Mosaic. This image of Mars is centered on the Valles Marineris (Mariner Valley) complex of canyons, which is as long as the United States is wide. (credit: modification of work by NASA)

- 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.

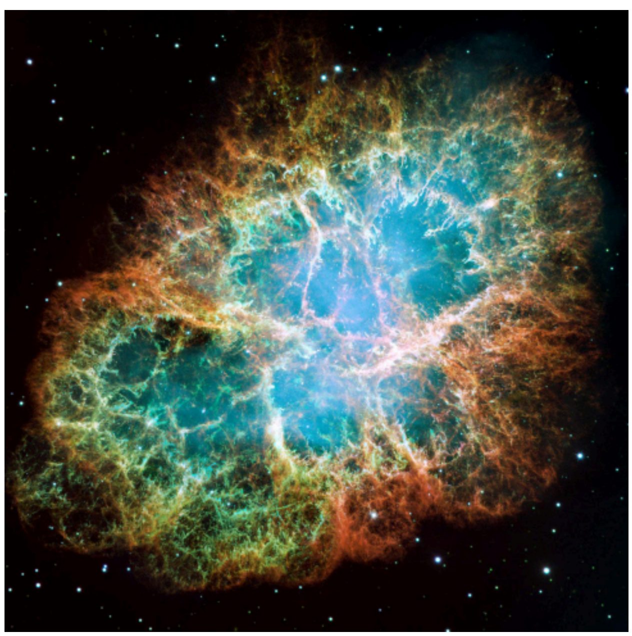


Figure 1.3 Stellar Corpse. We observe the remains of a star that was seen to explode in our skies in 1054 (and was, briefly, bright enough to be visible during the daytime). Today, the remnant is called the Crab Nebula and its central region is seen here. Such exploding stars are crucial to the development 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 theory, 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)** 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 is 4.3 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 $\$7.92 \times 10^{10}$.

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 $\times$ 3.6×10^3 s/h = 1.08×10^9 km/h.
- There are 24 or 2.4×10^1 h in a day, and 365.24 (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.

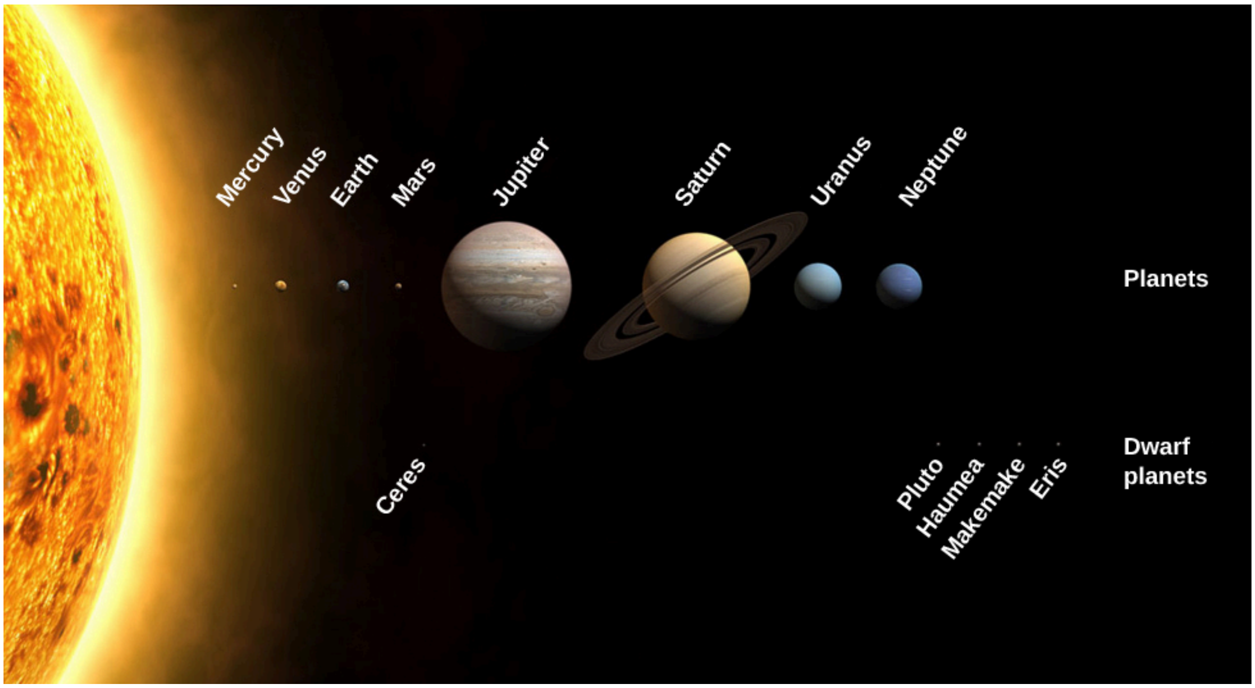


Figure 1.8 Our Solar Family. The Sun, the planets, and some dwarf planets are shown with their sizes drawn to scale. The orbits of the planets are much more widely separated than shown in this drawing. Notice the size of Earth compared to the giant planets. (credit: modification of work by NASA)

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 4.3 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 75,000 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 Fornax Cluster of Galaxies. In this image, you can see part of a cluster of galaxies located about 60 million light-years away in the constellation of Fornax. All the objects that are not pinpoints of light in the picture are galaxies of billions of stars. (credit: ESO, J. Emerson, VISTA. Acknowledgment: Cambridge Astronomical Survey Unit)

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.

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
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

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

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/l/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 1997 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**).

December						
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19 Vertebrates appear.	20 Land plants appear.	21
22	23	24	25 Dinosaurs appear.	26 Mammals appear.	27	28
29	30 Dinosaurs become extinct.	31 Humans appear.				

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

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: **http://hubblesite.org/images/gallery (https://www.hubblesite.org/newscenter/archive/browse/images)** . Starting at this page, you can select from among hundreds of Hubble pictures by subject or by date. Note that many of the images have supporting pictures with them, such as diagrams, animations, or comparisons. Excellent captions and background information are provided. Other ways to approach these images are through the more public-oriented Hubble Gallery (**www.hubblesite.org/gallery (https://www.hubblesite.org/gallery)**) and the European homepage (**www.spacetelescope.org/images (https://www.spacetelescope.org/images)**).
- 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 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. However, only NASA mission images are included. Note the Photojournal Search option on the menu at the top of the homepage to access ways to search their archives.

Videos

Cosmic Voyage: **www.youtube.com/watch?v=qxXf7AJZ73A (https://www.youtube.com/watch?v=qxXf7AJZ73A)** . This video presents a portion of Cosmic Voyage, narrated by Morgan Freeman (8:34).

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).

2 OBSERVING THE SKY: THE BIRTH OF ASTRONOMY

Figure 2.1 Night Sky. In this panoramic photograph of the night sky from the Atacama Desert in Chile, we can see the central portion of the Milky Way Galaxy arcing upward in the center of the frame. On the left, the Large Magellanic Cloud and the Small Magellanic Cloud (smaller galaxies that orbit the Milky Way Galaxy) are easily visible from the Southern Hemisphere. (credit: modification of work by ESO/Y. Beletsky)

Chapter Outline

- **2.1** The Sky Above
- **2.2** Ancient Astronomy
- **2.3** Astrology and Astronomy
- **2.4** The Birth of Modern Astronomy

Thinking Ahead

Much to your surprise, a member of the Flat Earth Society moves in next door. He believes that Earth is flat and all the NASA images of a spherical Earth are either faked or simply show the round (but flat) disk of Earth from above. How could you prove to your new neighbor that Earth really is a sphere? (When you've thought about this on your own, you can check later in the chapter for some suggested answers.)

Today, few people really spend much time looking at the night sky. In ancient days, before electric lights robbed so many people of the beauty of the sky, the stars and planets were an important aspect of everyone's daily life. All the records that we have—on paper and in stone—show that ancient civilizations around the world noticed, worshipped, and tried to understand the lights in the sky and fit them into their own view of the world. These ancient observers found both majestic regularity and never-ending surprise in the motions of the heavens. Through their careful study of the planets, the Greeks and later the Romans laid the foundation of the science of astronomy.

2.1 THE SKY ABOVE

Learning Objectives

By the end of this section, you will be able to:

- Define the main features of the celestial sphere
- Explain the system astronomers use to describe the sky
- Describe how motions of the stars appear to us on Earth
- Describe how motions of the Sun, Moon, and planets appear to us on Earth
- Understand the modern meaning of the term *constellation*

Our senses suggest to us that Earth is the center of the universe—the hub around which the heavens turn. This **geocentric** (Earth-centered) view was what almost everyone believed until the European Renaissance. After all, it is simple, logical, and seemingly self-evident. Furthermore, the geocentric perspective reinforced those philosophical and religious systems that taught the unique role of human beings as the central focus of the cosmos. However, the geocentric view happens to be wrong. One of the great themes of our intellectual history is the overthrow of the geocentric perspective. Let us, therefore, take a look at the steps by which we reevaluated the place of our world in the cosmic order.

The Celestial Sphere

If you go on a camping trip or live far from city lights, your view of the sky on a clear night is pretty much identical to that seen by people all over the world before the invention of the telescope. Gazing up, you get the impression that the sky is a great hollow dome with you at the center (Figure 2.2), and all the stars are an equal distance from you on the surface of the dome. The top of that dome, the point directly above your head, is called the **zenith**, and where the dome meets Earth is called the **horizon**. From the sea or a flat prairie, it is easy to see the horizon as a circle around you, but from most places where people live today, the horizon is at least partially hidden by mountains, trees, buildings, or smog.

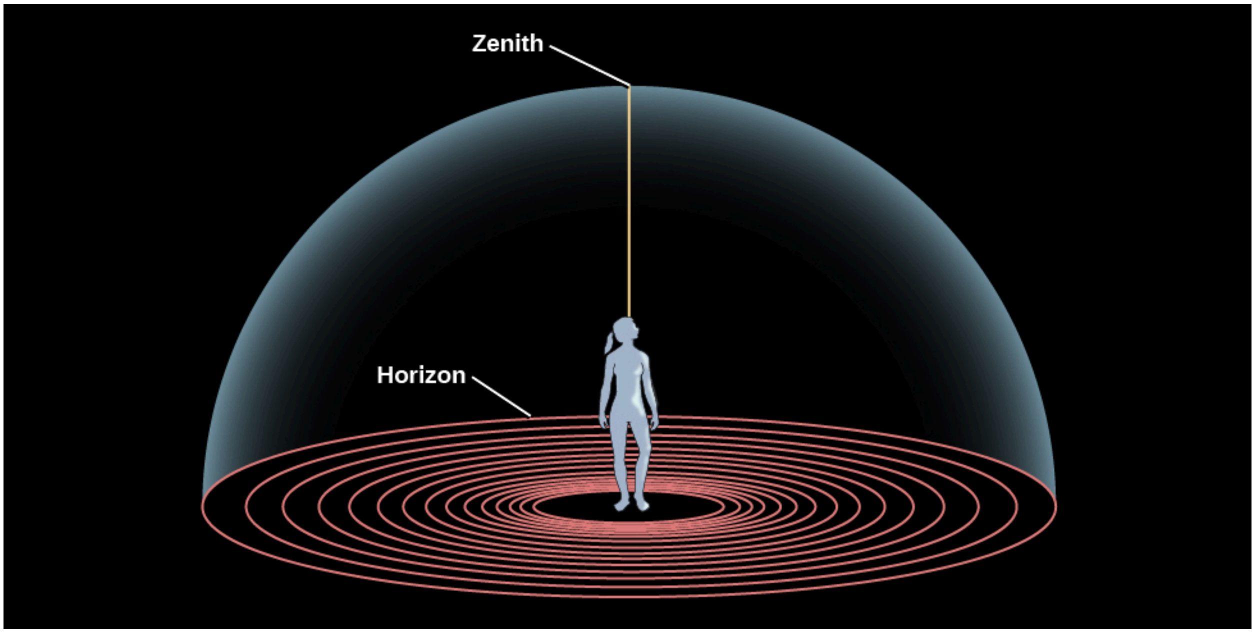


Figure 2.2 The Sky around Us. The horizon is where the sky meets the ground; an observer's zenith is the point directly overhead.

If you lie back in an open field and observe the night sky for hours, as ancient shepherds and travelers regularly did, you will see stars rising on the eastern horizon (just as the Sun and Moon do), moving across the dome of the sky in the course of the night, and setting on the western horizon. Watching the sky turn like this night after night, you might eventually get the idea that the dome of the sky is really part of a great sphere that is turning around you, bringing different stars into view as it turns. The early Greeks regarded the sky as just such a **celestial sphere** (Figure 2.3). Some thought of it as an actual sphere of transparent crystalline material, with the stars embedded in it like tiny jewels.

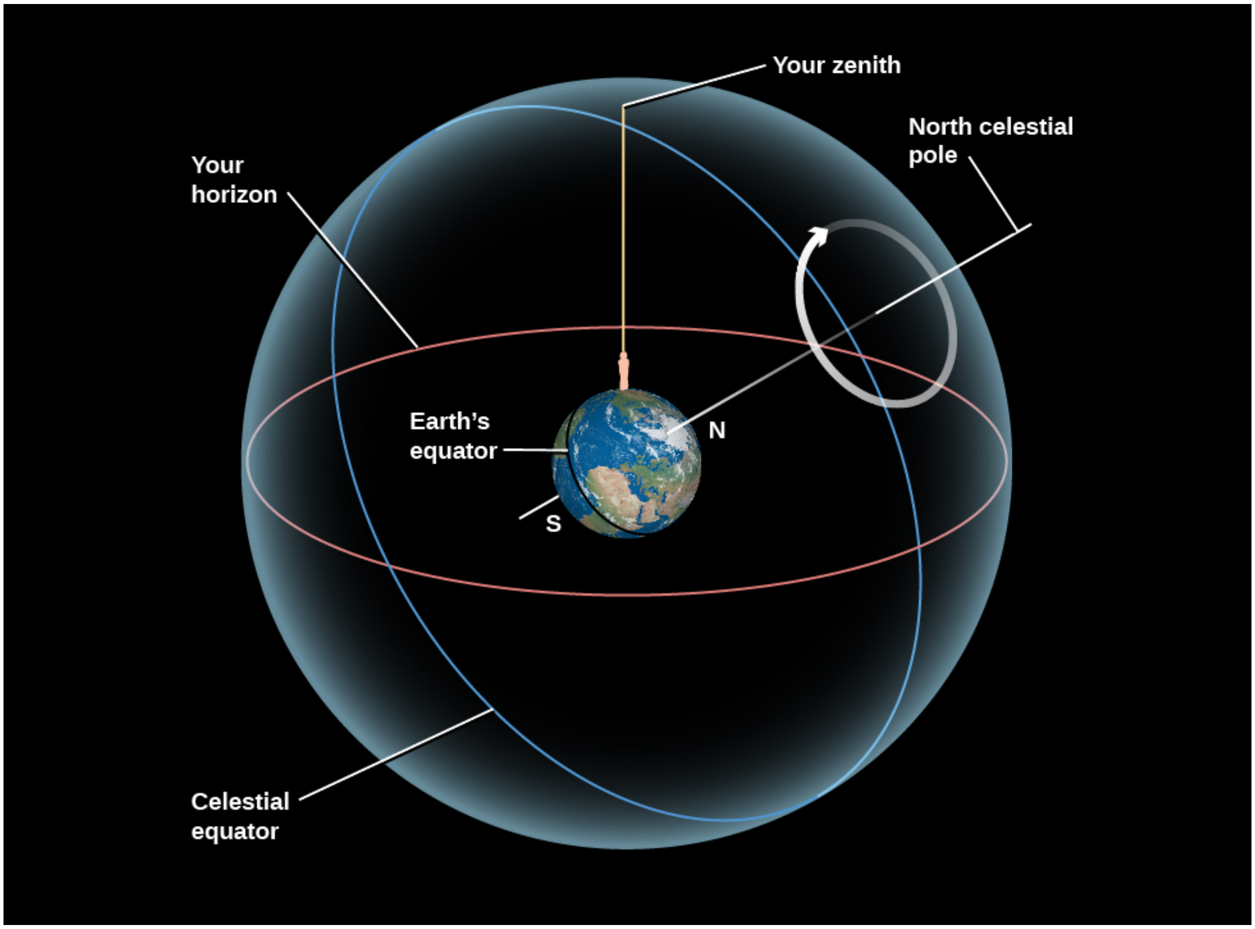


Figure 2.3 Circles on the Celestial Sphere. Here we show the (imaginary) celestial sphere around Earth, on which objects are fixed, and which rotates around Earth on an axis. In reality, it is Earth that turns around this axis, creating the illusion that the sky revolves around us. Note that Earth in this picture has been tilted so that your location is at the top and the North Pole is where the N is. The apparent motion of celestial objects in the sky around the pole is shown by the circular arrow.

Today, we know that it is not the celestial sphere that turns as night and day proceed, but rather the planet on which we live. We can put an imaginary stick through Earth's North and South Poles, representing our planet's axis. It is because Earth turns on this axis every 24 hours that we see the Sun, Moon, and stars rise and set with clockwork regularity. Today, we know that these celestial objects are not really on a dome, but at greatly varying distances from us in space. Nevertheless, it is sometimes still convenient to talk about the celestial dome or sphere to help us keep track of objects in the sky. There is even a special theater, called a *planetarium*, in which we project a simulation of the stars and planets onto a white dome.

As the celestial sphere rotates, the objects on it maintain their positions with respect to one another. A grouping of stars such as the Big Dipper has the same shape during the course of the night, although it turns with the sky. During a single night, even objects we know to have significant motions of their own, such as the nearby planets, seem fixed relative to the stars. Only meteors—brief “shooting stars” that flash into view for just a few seconds—move appreciably with respect to other objects on the celestial sphere. (This is because they are not stars at all. Rather, they are small pieces of cosmic dust, burning up as they hit Earth’s atmosphere.) We can use the fact that the entire celestial sphere seems to turn together to help us set up systems for keeping track of what things are visible in the sky and where they happen to be at a given time.

Celestial Poles and Celestial Equator

To help orient us in the turning sky, astronomers use a system that extends Earth’s axis points into the sky. Imagine a line going through Earth, connecting the North and South Poles. This is Earth’s axis, and Earth rotates about this line. If we extend this imaginary line outward from Earth, the points where this line intersects the celestial sphere are called the *north celestial pole* and the *south celestial pole*. As Earth rotates about its axis, the sky appears to turn in the opposite direction around those **celestial poles** (Figure 2.4). We also (in our imagination) throw Earth’s equator onto the sky and call this the **celestial equator**. It lies halfway between the celestial poles, just as Earth’s equator lies halfway between our planet’s poles.

Figure 2.4 Circling the South Celestial Pole. This long-exposure photo shows trails left by stars as a result of the apparent rotation of the celestial sphere around the south celestial pole. (In reality, it is Earth that rotates.) (Credit: ESO/Iztok Bončina)

Now let’s imagine how riding on different parts of our spinning Earth affects our view of the sky. The apparent motion of the celestial sphere depends on your latitude (position north or south of the equator). First of all, notice that Earth’s axis is pointing at the celestial poles, so these two points in the sky do not appear to turn.

If you stood at the North Pole of Earth, for example, you would see the north celestial pole overhead, at your zenith. The celestial equator, 90° from the celestial poles, would lie along your horizon. As you watched the stars during the course of the night, they would all circle around the celestial pole, with none rising or setting. Only that half of the sky north of the celestial equator is ever visible to an observer at the North Pole. Similarly, an observer at the South Pole would see only the southern half of the sky.

If you were at Earth’s equator, on the other hand, you see the celestial equator (which, after all, is just an “extension” of Earth’s equator) pass overhead through your zenith. The celestial poles, being 90° from the celestial equator, must then be at the north and south points on your horizon. As the sky turns, all stars rise and set; they move straight up from the east side of the horizon and set straight down on the west side. During a 24-hour period, all stars are above the horizon exactly half the time. (Of course, during some of those hours, the Sun is too bright for us to see them.)

What would an observer in the latitudes of the United States or Europe see? Remember, we are neither at Earth's pole nor at the equator, but in between them. For those in the continental United States and Europe, the north celestial pole is neither overhead nor on the horizon, but in between. It appears above the northern horizon at an angular height, or altitude, equal to the observer's latitude. In San Francisco, for example, where the latitude is 38° N, the north celestial pole is 38° above the northern horizon.

For an observer at 38° N latitude, the south celestial pole is 38° below the southern horizon and, thus, never visible. As Earth turns, the whole sky seems to pivot about the north celestial pole. For this observer, stars within 38° of the North Pole can never set. They are always above the horizon, day and night. This part of the sky is called the north **circumpolar zone**. For observers in the continental United States, the Big Dipper, Little Dipper, and Cassiopeia are examples of star groups in the north circumpolar zone. On the other hand, stars within 38° of the south celestial pole never rise. That part of the sky is the south circumpolar zone. To most U.S. observers, the Southern Cross is in that zone. (Don't worry if you are not familiar with the star groups just mentioned; we will introduce them more formally later on.)

LINK TO LEARNING

The **Rotating Sky Lab (https://openstaxcollege.org/l/30rotatingsky)** created by the University of Nebraska–Lincoln provides an interactive demonstration that introduces the horizon coordinate system, the apparent rotation of the sky, and allows for exploration of the relationship between the horizon and celestial equatorial coordinate systems.

At this particular time in Earth's history, there happens to be a star very close to the north celestial pole. It is called Polaris, the pole star, and has the distinction of being the star that moves the least amount as the northern sky turns each day. Because it moved so little while the other stars moved much more, it played a special role in the mythology of several Native American tribes, for example (some called it the "fastener of the sky").

ASTRONOMY BASICS

What's Your Angle?

Astronomers measure how far apart objects appear in the sky by using angles. By definition, there are 360° in a circle, so a circle stretching completely around the celestial sphere contains 360°. The half-sphere or dome of the sky then contains 180° from horizon to opposite horizon. Thus, if two stars are 18° apart, their separation spans about 1/10 of the dome of the sky. To give you a sense of how big a degree is, the full Moon is about half a degree across. This is about the width of your smallest finger (pinkie) seen at arm's length.

Rising and Setting of the Sun

We described the movement of stars in the night sky, but what about during the daytime? The stars continue to circle during the day, but the brilliance of the Sun makes them difficult to see. (The Moon can often be seen in the daylight, however.) On any given day, we can think of the Sun as being located at some position on the hypothetical celestial sphere. When the Sun rises—that is, when the rotation of Earth carries the Sun above the horizon—sunlight is scattered by the molecules of our atmosphere, filling our sky with light and hiding the stars above the horizon.

For thousands of years, astronomers have been aware that the Sun does more than just rise and set. It changes position gradually on the celestial sphere, moving each day about 1° to the east relative to the stars. Very reasonably, the ancients thought this meant the Sun was slowly moving around Earth, taking a period of time we call 1 **year** to make a full circle. Today, of course, we know it is Earth that is going around the Sun, but the effect is the same: the Sun's position in our sky changes day to day. We have a similar experience when we walk around a campfire at night; we see the flames appear in front of each person seated about the fire in turn.

The path the Sun appears to take around the celestial sphere each year is called the **ecliptic** (Figure 2.6). Because of its motion on the ecliptic, the Sun rises about 4 minutes later each day with respect to the stars. Earth must make just a bit more than one complete rotation (with respect to the stars) to bring the Sun up again.

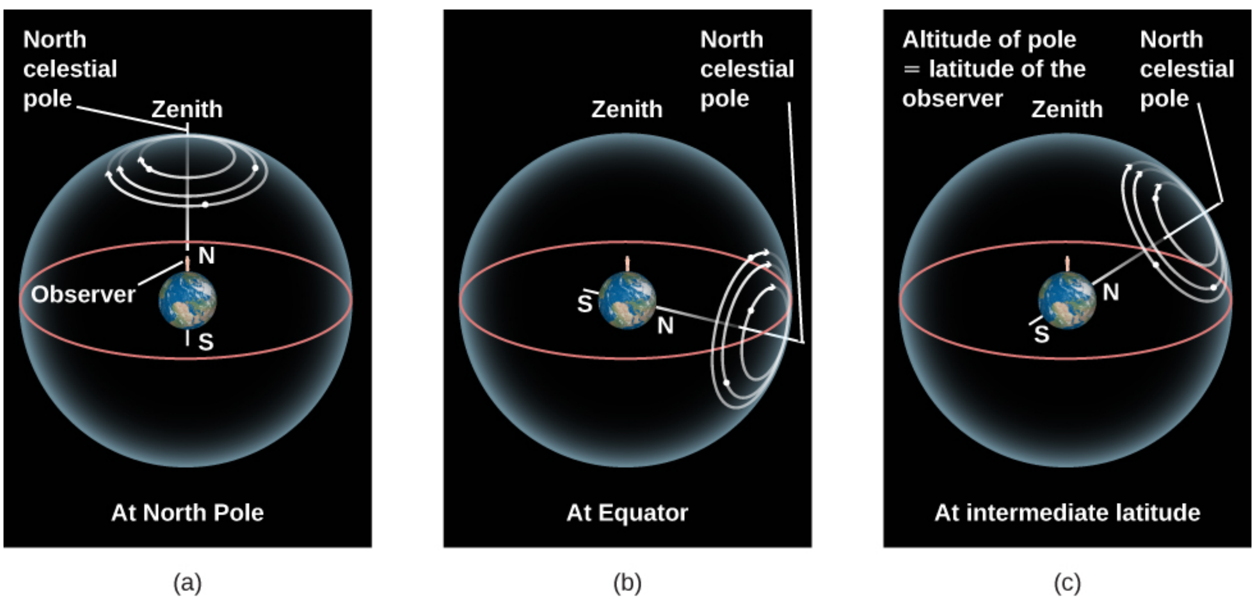


Figure 2.5 Star Circles at Different Latitudes. The turning of the sky looks different depending on your latitude on Earth. (a) At the North Pole, the stars circle the zenith and do not rise and set. (b) At the equator, the celestial poles are on the horizon, and the stars rise straight up and set straight down. (c) At intermediate latitudes, the north celestial pole is at some position between overhead and the horizon. Its angle above the horizon turns out to be equal to the observer's latitude. Stars rise and set at an angle to the horizon.

As the months go by and we look at the Sun from different places in our orbit, we see it projected against different places in our orbit, and thus against different stars in the background (Figure 2.6 and Table 2.1)—or we would, at least, if we could see the stars in the daytime. In practice, we must deduce which stars lie behind and beyond the Sun by observing the stars visible in the opposite direction at night. After a year, when Earth has completed one trip around the Sun, the Sun will appear to have completed one circuit of the sky along the ecliptic.

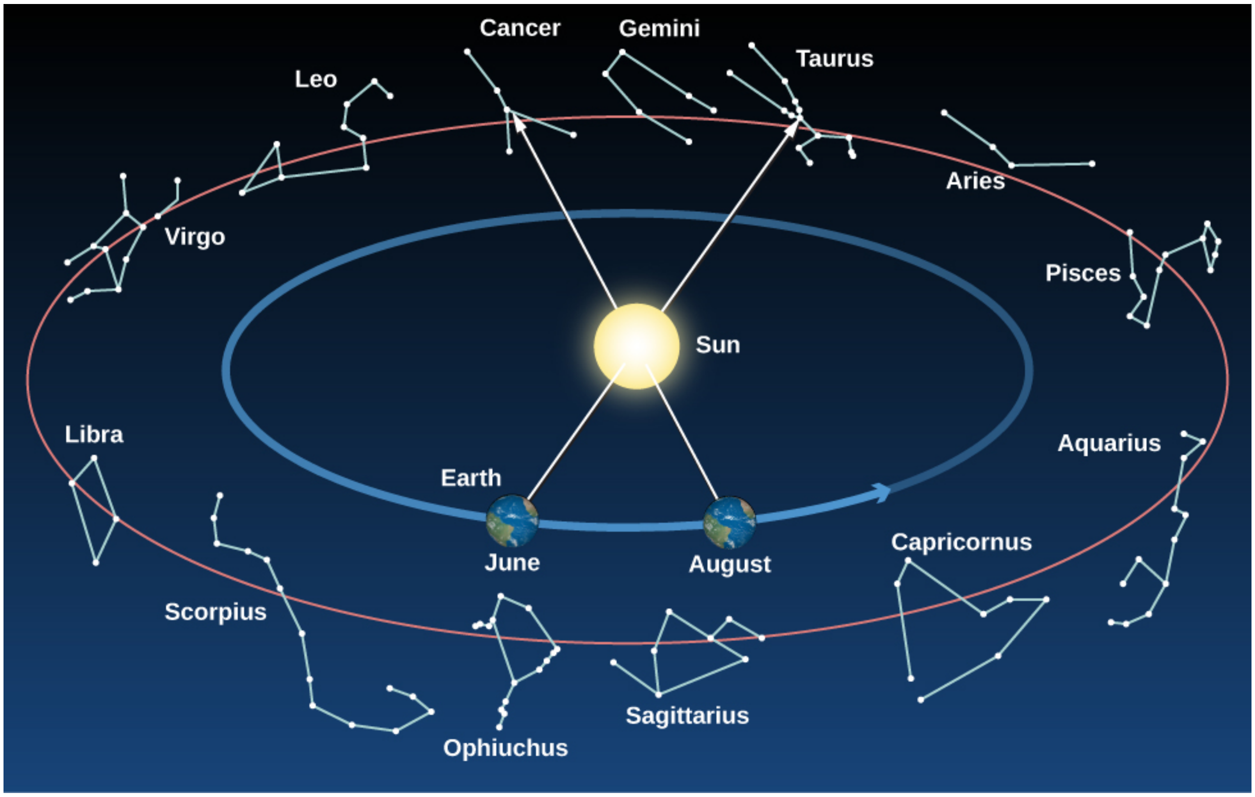


Figure 2.6 Constellations on the Ecliptic. As Earth revolves around the Sun, we sit on “platform Earth” and see the Sun moving around the sky. The circle in the sky that the Sun appears to make around us in the course of a year is called the *ecliptic*. This circle (like all circles in the sky) goes through a set of constellations. The ancients thought these constellations, which the Sun (and the Moon and planets) visited, must be special and incorporated them into their system of astrology. Note that at any given time of the year, some of the constellations crossed by the ecliptic are visible in the night sky; others are in the day sky and are thus hidden by the brilliance of the Sun.

Constellations on the Ecliptic

Constellation on the Ecliptic	Dates When the Sun Crosses It
Capricornus	January 21–February 16
Aquarius	February 16–March 11
Pisces	March 11–April 18
Aries	April 18–May 13
Taurus	May 13–June 22
Gemini	June 22–July 21
Cancer	July 21–August 10
Leo	August 10–September 16
Virgo	September 16–October 31

Table 2.1

Constellations on the Ecliptic

Constellation on the Ecliptic	Dates When the Sun Crosses It
Libra	October 31–November 23
Scorpius	November 23–November 29
Ophiuchus	November 29–December 18
Sagittarius	December 18–January 21

Table 2.1

The ecliptic does not lie along the celestial equator but is inclined to it at an angle of about 23.5°. In other words, the Sun's annual path in the sky is not linked with Earth's equator. This is because our planet's axis of rotation is tilted by about 23.5° from a vertical line sticking out of the plane of the ecliptic (Figure 2.7). Being tilted from "straight up" is not at all unusual among celestial bodies; Uranus and Pluto are actually tilted so much that they orbit the Sun "on their side."

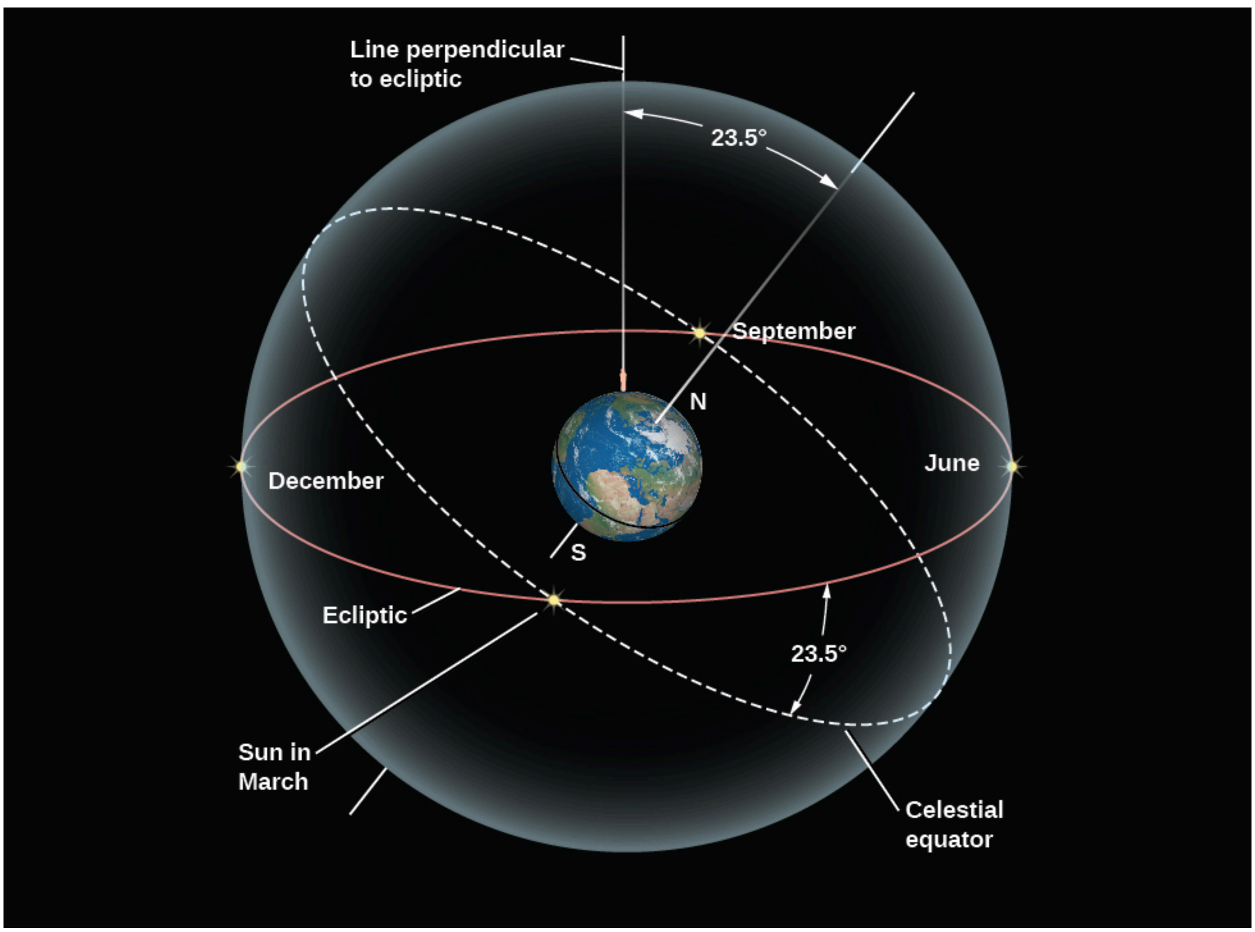


Figure 2.7 The Celestial Tilt. The celestial equator is tilted by 23.5° to the ecliptic. As a result, North Americans and Europeans see the Sun north of the celestial equator and high in our sky in June, and south of the celestial equator and low in the sky in December.

The inclination of the ecliptic is the reason the Sun moves north and south in the sky as the seasons change. In **Earth, Moon, and Sky**, we discuss the progression of the seasons in more detail.

Fixed and Wandering Stars

The Sun is not the only object that moves among the fixed stars. The Moon and each of the planets that are visible to the unaided eye—Mercury, Venus, Mars, Jupiter, Saturn, and Uranus (although just barely)—also change their positions slowly from day to day. During a single day, the Moon and planets all rise and set as Earth turns, just as the Sun and stars do. But like the Sun, they have independent motions among the stars, superimposed on the daily rotation of the celestial sphere. Noticing these motions, the Greeks of 2000 years ago distinguished between what they called the *fixed stars*—those that maintain fixed patterns among themselves through many generations—and the *wandering stars*, or **planets**. The word “planet,” in fact, means “wanderer” in ancient Greek.

Today, we do not regard the Sun and Moon as planets, but the ancients applied the term to all seven of the moving objects in the sky. Much of ancient astronomy was devoted to observing and predicting the motions of these celestial wanderers. They even dedicated a unit of time, the week, to the seven objects that move on their own; that’s why there are 7 days in a week. The Moon, being Earth’s nearest celestial neighbor, has the fastest apparent motion; it completes a trip around the sky in about 1 month (or *moonth*). To do this, the Moon moves about 12°, or 24 times its own apparent width on the sky, each day.

EXAMPLE 2.1

Angles in the Sky

A circle consists of 360 degrees (°). When we measure the angle in the sky that something moves, we can use this formula:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

This is true whether the motion is measured in kilometers per hour or degrees per hour; we just need to use consistent units.

As an example, let’s say you notice the bright star Sirius due south from your observing location in the Northern Hemisphere. You note the time, and then later, you note the time that Sirius sets below the horizon. You find that Sirius has traveled an angular distance of about 75° in 5 h. About how many hours will it take for Sirius to return to its original location?

Solution

The speed of Sirius is $\frac{75°}{5\text{ h}} = \frac{15°}{1\text{ h}}$. If we want to know the time required for Sirius to return to its original location, we need to wait until it goes around a full circle, or 360°. Rearranging the formula for speed we were originally given, we find:

$$\text{time} = \frac{\text{distance}}{\text{speed}} = \frac{360°}{15°/\text{h}} = 24\text{ h}$$

The actual time is a few minutes shorter than this, and we will explore why in a later chapter.

Check Your Learning

The Moon moves in the sky relative to the background stars (in addition to moving with the stars as a result of Earth's rotation.) Go outside at night and note the position of the Moon relative to nearby stars. Repeat the observation a few hours later. How far has the Moon moved? (For reference, the diameter of the Moon is about 0.5°.) Based on your estimate of its motion, how long will it take for the Moon to return to the position relative to the stars in which you first observed it?

Answer:

The speed of the moon is 0.5°/1 h. To move a full 360°, the moon needs 720 h: $\frac{0.5°}{1\text{ h}} = \frac{360°}{720\text{ h}}$. Dividing 720 h by the conversion factor of 24 h/day reveals the lunar cycle is about 30 days.

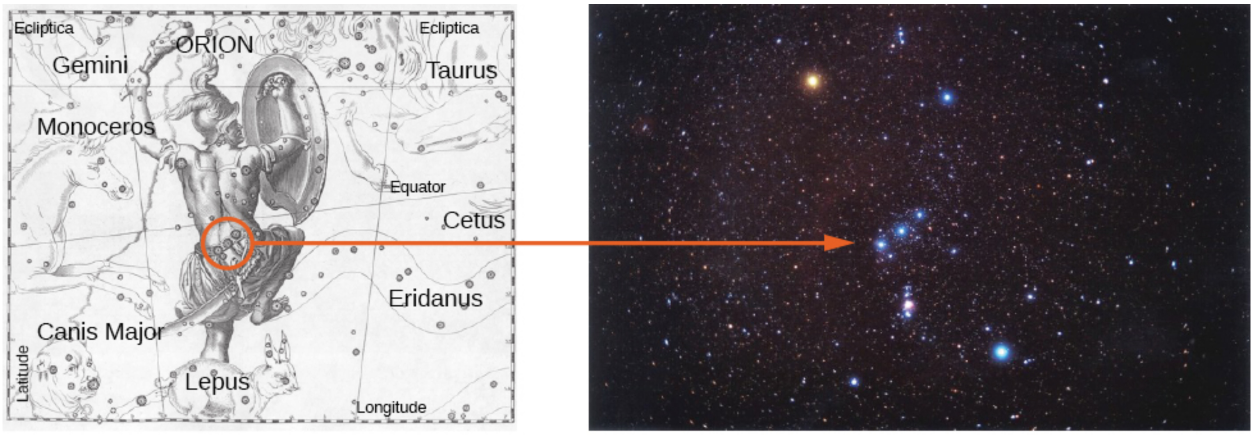
The individual paths of the Moon and planets in the sky all lie close to the ecliptic, although not exactly on it. This is because the paths of the planets about the Sun, and of the Moon about Earth, are all in nearly the same plane, as if they were circles on a huge sheet of paper. The planets, the Sun, and the Moon are thus always found in the sky within a narrow 18-degree-wide belt, centered on the ecliptic, called the **zodiac** (**Figure 2.6**). (The root of the term "zodiac" is the same as that of the word "zoo" and means a collection of animals; many of the patterns of stars within the zodiac belt reminded the ancients of animals, such as a fish or a goat.)

How the planets appear to move in the sky as the months pass is a combination of their actual motions plus the motion of Earth about the Sun; consequently, their paths are somewhat complex. As we will see, this complexity has fascinated and challenged astronomers for centuries.

Constellations

The backdrop for the motions of the "wanderers" in the sky is the canopy of stars. If there were no clouds in the sky and we were on a flat plain with nothing to obstruct our view, we could see about 3000 stars with the unaided eye. To find their way around such a multitude, the ancients found groupings of stars that made some familiar geometric pattern or (more rarely) resembled something they knew. Each civilization found its own patterns in the stars, much like a modern Rorschach test in which you are asked to discern patterns or pictures in a set of inkblots. The ancient Chinese, Egyptians, and Greeks, among others, found their own groupings—or constellations—of stars. These were helpful in navigating among the stars and in passing their star lore on to their children.

You may be familiar with some of the old star patterns we still use today, such as the Big Dipper, Little Dipper, and Orion the hunter, with his distinctive belt of three stars (**Figure 2.8**). However, many of the stars we see are not part of a distinctive star pattern at all, and a telescope reveals millions of stars too faint for the eye to see. Therefore, during the early decades of the 20th century, astronomers from many countries decided to establish a more formal system for organizing the sky.



(a) (b)

Figure 2.8 Orion. (a) The winter constellation of Orion, the hunter, is surrounded by neighboring constellations, as illustrated in the seventeenth-century atlas by Hevelius. (b) A photograph shows the Orion region in the sky. Note the three blue stars that make up the belt of the hunter. The bright red star above the belt denotes his armpit and is called Betelgeuse (pronounced "Beetel-juice"). The bright blue star below the belt is his foot and is called Rigel. (credit a: modification of work by Johannes Hevelius; b: modification of work by Matthew Spinelli)

Today, we use the term *constellation* to mean one of 88 sectors into which we divide the sky, much as the United States is divided into 50 states. The modern boundaries between the constellations are imaginary lines in the sky running north–south and east–west, so that each point in the sky falls in a specific constellation, although, like the states, not all constellations are the same size. All the constellations are listed in **Appendix L**. Whenever possible, we have named each modern constellation after the Latin translations of one of the ancient Greek star patterns that lies within it. Thus, the modern constellation of Orion is a kind of box on the sky, which includes, among many other objects, the stars that made up the ancient picture of the hunter. Some people use the term *asterism* to denote an especially noticeable star pattern within a constellation (or sometimes spanning parts of several constellations). For example, the Big Dipper is an asterism within the constellation of Ursa Major, the Big Bear.

Students are sometimes puzzled because the constellations seldom resemble the people or animals for which they were named. In all likelihood, the Greeks themselves did not name groupings of stars because they looked like actual people or subjects (any more than the outline of Washington state resembles George Washington). Rather, they named sections of the sky in honor of the characters in their mythology and then fit the star configurations to the animals and people as best they could.

LINK TO LEARNING

This **website about objects in the sky (https://openstaxcollege.org/l/30heavensabove)** allows users to construct a detailed sky map showing the location and information about the Sun, Moon, planets, stars, constellations, and even satellites orbiting Earth. Begin by setting your observing location using the option in the menu in the upper right corner of the screen.

2.2 ANCIENT ASTRONOMY

Learning Objectives

By the end of this section, you will be able to:

- Describe early examples of astronomy around the world
- Explain how Greek astronomers were able to deduce that Earth is spherical
- Explain how Greek astronomers were able to calculate Earth's size
- Describe the motion of Earth called precession
- Describe Ptolemy's geocentric system of planetary motion

Let us now look briefly back into history. Much of modern Western civilization is derived in one way or another from the ideas of the ancient Greeks and Romans, and this is true in astronomy as well. However, many other ancient cultures also developed sophisticated systems for observing and interpreting the sky.

Astronomy around the World

Ancient Babylonian, Assyrian, and Egyptian astronomers knew the approximate length of the year. The Egyptians of 3000 years ago, for example, adopted a calendar based on a 365-day year. They kept careful track of the rising time of the bright star Sirius in the predawn sky, which has a yearly cycle that corresponded with the flooding of the Nile River. The Chinese also had a working calendar; they determined the length of the year at about the same time as the Egyptians. The Chinese also recorded comets, bright meteors, and dark spots on the Sun. (Many types of astronomical objects were introduced in **Science and the Universe: A Brief Tour**. If you are not familiar with terms like *comets* and *meteors*, you may want to review that chapter.) Later, Chinese astronomers kept careful records of "guest stars"—those that are normally too faint to see but suddenly flare up to become visible to the unaided eye for a few weeks or months. We still use some of these records in studying stars that exploded a long time ago.

The Mayan culture in Mexico and Central America developed a sophisticated calendar based on the planet Venus, and they made astronomical observations from sites dedicated to this purpose a thousand years ago. The Polynesians learned to navigate by the stars over hundreds of kilometers of open ocean—a skill that enabled them to colonize new islands far away from where they began.

In Britain, before the widespread use of writing, ancient people used stones to keep track of the motions of the Sun and Moon. We still find some of the great stone circles they built for this purpose, dating from as far back as 2800 BCE. The best known of these is Stonehenge, which is discussed in **Earth, Moon, and Sky**.

Early Greek and Roman Cosmology

Our concept of the cosmos—its basic structure and origin—is called **cosmology**, a word with Greek roots. Before the invention of telescopes, humans had to depend on the simple evidence of their senses for a picture of the universe. The ancients developed cosmologies that combined their direct view of the heavens with a rich variety of philosophical and religious symbolism.

At least 2000 years before Columbus, educated people in the eastern Mediterranean region knew Earth was round. Belief in a spherical Earth may have stemmed from the time of Pythagoras, a philosopher and mathematician who lived 2500 years ago. He believed circles and spheres to be "perfect forms" and suggested that Earth should therefore be a sphere. As evidence that the gods liked spheres, the Greeks cited the fact that the Moon is a sphere, using evidence we describe later.

The writings of Aristotle (384–322 BCE), the tutor of Alexander the Great, summarize many of the ideas of his day. They describe how the progression of the Moon's phases—its apparent changing shape—results from our seeing different portions of the Moon's sunlit hemisphere as the month goes by (see **Earth, Moon, and Sky**). Aristotle also knew that the Sun has to be farther away from Earth than is the Moon because occasionally the Moon passed exactly between Earth and the Sun and hid the Sun temporarily from view. We call this a *solar eclipse*.

Aristotle cited convincing arguments that Earth must be round. First is the fact that as the Moon enters or emerges from Earth's shadow during an eclipse of the Moon, the shape of the shadow seen on the Moon is always round (**Figure 2.9**). Only a spherical object always produces a round shadow. If Earth were a disk, for example, there would be some occasions when the sunlight would strike it edge-on and its shadow on the Moon would be a line.

Figure 2.9 Earth's Round Shadow. A lunar eclipse occurs when the Moon moves into and out of Earth's shadow. Note the curved shape of the shadow—evidence for a spherical Earth that has been recognized since antiquity. (credit: modification of work by Brian Paczkowski)

As a second argument, Aristotle explained that travelers who go south a significant distance are able to observe stars that are not visible farther north. And the height of the North Star—the star nearest the north celestial pole—decreases as a traveler moves south. On a flat Earth, everyone would see the same stars overhead. The only possible explanation is that the traveler must have moved over a curved surface on Earth, showing stars from a different angle. (See the **How Do We Know Earth Is Round?** feature for more ideas on proving Earth is round.)

One Greek thinker, Aristarchus of Samos (310–230 BCE), even suggested that Earth was moving around the Sun, but Aristotle and most of the ancient Greek scholars rejected this idea. One of the reasons for their conclusion was the thought that if Earth moved about the Sun, they would be observing the stars from different places along Earth's orbit. As Earth moved along, nearby stars should shift their positions in the sky relative to more distant stars. In a similar way, we see foreground objects appear to move against a more distant background whenever we are in motion. When we ride on a train, the trees in the foreground appear to shift their position relative to distant hills as the train rolls by. Unconsciously, we use this phenomenon all of the time to estimate distances around us.

The apparent shift in the direction of an object as a result of the motion of the observer is called **parallax**. We call the shift in the apparent direction of a star due to Earth's orbital motion *stellar parallax*. The Greeks made dedicated efforts to observe stellar parallax, even enlisting the aid of Greek soldiers with the clearest vision, but to no avail. The brighter (and presumably nearer) stars just did not seem to shift as the Greeks observed them in the spring and then again in the fall (when Earth is on the opposite side of the Sun).

This meant either that Earth was not moving or that the stars had to be so tremendously far away that the parallax shift was immeasurably small. A cosmos of such enormous extent required a leap of imagination that most ancient philosophers were not prepared to make, so they retreated to the safety of the Earth-centered view, which would dominate Western thinking for nearly two millennia.

ASTRONOMY BASICS

How Do We Know Earth Is Round?

In addition to the two ways (from Aristotle's writings) discussed in this chapter, you might also reason as follows:

1. Let's watch a ship leave its port and sail into the distance on a clear day. On a flat Earth, we would just see the ship get smaller and smaller as it sails away. But this isn't what we actually observe. Instead, ships sink below the horizon, with the hull disappearing first and the mast remaining visible for a while longer. Eventually, only the top of the mast can be seen as the ship sails around the curvature of Earth. Finally, the ship disappears under the horizon.
2. The International Space Station circles Earth once every 90 minutes or so. Photographs taken from the shuttle and other satellites show that Earth is round from every perspective.
3. Suppose you made a friend in each time zone of Earth. You call all of them at the same hour and ask, "Where is the Sun?" On a flat Earth, each caller would give you roughly the same answer. But on a round Earth you would find that, for some friends, the Sun would be high in the sky whereas for others it would be rising, setting, or completely out of sight (and this last group of friends would be upset with you for waking them up).

Measurement of Earth by Eratosthenes

The Greeks not only knew Earth was round, but also they were able to measure its size. The first fairly accurate determination of Earth's diameter was made in about 200 BCE by Eratosthenes (276–194 BCE), a Greek living in Alexandria, Egypt. His method was a geometric one, based on observations of the Sun.

The Sun is so distant from us that all the light rays that strike our planet approach us along essentially parallel lines. To see why, look at Figure 2.10. Take a source of light near Earth—say, at position A. Its rays strike different parts of Earth along diverging paths. From a light source at B, or at C (which is still farther away), the angle between rays that strike opposite parts of Earth is smaller. The more distant the source, the smaller the angle between the rays. For a source infinitely distant, the rays travel along parallel lines.

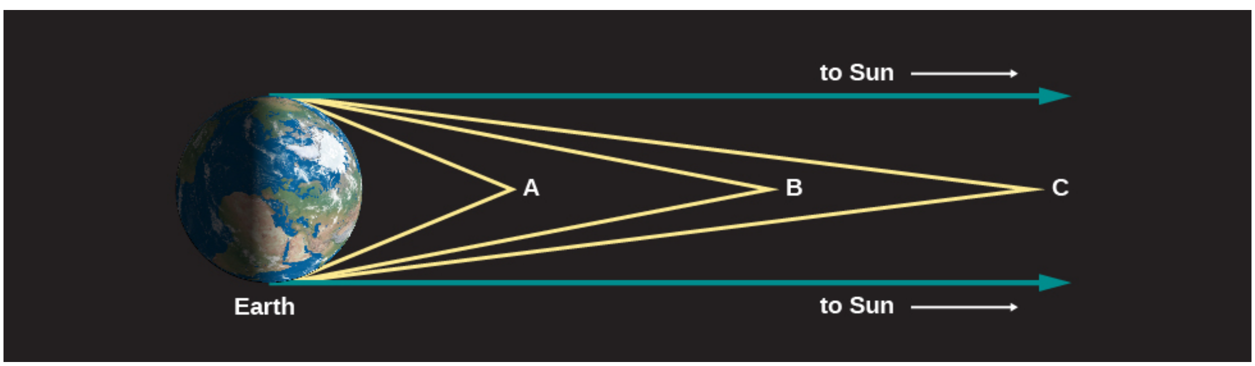


Figure 2.10 Light Rays from Space. The more distant an object, the more nearly parallel the rays of light coming from it.

Of course, the Sun is not infinitely far away, but given its distance of 150 million kilometers, light rays striking Earth from a point on the Sun diverge from one another by an angle far too small to be observed with the unaided eye. As a consequence, if people all over Earth who could see the Sun were to point at it, their fingers would, essentially, all be parallel to one another. (The same is also true for the planets and stars—an idea we will use in our discussion of how telescopes work.)

Eratosthenes was told that on the first day of summer at Syene, Egypt (near modern Aswan), sunlight struck the bottom of a vertical well at noon. This indicated that the Sun was directly over the well—meaning that Syene was on a direct line from the center of Earth to the Sun. At the corresponding time and date in Alexandria, Eratosthenes observed the shadow a column made and saw that the Sun was not directly overhead, but was slightly south of the zenith, so that its rays made an angle with the vertical equal to about 1/50 of a circle (7°). Because the Sun's rays striking the two cities are parallel to one another, why would the two rays not make the same angle with Earth's surface? Eratosthenes reasoned that the curvature of the round Earth meant that "straight up" was not the same in the two cities. And the measurement of the angle in Alexandria, he realized, allowed him to figure out the size of Earth. Alexandria, he saw, must be 1/50 of Earth's circumference north of Syene (**Figure 2.11**). Alexandria had been measured to be 5000 stadia north of Syene. (The *stadium* was a Greek unit of length, derived from the length of the racetrack in a stadium.) Eratosthenes thus found that Earth's circumference must be 50 × 5000, or 250,000 stadia.

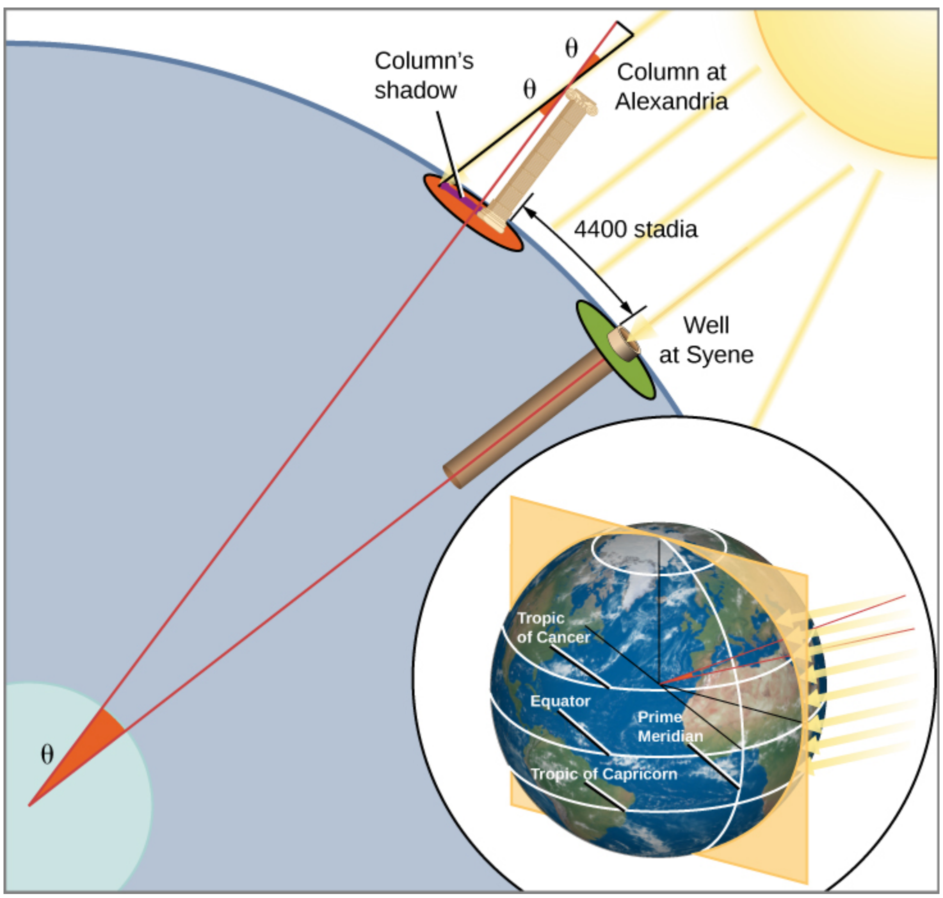


Figure 2.11 How Eratosthenes Measured the Size of Earth. Eratosthenes measured the size of Earth by observing the angle at which the Sun's rays hit our planet's surface. The Sun's rays come in parallel, but because Earth's surface curves, a ray at Syene comes straight down whereas a ray at Alexandria makes an angle of 7° with the vertical. That means, in effect, that at Alexandria, Earth's surface has curved away from Syene by 7° of 360°, or 1/50 of a full circle. Thus, the distance between the two cities must be 1/50 the circumference of Earth. (credit: modification of work by NOAA Ocean Service Education)

It is not possible to evaluate precisely the accuracy of Eratosthenes solution because there is doubt about which of the various kinds of Greek stadia he used as his unit of distance. If it was the common Olympic stadium, his result is about 20% too large. According to another interpretation, he used a stadium equal to about 1/6 kilometer, in which case his figure was within 1% of the correct value of 40,000 kilometers. Even if his measurement was not exact, his success at measuring the size of our planet by using only shadows, sunlight, and the power of human thought was one of the greatest intellectual achievements in history.

Hipparchus and Precession

Perhaps the greatest astronomer of antiquity was Hipparchus, born in Nicaea in what is present-day Turkey. He erected an observatory on the island of Rhodes around 150 BCE, when the Roman Republic was expanding its influence throughout the Mediterranean region. There he measured, as accurately as possible, the positions of objects in the sky, compiling a pioneering star catalog with about 850 entries. He designated celestial coordinates for each star, specifying its position in the sky, just as we specify the position of a point on Earth by giving its latitude and longitude.

He also divided the stars into **apparent magnitudes** according to their apparent brightness. He called the brightest ones “stars of the first magnitude”; the next brightest group, “stars of the second magnitude”; and so forth. This rather arbitrary system, in modified form, still remains in use today (although it is less and less useful for professional astronomers).

By observing the stars and comparing his data with older observations, Hipparchus made one of his most remarkable discoveries: the position in the sky of the north celestial pole had altered over the previous century and a half. Hipparchus deduced correctly that this had happened not only during the period covered by his observations, but was in fact happening all the time: the direction around which the sky appears to rotate changes slowly but continuously. Recall from the section on celestial poles and the celestial equator that the north celestial pole is just the projection of Earth’s North Pole into the sky. If the north celestial pole is wobbling around, then Earth itself must be doing the wobbling. Today, we understand that the direction in which Earth’s axis points does indeed change slowly but regularly—a motion we call **precession**. If you have ever watched a spinning top wobble, you observed a similar kind of motion. The top’s axis describes a path in the shape of a cone, as Earth’s gravity tries to topple it (**Figure 2.12**).

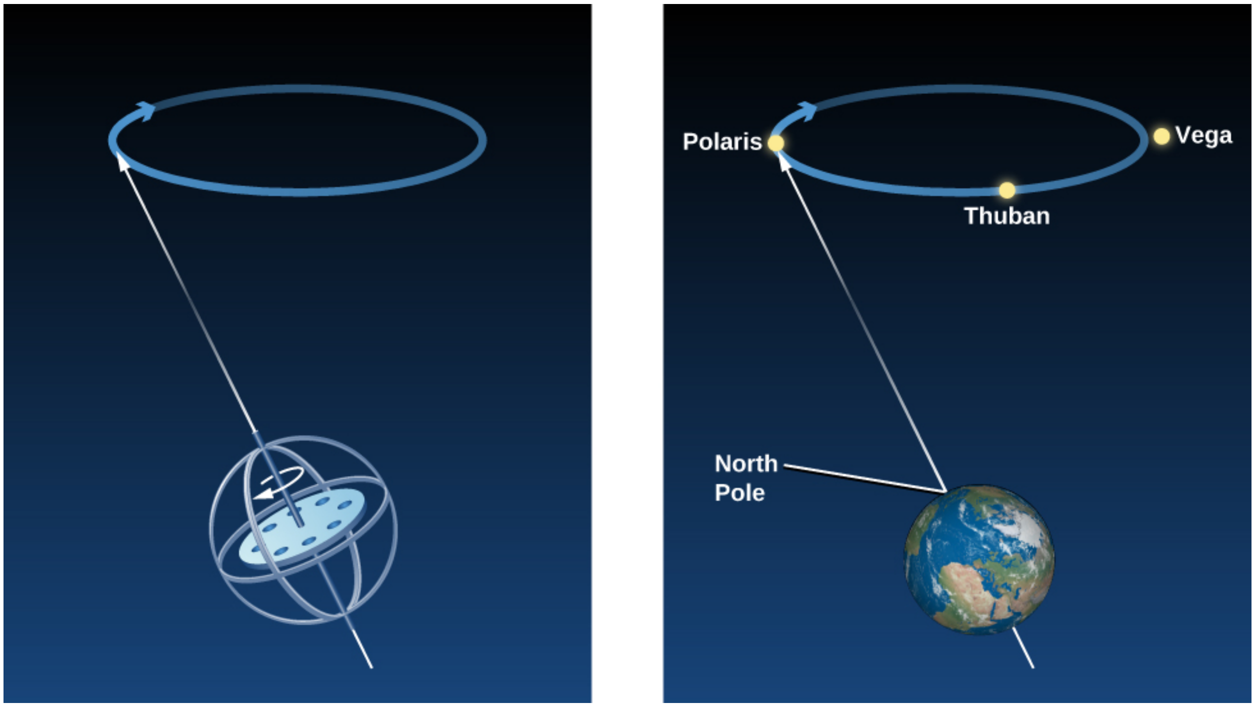


Figure 2.12 Precession. Just as the axis of a rapidly spinning top wobbles slowly in a circle, so the axis of Earth wobbles in a 26,000-year cycle. Today the north celestial pole is near the star Polaris, but about 5000 years ago it was close to a star called Thuban, and in 14,000 years it will be closest to the star Vega.

Because our planet is not an exact sphere, but bulges a bit at the equator, the pulls of the Sun and Moon cause it to wobble like a top. It takes about 26,000 years for Earth's axis to complete one circle of precession. As a result of this motion, the point where our axis points in the sky changes as time goes on. While Polaris is the star closest to the north celestial pole today (it will reach its closest point around the year 2100), the star Vega in the constellation of Lyra will be the North Star in 14,000 years.

Ptolemy's Model of the Solar System

The last great astronomer of the Roman era was Claudius Ptolemy (or Ptolemaeus), who flourished in Alexandria in about the year 140. He wrote a mammoth compilation of astronomical knowledge, which today is called by its Arabic name, *Almagest* (meaning "The Greatest"). *Almagest* does not deal exclusively with Ptolemy's own work; it includes a discussion of the astronomical achievements of the past, principally those of Hipparchus. Today, it is our main source of information about the work of Hipparchus and other Greek astronomers.

Ptolemy's most important contribution was a geometric representation of the solar system that predicted the positions of the planets for any desired date and time. Hipparchus, not having enough data on hand to solve the problem himself, had instead amassed observational material for posterity to use. Ptolemy supplemented this material with new observations of his own and produced a cosmological model that endured more than a thousand years, until the time of Copernicus.

The complicating factor in explaining the motions of the planets is that their apparent wandering in the sky results from the combination of their own motions with Earth's orbital revolution. As we watch the planets from our vantage point on the moving Earth, it is a little like watching a car race while you are competing in it. Sometimes opponents' cars pass you, but at other times you pass them, making them appear to move backward for a while with respect to you.

Figure 2.13 shows the motion of Earth and a planet farther from the Sun—in this case, Mars. Earth travels around the Sun in the same direction as the other planet and in nearly the same plane, but its orbital speed is faster. As a result, it overtakes the planet periodically, like a faster race car on the inside track. The figure shows where we see the planet in the sky at different times. The path of the planet among the stars is illustrated in the star field on the right side of the figure.

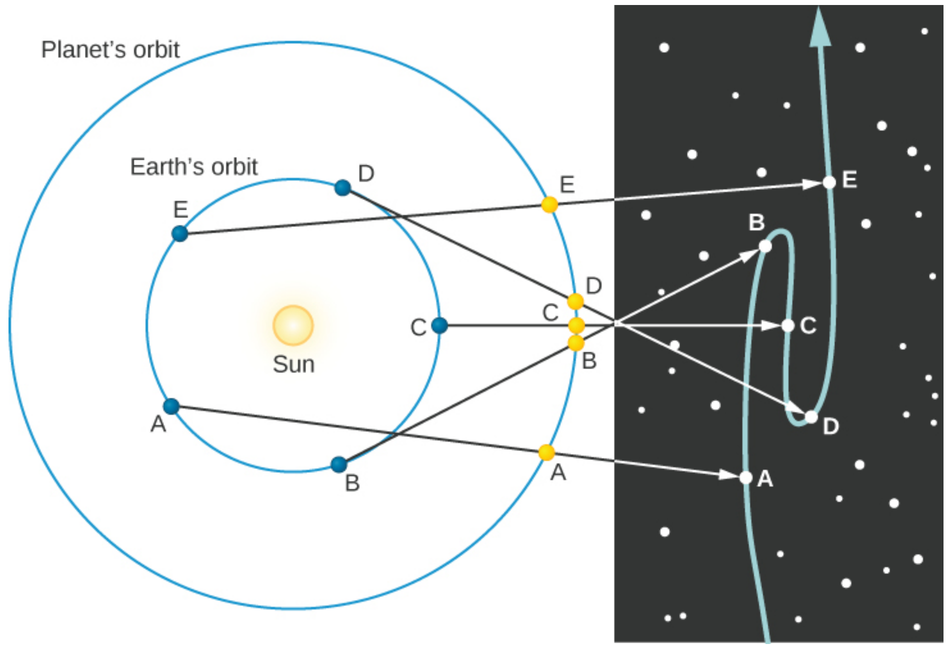


Figure 2.13 Retrograde Motion of a Planet beyond Earth's Orbit. The letters on the diagram show where Earth and Mars are at different times. By following the lines from each Earth position through each corresponding Mars position, you can see how the retrograde path of Mars looks against the background stars.

LINK TO LEARNING

This **retrograde simulation of Mars (https://openstaxcollege.org/l/30marsretrograd)** illustrates the motion of Mars as seen from Earth as well as Earth's retrograde motion as seen from Mars. There is also an animation of the movement of the two planets relative to each other that creates the appearance of this motion.

Normally, planets move eastward in the sky over the weeks and months as they orbit the Sun, but from positions B to D in **Figure 2.13**, as Earth passes the planets in our example, it appears to drift backward, moving west in the sky. Even though it is actually moving to the east, the faster-moving Earth has overtaken it and seems, from our perspective, to be leaving it behind. As Earth rounds its orbit toward position E, the planet again takes up its apparent eastward motion in the sky. The temporary apparent westward motion of a planet as Earth swings between it and the Sun is called **retrograde motion**. Such backward motion is much easier for us to understand today, now that we know Earth is one of the moving planets and not the unmoving center of all creation. But Ptolemy was faced with the far more complex problem of explaining such motion while assuming a stationary Earth.

Furthermore, because the Greeks believed that celestial motions had to be circles, Ptolemy had to construct his model using circles alone. To do it, he needed dozens of circles, some moving around other circles, in a complex structure that makes a modern viewer dizzy. But we must not let our modern judgment cloud our admiration for Ptolemy's achievement. In his day, a complex universe centered on Earth was perfectly reasonable and, in its own way, quite beautiful. However, as Alfonso X, the King of Castile, was reported to have said after having the Ptolemaic system of planet motions explained to him, "If the Lord Almighty had consulted me before embarking upon Creation, I should have recommended something simpler."

Ptolemy solved the problem of explaining the observed motions of planets by having each planet revolve in a small orbit called an **epicycle**. The center of the epicycle then revolved about Earth on a circle called a *deferent* (**Figure 2.14**). When the planet is at position *x* in **Figure 2.14** on the epicycle orbit, it is moving in the same direction as the center of the epicycle; from Earth, the planet appears to be moving eastward. When the planet is at *y*, however, its motion is in the direction opposite to the motion of the epicycle's center around Earth. By choosing the right combination of speeds and distances, Ptolemy succeeded in having the planet moving westward at the correct speed and for the correct interval of time, thus replicating retrograde motion with his model.

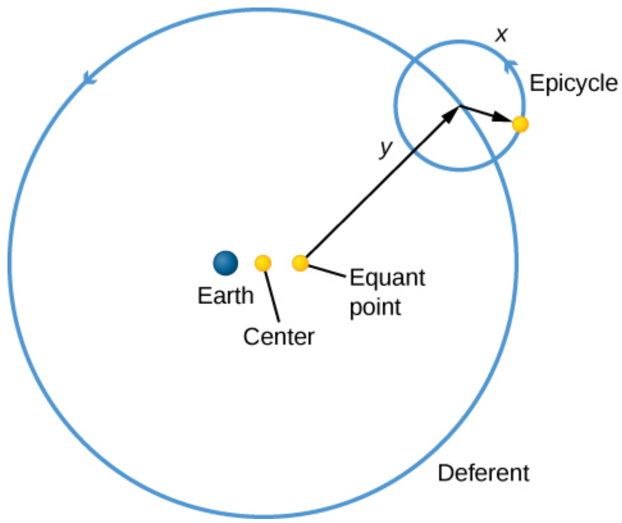


Figure 2.14 Ptolemy's Complicated Cosmological System. Each planet orbits around a small circle called an *epicycle*. Each epicycle orbits on a larger circle called the *deferent*. This system is not centered exactly on Earth but on an offset point called the *equant*. The Greeks needed all this complexity to explain the actual motions in the sky because they believed that Earth was stationary and that all sky motions had to be circular.

However, we shall see in **Orbits and Gravity** that the planets, like Earth, travel about the Sun in orbits that are ellipses, not circles. Their actual behavior cannot be represented accurately by a scheme of uniform circular motions. In order to match the observed motions of the planets, Ptolemy had to center the deferent circles, not on Earth, but at points some distance from Earth. In addition, he introduced uniform circular motion around yet another axis, called the *equant point*. All of these considerably complicated his scheme.

It is a tribute to the genius of Ptolemy as a mathematician that he was able to develop such a complex system to account successfully for the observations of planets. It may be that Ptolemy did not intend for his cosmological model to describe reality, but merely to serve as a mathematical representation that allowed him to predict the positions of the planets at any time. Whatever his thinking, his model, with some modifications, was eventually accepted as authoritative in the Muslim world and (later) in Christian Europe.

2.3 ASTROLOGY AND ASTRONOMY

Learning Objectives

By the end of this section, you will be able to:

- Explain the origins of astrology
- Explain what a horoscope is
- Summarize the arguments that invalidate astrology as a scientific practice

Many ancient cultures regarded the planets and stars as representatives or symbols of the gods or other supernatural forces that controlled their lives. For them, the study of the heavens was not an abstract subject; it was connected directly to the life-and-death necessity of understanding the actions of the gods and currying favor with them. Before the time of our scientific perspectives, everything that happened in nature—from the weather, to diseases and accidents, to celestial surprises such as eclipses or new comets—was thought to be an expression of the whims or displeasure of the gods. Any signs that helped people understand what these gods had in mind were considered extremely important.

The movements of the seven objects that had the power to "wander" through the realm of the sky—the Sun, the Moon, and five planets visible to the unaided eye—clearly must have special significance in such a system of thinking.

Most ancient cultures associated these seven objects with various supernatural rulers in their pantheon and kept track of them for religious reasons. Even in the comparatively sophisticated Greece of antiquity, the planets had the names of gods and were credited with having the same powers and influences as the gods whose names they bore. From such ideas was born the ancient system called **astrology**, still practiced by some people today, in which the positions of these bodies among the stars of the zodiac are thought to hold the key to understanding what we can expect from life.

The Beginnings of Astrology

Astrology began in Babylonia about two and half millennia ago. The Babylonians, believing the planets and their motions influenced the fortunes of kings and nations, used their knowledge of astronomy to guide their rulers. When the Babylonian culture was absorbed by the Greeks, astrology gradually came to influence the entire Western world and eventually spread to Asia as well.

By the 2nd century BCE the Greeks democratized astrology by developing the idea that the planets influence every individual. In particular, they believed that the configuration of the Sun, Moon, and planets at the moment of birth affected a person's personality and fortune—a doctrine called *natal astrology*. Natal astrology reached its peak with Ptolemy 400 years later. As famous for his astrology as for his astronomy, Ptolemy compiled the *Tetrabiblos*, a treatise on astrology that remains the "bible" of the subject. It is essentially this ancient religion, older than Christianity or Islam, that is still practiced by today's astrologers.

The Horoscope

The key to natal astrology is the **horoscope**, a chart showing the positions of the planets in the sky at the moment of an individual's birth. The word "horoscope" comes from the Greek words *hora* (meaning "time") and *skopos* (meaning a "watcher" or "marker"), so "horoscope" can literally be translated as "marker of the hour." When a horoscope is charted, the planets (including the Sun and Moon, classed as *wanderers* by the ancients) must first be located in the zodiac. At the time astrology was set up, the zodiac was divided into 12 sectors called *signs* (Figure 2.15), each 30° long. Each sign was named after a constellation in the sky through which the Sun, Moon, and planets were seen to pass—the sign of Virgo after the constellation of Virgo, for example.

Figure 2.15 Zodiac Signs. The signs of the zodiac are shown in a medieval woodcut.

When someone today casually asks you your “sign,” they are asking for your “sun sign”—which zodiac sign the Sun was in at the moment you were born. However, more than 2000 years have passed since the signs received their names from the constellations. Because of precession, the constellations of the zodiac slide westward along the ecliptic, going once around the sky in about 26,000 years. Thus, today the real stars have slipped around by about 1/12 of the zodiac—about the width of one sign.

In most forms of astrology, however, the signs have remained assigned to the dates of the year they had when astrology was first set up. This means that the astrological signs and the real constellations are out of step; the sign of Aries, for example, now occupies the constellation of Pisces. When you look up your sun sign in a newspaper astrology column, the name of the sign associated with your birthday is no longer the name of the constellation in which the Sun was actually located when you were born. To know that constellation, you must look for the sign before the one that includes your birthday.

A complete horoscope shows the location of not only the Sun, but also the Moon and each planet in the sky by indicating its position in the appropriate sign of the zodiac. However, as the celestial sphere turns (owing to the rotation of Earth), the entire zodiac moves across the sky to the west, completing a circuit of the heavens each day. Thus, the position in the sky (or “house” in astrology) must also be calculated. There are more or less standardized rules for the interpretation of the horoscope, most of which (at least in Western schools of astrology) are derived from the *Tetrabiblos* of Ptolemy. Each sign, each house, and each planet—the last acting as a center of force—is supposed to be associated with particular matters in a person’s life.

The detailed interpretation of a horoscope is a very complicated business, and there are many schools of astrological thought on how it should be done. Although some of the rules may be standardized, how each rule is to be weighed and applied is a matter of judgment—and “art.” It also means that it is very difficult to tie down astrology to specific predictions or to get the same predictions from different astrologers.

Astrology Today

Astrologers today use the same basic principles laid down by Ptolemy nearly 2000 years ago. They cast horoscopes (a process much simplified by the development of appropriate computer programs) and suggest interpretations. Sun sign astrology (which you read in the newspapers and many magazines) is a recent, simplified variant of natal astrology. Although even professional astrologers do not place much trust in such a limited scheme, which tries to fit everyone into just 12 groups, sun sign astrology is taken seriously by many people (perhaps because it is discussed so commonly in the media).

Today, we know much more about the nature of the planets as physical bodies, as well as about human genetics, than the ancients could. It is hard to imagine how the positions of the Sun, Moon, or planets in the sky at the moment of our birth could have anything to do with our personality or future. There are no known forces, not gravity or anything else, that could cause such effects. (For example, a straightforward calculation shows that the gravitational pull of the obstetrician delivering a newborn baby is greater than that of Mars.) Astrologers thus have to argue there must be unknown forces exerted by the planets that depend on their configurations with respect to one another and that do not vary according to the distance of the planet—forces for which there is no shred of evidence.

Another curious aspect of astrology is its emphasis on planet configurations at birth. What about the forces that might influence us at conception? Isn't our genetic makeup more important for determining our personality than the circumstances of our birth? Would we really be a different person if we had been born a few hours earlier or later, as astrology claims? (Back when astrology was first conceived, birth was thought of as a moment of magic significance, but today we understand a lot more about the long process that precedes it.)

Actually, very few well-educated people today buy the claim that our entire lives are predetermined by astrological influences at birth, but many people apparently believe that astrology has validity as an indicator of affinities and personality. A surprising number of Americans make judgments about people—whom they will hire, associate with, and even marry—on the basis of astrological information. To be sure, these are difficult decisions, and you might argue that we should use any relevant information that might help us to make the right choices. But does astrology actually provide any useful information on human personality? This is the kind of question that can be tested using the scientific method (see **Testing Astrology**).

The results of hundreds of tests are all the same: there is no evidence that natal astrology has any predictive power, even in a statistical sense. Why, then, do people often seem to have anecdotes about how well their own astrologer advised them? Effective astrologers today use the language of the zodiac and the horoscope only as the outward trappings of their craft. Mostly they work as amateur therapists, offering simple truths that clients like or need to hear. (Recent studies have shown that just about any sort of short-term therapy makes people feel a little better because the very act of talking about our problems with someone who listens attentively is, in itself, beneficial.)

The scheme of astrology has no basis in scientific fact, however; at best, it can be described as a pseudoscience. It is an interesting historical system, left over from prescientific days and best remembered for the impetus it gave people to learn the cycles and patterns of the sky. From it grew the science of astronomy, which is our main subject for discussion.

MAKING CONNECTIONS

Testing Astrology

In response to modern public interest in astrology, scientists have carried out a wide range of statistical tests to assess its predictive power. The simplest of these examine sun sign astrology to determine whether—as astrologers assert—some signs are more likely than others to be associated with some objective measure of success, such as winning Olympic medals, earning high corporate salaries, or achieving elective office or high military rank. (You can devise such a test yourself by looking up the birth dates of all members of Congress, for example, or all members of the U.S. Olympic team.) Are our political leaders somehow selected at birth by their horoscopes and thus more likely to be Leos, say, than Scorpios?

You do not even need to be specific about your prediction in such tests. After all, many schools of astrology disagree about which signs go with which personality characteristics. To demonstrate the validity of the astrological hypothesis, it would be sufficient if the birthdays of all our leaders clustered in any one or two signs in some statistically significant way. Dozens of such tests have been performed, and all have come up completely negative: the birth dates of leaders in all fields tested have been found to be distributed randomly among *all* the signs. Sun sign astrology does not predict anything about a person's future occupation or strong personality traits.

In a fine example of such a test, two statisticians examined the reenlistment records of the United States Marine Corps. We suspect you will agree that it takes a certain kind of personality not only to enlist, but also to reenlist in the Marines. If sun signs can predict strong personality traits—as astrologers claim—then those who reenlisted (with similar personalities) should have been distributed preferentially in those one or few signs that matched the personality of someone who loves being a Marine. However, the reenlisted were distributed randomly among all the signs.

More sophisticated studies have also been done, involving full horoscopes calculated for thousands of individuals. The results of all these studies are also negative: none of the systems of astrology has been shown to be at all effective in connecting astrological aspects to personality, success, or finding the right person to love.

Other tests show that it hardly seems to matter what a horoscope interpretation says, as long as it is vague enough, and as long as each subject feels it was prepared personally just for him or her. The French statistician Michel Gauquelin, for example, sent the horoscope interpretation for one of the worst mass murderers in history to 150 people, but told each recipient that it was a "reading" prepared exclusively for him or her. Ninety-four percent of the readers said they recognized themselves in the interpretation of the mass murderer's horoscope.

Geoffrey Dean, an Australian researcher, reversed the astrological readings of 22 subjects, substituting phrases that were the opposite of what the horoscope actually said. Yet, his subjects said that the resulting readings applied to them just as often (95%) as the people to whom the original phrases were given.

LINK TO LEARNING

For more on astrology and science from an astronomer's point of view, read this **article (https://openstaxcollege.org/l/30astrosociety)** that shines light on the topic through an accessible Q&A.

2.4 THE BIRTH OF MODERN ASTRONOMY

Learning Objectives

By the end of this section, you will be able to:

- Explain how Copernicus developed the heliocentric model of the solar system
- Explain the Copernican model of planetary motion and describe evidence or arguments in favor of it
- Describe Galileo's discoveries concerning the study of motion and forces
- Explain how Galileo's discoveries tilted the balance of evidence in favor of the Copernican model

Astronomy made no major advances in strife-torn medieval Europe. The birth and expansion of Islam after the seventh century led to a flowering of Arabic and Jewish cultures that preserved, translated, and added to many of the astronomical ideas of the Greeks. Many of the names of the brightest stars, for example, are today taken from the Arabic, as are such astronomical terms as "zenith."

As European culture began to emerge from its long, dark age, trading with Arab countries led to a rediscovery of ancient texts such as *Almagest* and to a reawakening of interest in astronomical questions. This time of rebirth (in French, "*renaissance*") in astronomy was embodied in the work of Copernicus (**Figure 2.16**).

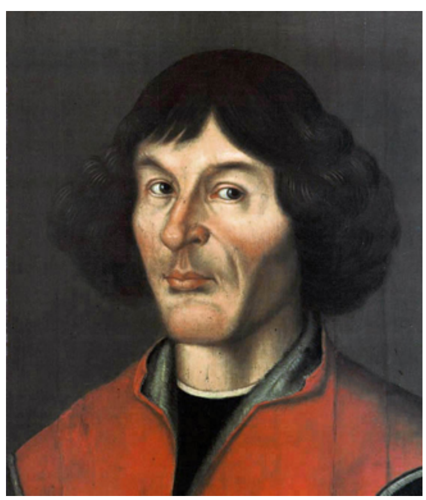


Figure 2.16 Nicolaus Copernicus (1473–1543). Copernicus was a cleric and scientist who played a leading role in the emergence of modern science. Although he could not prove that Earth revolves about the Sun, he presented such compelling arguments for this idea that he turned the tide of cosmological thought and laid the foundations upon which Galileo and Kepler so effectively built in the following century.

Copernicus

One of the most important events of the Renaissance was the displacement of Earth from the center of the universe, an intellectual revolution initiated by a Polish cleric in the sixteenth century. Nicolaus Copernicus was born in Torun, a mercantile town along the Vistula River. His training was in law and medicine, but his main interests were astronomy and mathematics. His great contribution to science was a critical reappraisal of the existing theories of planetary motion and the development of a new Sun-centered, or **heliocentric**, model of the solar system. Copernicus concluded that Earth is a planet and that all the planets circle the Sun. Only the Moon orbits Earth (**Figure 2.17**).

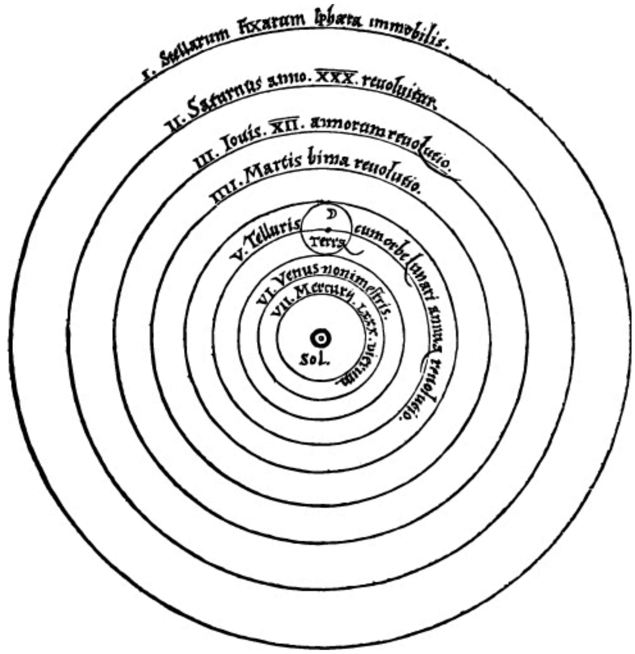


Figure 2.17 Copernicus' System. Copernicus developed a heliocentric plan of the solar system. This system was published in the first edition of *De Revolutionibus Orbium Coelestium*. Notice the word *Sol* for "Sun" in the middle. (credit: Nicolai Copernici)

Copernicus described his ideas in detail in his book *De Revolutionibus Orbium Coelestium* (*On the Revolution of Celestial Orbs*), published in 1543, the year of his death. By this time, the old Ptolemaic system needed significant adjustments to predict the positions of the planets correctly. Copernicus wanted to develop an improved theory from which to calculate planetary positions, but in doing so, he was himself not free of all traditional prejudices.

He began with several assumptions that were common in his time, such as the idea that the motions of the heavenly bodies must be made up of combinations of uniform circular motions. But he did not assume (as most people did) that Earth had to be in the center of the universe, and he presented a defense of the heliocentric system that was elegant and persuasive. His ideas, although not widely accepted until more than a century after his death, were much discussed among scholars and, ultimately, had a profound influence on the course of world history.

One of the objections raised to the heliocentric theory was that if Earth were moving, we would all sense or feel this motion. Solid objects would be ripped from the surface, a ball dropped from a great height would not strike the ground directly below it, and so forth. But a moving person is not necessarily aware of that motion. We have all experienced seeing an adjacent train, bus, or ship appear to move, only to discover that it is we who are moving.

Copernicus argued that the apparent motion of the Sun about Earth during the course of a year could be represented equally well by a motion of Earth about the Sun. He also reasoned that the apparent rotation of the celestial sphere could be explained by assuming that Earth rotates while the celestial sphere is stationary. To the objection that if Earth rotated about an axis it would fly into pieces, Copernicus answered that if such motion would tear Earth apart, the still faster motion of the much larger celestial sphere required by the geocentric hypothesis would be even more devastating.

The Heliocentric Model

The most important idea in Copernicus' *De Revolutionibus* is that Earth is one of six (then-known) planets that revolve about the Sun. Using this concept, he was able to work out the correct general picture of the solar system. He placed the planets, starting nearest the Sun, in the correct order: Mercury, Venus, Earth, Mars, Jupiter, and Saturn. Further, he deduced that the nearer a planet is to the Sun, the greater its orbital speed. With his theory, he was able to explain the complex retrograde motions of the planets without epicycles and to work out a roughly correct scale for the solar system.

Copernicus could not prove that Earth revolves about the Sun. In fact, with some adjustments, the old Ptolemaic system could have accounted, as well, for the motions of the planets in the sky. But Copernicus pointed out that the Ptolemaic cosmology was clumsy and lacking the beauty and symmetry of its successor.

In Copernicus' time, in fact, few people thought there were ways to prove whether the heliocentric or the older geocentric system was correct. A long philosophical tradition, going back to the Greeks and defended by the Catholic Church, held that pure human thought combined with divine revelation represented the path to truth. Nature, as revealed by our senses, was suspect. For example, Aristotle had reasoned that heavier objects (having more of the quality that made them heavy) must fall to Earth faster than lighter ones. This is absolutely incorrect, as any simple experiment dropping two balls of different weights shows. However, in Copernicus' day, experiments did not carry much weight (if you will pardon the expression); Aristotle's reasoning was more convincing.

In this environment, there was little motivation to carry out observations or experiments to distinguish between competing cosmological theories (or anything else). It should not surprise us, therefore, that the heliocentric idea was debated for more than half a century without any tests being applied to determine its validity. (In fact, in the North American colonies, the older geocentric system was still taught at Harvard University in the first years after it was founded in 1636.)

Contrast this with the situation today, when scientists rush to test each new hypothesis and do not accept any ideas until the results are in. For example, when two researchers at the University of Utah announced in 1989 that they had discovered a way to achieve nuclear fusion (the process that powers the stars) at room temperature, other scientists at more than 25 laboratories around the United States attempted to duplicate "cold fusion" within a few weeks—without success, as it turned out. The cold fusion theory soon went down in flames.

How would we look at Copernicus' model today? When a new hypothesis or theory is proposed in science, it must first be checked for consistency with what is already known. Copernicus' heliocentric idea passes this test, for it allows planetary positions to be calculated at least as well as does the geocentric theory. The next step is to determine which predictions the new hypothesis makes that differ from those of competing ideas. In the case of Copernicus, one example is the prediction that, if Venus circles the Sun, the planet should go through the full range of phases just as the Moon does, whereas if it circles Earth, it should not (**Figure 2.18**). Also, we should not be able to see the full phase of Venus from Earth because the Sun would then be between Venus and Earth. But in those days, before the telescope, no one imagined testing these predictions.

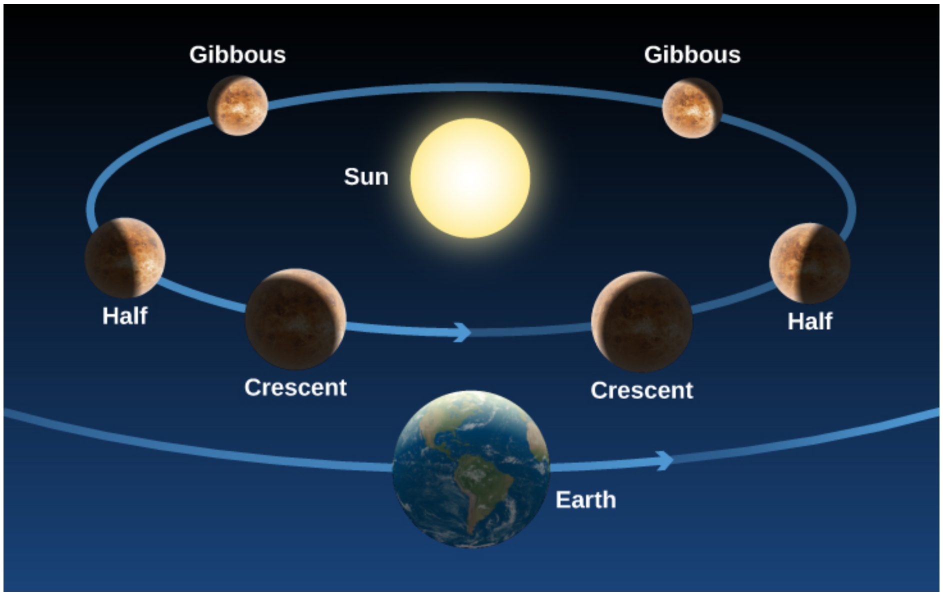


Figure 2.18 Phases of Venus. As Venus moves around the Sun, we see changing illumination of its surface, just as we see the face of the Moon illuminated differently in the course of a month.

LINK TO LEARNING

This **animation (https://openstaxcollege.org/l/30venusphases)** shows the phases of Venus. You can also see its distance from Earth as it orbits the Sun.

Galileo and the Beginning of Modern Science

Many of the modern scientific concepts of observation, experimentation, and the testing of hypotheses through careful quantitative measurements were pioneered by a man who lived nearly a century after Copernicus. Galileo Galilei (**Figure 2.19**), a contemporary of Shakespeare, was born in Pisa. Like Copernicus, he began training for a medical career, but he had little interest in the subject and later switched to mathematics. He held faculty positions at the University of Pisa and the University of Padua, and eventually became mathematician to the Grand Duke of Tuscany in Florence.

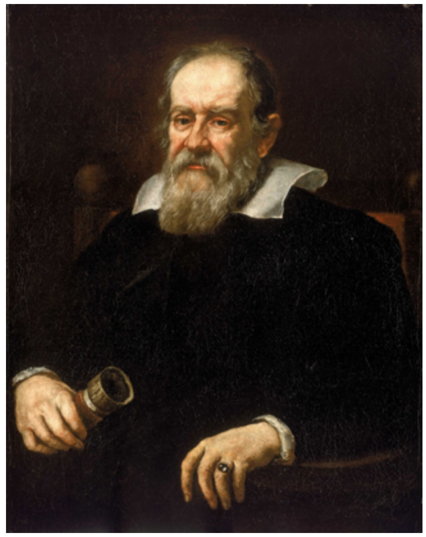


Figure 2.19 Galileo Galilei (1564–1642). Galileo advocated that we perform experiments or make observations to ask nature its ways. When Galileo turned the telescope to the sky, he found things were not the way philosophers had supposed.

Galileo's greatest contributions were in the field of mechanics, the study of motion and the actions of forces on bodies. It was familiar to all persons then, as it is to us now, that if something is at rest, it tends to remain at rest and requires some outside influence to start it in motion. Rest was thus generally regarded as the natural state of matter. Galileo showed, however, that rest is no more natural than motion.

If an object is slid along a rough horizontal floor, it soon comes to rest because friction between it and the floor acts as a retarding force. However, if the floor and the object are both highly polished, the object, given the same initial speed, will slide farther before stopping. On a smooth layer of ice, it will slide farther still. Galileo reasoned that if all resisting effects could be removed, the object would continue in a steady state of motion indefinitely. He argued that a force is required not only to start an object moving from rest but also to slow down, stop, speed up, or change the direction of a moving object. You will appreciate this if you have ever tried to stop a rolling car by leaning against it, or a moving boat by tugging on a line.

Galileo also studied the way objects **accelerate**—change their speed or direction of motion. Galileo watched objects as they fell freely or rolled down a ramp. He found that such objects accelerate uniformly; that is, in equal intervals of time they gain equal increments in speed. Galileo formulated these newly found laws in precise mathematical terms that enabled future experimenters to predict how far and how fast objects would move in various lengths of time.

LINK TO LEARNING

In theory, if Galileo is right, a feather and a hammer, dropped at the same time from a height, should land at the same moment. On Earth, this experiment is not possible because air resistance and air movements make the feather flutter, instead of falling straight down, accelerated only by the force of gravity. For generations, physics teachers had said that the place to try this experiment is somewhere where there is no air, such as the Moon. In 1971, *Apollo 15* astronaut David Scott took a hammer and feather to the Moon and tried it, to the delight of physics nerds everywhere. NASA provides the **video of the hammer and feather (https://openstaxcollege.org/l/30HamVsFeath)** as well as a brief explanation.

Sometime in the 1590s, Galileo adopted the Copernican hypothesis of a heliocentric solar system. In Roman Catholic Italy, this was not a popular philosophy, for Church authorities still upheld the ideas of Aristotle and Ptolemy, and they had powerful political and economic reasons for insisting that Earth was the center of creation. Galileo not only challenged this thinking but also had the audacity to write in Italian rather than scholarly Latin, and to lecture publicly on those topics. For him, there was no contradiction between the authority of the Church in matters of religion and morality, and the authority of nature (revealed by experiments) in matters of science. It was primarily because of Galileo and his “dangerous” opinions that, in 1616, the Church issued a prohibition decree stating that the Copernican doctrine was “false and absurd” and not to be held or defended.

Galileo’s Astronomical Observations

It is not certain who first conceived of the idea of combining two or more pieces of glass to produce an instrument that enlarged images of distant objects, making them appear nearer. The first such “spyglasses” (now called *telescopes*) that attracted much notice were made in 1608 by the Dutch spectacle maker Hans Lippershey (1570–1619). Galileo heard of the discovery and, without ever having seen an assembled telescope, constructed one of his own with a three-power magnification (3×), which made distant objects appear three times nearer and larger (**Figure 2.20**).

Figure 2.20 Telescope Used by Galileo. The telescope has a wooden tube covered with paper and a lens 26 millimeters across.

On August 25, 1609, Galileo demonstrated a telescope with a magnification of 9× to government officials of the city-state of Venice. By a magnification of 9×, we mean the linear dimensions of the objects being viewed appeared nine times larger or, alternatively, the objects appeared nine times closer than they really were. There were obvious military advantages associated with a device for seeing distant objects. For his invention, Galileo’s salary was nearly doubled, and he was granted lifetime tenure as a professor. (His university colleagues were outraged, particularly because the invention was not even original.)

Others had used the telescope before Galileo to observe things on Earth. But in a flash of insight that changed the history of astronomy, Galileo realized that he could turn the power of the telescope toward the heavens. Before using his telescope for astronomical observations, Galileo had to devise a stable mount and improve the optics. He increased the magnification to 30×. Galileo also needed to acquire confidence in the telescope.

At that time, human eyes were believed to be the final arbiter of truth about size, shape, and color. Lenses, mirrors, and prisms were known to distort distant images by enlarging, reducing, or inverting them, or spreading the light into a spectrum (rainbow of colors). Galileo undertook repeated experiments to convince himself that what he saw through the telescope was identical to what he saw up close. Only then could he begin to believe that the miraculous phenomena the telescope revealed in the heavens were real.

Beginning his astronomical work late in 1609, Galileo found that many stars too faint to be seen with the unaided eye became visible with his telescope. In particular, he found that some nebulous blurs resolved into many stars, and that the Milky Way—the strip of whiteness across the night sky—was also made up of a multitude of individual stars.

Examining the planets, Galileo found four moons revolving about Jupiter in times ranging from just under 2 days to about 17 days. This discovery was particularly important because it showed that not everything has to revolve around Earth. Furthermore, it demonstrated that there could be centers of motion that are themselves in motion. Defenders of the geocentric view had argued that if Earth was in motion, then the Moon would be left behind because it could hardly keep up with a rapidly moving planet. Yet, here were Jupiter's moons doing exactly that. (To recognize this discovery and honor his work, NASA named a spacecraft that explored the Jupiter system Galileo.)

With his telescope, Galileo was able to carry out the test of the Copernican theory mentioned earlier, based on the phases of Venus. Within a few months, he had found that Venus goes through phases like the Moon, showing that it must revolve about the Sun, so that we see different parts of its daylight side at different times (see **Figure 2.18**.) These observations could not be reconciled with Ptolemy's model, in which Venus circled about Earth. In Ptolemy's model, Venus could also show phases, but they were the wrong phases in the wrong order from what Galileo observed.

Galileo also observed the Moon and saw craters, mountain ranges, valleys, and flat, dark areas that he thought might be water. These discoveries showed that the Moon might be not so dissimilar to Earth—suggesting that Earth, too, could belong to the realm of celestial bodies.

LINK TO LEARNING

For more information about the life and work of Galileo, see the **Galileo Project (https://openstaxcollege.org/l/30GalProj)** at Rice University.

After Galileo's work, it became increasingly difficult to deny the Copernican view, and Earth was slowly dethroned from its central position in the universe and given its rightful place as one of the planets attending the Sun. Initially, however, Galileo met with a great deal of opposition. The Roman Catholic Church, still reeling from the Protestant Reformation, was looking to assert its authority and chose to make an example of Galileo. He had to appear before the Inquisition to answer charges that his work was heretical, and he was ultimately condemned to house arrest. His books were on the Church's forbidden list until 1836, although in countries where the Roman Catholic Church held less sway, they were widely read and discussed. Not until 1992 did the Catholic Church admit publicly that it had erred in the matter of censoring Galileo's ideas.

The new ideas of Copernicus and Galileo began a revolution in our conception of the cosmos. It eventually became evident that the universe is a vast place and that Earth's role in it is relatively unimportant. The idea that Earth moves around the Sun like the other planets raised the possibility that they might be worlds themselves, perhaps even supporting life. As Earth was demoted from its position at the center of the universe, so, too, was humanity. The universe, despite what we may wish, does not revolve around us.

Most of us take these things for granted today, but four centuries ago such concepts were frightening and heretical for some, immensely stimulating for others. The pioneers of the Renaissance started the European world along the path toward science and technology that we still tread today. For them, nature was rational and ultimately knowable, and experiments and observations provided the means to reveal its secrets.

SEEING FOR YOURSELF

Observing the Planets

At most any time of the night, and at any season, you can spot one or more bright planets in the sky. All five of the planets known to the ancients—Mercury, Venus, Mars, Jupiter, and Saturn—are more prominent than any but the brightest stars, and they can be seen even from urban locations if you know where and when to look. One way to tell planets from bright stars is that planets twinkle less.

Venus, which stays close to the Sun from our perspective, appears either as an “evening star” in the west after sunset or as a “morning star” in the east before sunrise. It is the brightest object in the sky after the Sun and Moon. It far outshines any real star, and under the most favorable circumstances, it can even cast a visible shadow. Some young military recruits have tried to shoot Venus down as an approaching enemy craft or UFO.

Mars, with its distinctive red color, can be nearly as bright as Venus is when close to Earth, but normally it remains much less conspicuous. Jupiter is most often the second-brightest planet, approximately equaling in brilliance the brightest stars. Saturn is dimmer, and it varies considerably in brightness, depending on whether its large rings are seen nearly edge-on (faint) or more widely opened (bright).

Mercury is quite bright, but few people ever notice it because it never moves very far from the Sun (it’s never more than 28° away in the sky) and is always seen against bright twilight skies.

True to their name, the planets “wander” against the background of the “fixed” stars. Although their apparent motions are complex, they reflect an underlying order upon which the heliocentric model of the solar system, as described in this chapter, was based. The positions of the planets are often listed in newspapers (sometimes on the weather page), and clear maps and guides to their locations can be found each month in such magazines as *Sky & Telescope* and *Astronomy* (available at most libraries and online). There are also a number of computer programs and phone and tablet apps that allow you to display where the planets are on any night.

CHAPTER 2 REVIEW

KEY TERMS

accelerate to change velocity; to speed up, slow down, or change direction.

apparent magnitude a measure of how bright a star looks in the sky; the larger the number, the dimmer the star appears to us

astrology the pseudoscience that deals with the supposed influences on human destiny of the configurations and locations in the sky of the Sun, Moon, and planets

celestial equator a great circle on the celestial sphere 90° from the celestial poles; where the celestial sphere intersects the plane of Earth's equator

celestial poles points about which the celestial sphere appears to rotate; intersections of the celestial sphere with Earth's polar axis

celestial sphere the apparent sphere of the sky; a sphere of large radius centered on the observer; directions of objects in the sky can be denoted by their position on the celestial sphere

circumpolar zone those portions of the celestial sphere near the celestial poles that are either always above or always below the horizon

cosmology the study of the organization and evolution of the universe

ecliptic the apparent annual path of the Sun on the celestial sphere

epicycle the circular orbit of a body in the Ptolemaic system, the center of which revolves about another circle (the deferent)

geocentric centered on Earth

heliocentric centered on the Sun

horizon (astronomical) a great circle on the celestial sphere 90° from the zenith; more popularly, the circle around us where the dome of the sky meets Earth

horoscope a chart used by astrologers that shows the positions along the zodiac and in the sky of the Sun, Moon, and planets at some given instant and as seen from a particular place on Earth—usually corresponding to the time and place of a person's birth

parallax the apparent displacement of a nearby star that results from the motion of Earth around the Sun

planet today, any of the larger objects revolving about the Sun or any similar objects that orbit other stars; in ancient times, any object that moved regularly among the fixed stars

precession (of Earth) the slow, conical motion of Earth's axis of rotation caused principally by the gravitational pull of the Moon and Sun on Earth's equatorial bulge

retrograde motion the apparent westward motion of a planet on the celestial sphere or with respect to the stars

year the period of revolution of Earth around the Sun

zenith the point on the celestial sphere opposite the direction of gravity; point directly above the observer

zodiac a belt around the sky about 18° wide centered on the ecliptic

SUMMARY

2.1 The Sky Above

The direct evidence of our senses supports a geocentric perspective, with the celestial sphere pivoting on the celestial poles and rotating about a stationary Earth. We see only half of this sphere at one time, limited by the horizon; the point directly overhead is our zenith. The Sun's annual path on the celestial sphere is the ecliptic—a line that runs through the center of the zodiac, which is the 18-degree-wide strip of the sky within which we always find the Moon and planets. The celestial sphere is organized into 88 constellations, or sectors.

2.2 Ancient Astronomy

Ancient Greeks such as Aristotle recognized that Earth and the Moon are spheres, and understood the phases of the Moon, but because of their inability to detect stellar parallax, they rejected the idea that Earth moves. Eratosthenes measured the size of Earth with surprising precision. Hipparchus carried out many astronomical observations, making a star catalog, defining the system of stellar magnitudes, and discovering precession from the apparent shift in the position of the north celestial pole. Ptolemy of Alexandria summarized classic astronomy in his *Almagest*; he explained planetary motions, including retrograde motion, with remarkably good accuracy using a model centered on Earth. This geocentric model, based on combinations of uniform circular motion using epicycles, was accepted as authority for more than a thousand years.

2.3 Astrology and Astronomy

The ancient religion of astrology, with its main contribution to civilization a heightened interest in the heavens, began in Babylonia. It reached its peak in the Greco-Roman world, especially as recorded in the *Tetrabiblos* of Ptolemy. Natal astrology is based on the assumption that the positions of the planets at the time of our birth, as described by a horoscope, determine our future. However, modern tests clearly show that there is no evidence for this, even in a broad statistical sense, and there is no verifiable theory to explain what might cause such an astrological influence.

2.4 The Birth of Modern Astronomy

Nicolaus Copernicus introduced the heliocentric cosmology to Renaissance Europe in his book *De Revolutionibus*. Although he retained the Aristotelian idea of uniform circular motion, Copernicus suggested that Earth is a planet and that the planets all circle about the Sun, dethroning Earth from its position at the center of the universe. Galileo was the father of both modern experimental physics and telescopic astronomy. He studied the acceleration of moving objects and, in 1610, began telescopic observations, discovering the nature of the Milky Way, the large-scale features of the Moon, the phases of Venus, and four moons of Jupiter. Although he was accused of heresy for his support of heliocentric cosmology, Galileo is credited with observations and brilliant writings that convinced most of his scientific contemporaries of the reality of the Copernican theory.

FOR FURTHER EXPLORATION

Articles

Ancient Astronomy

Gingerich, O. "From Aristarchus to Copernicus." *Sky & Telescope* (November 1983): 410.

Gingerich, O. “Islamic Astronomy.” *Scientific American* (April 1986): 74.

Astronomy and Astrology

Fraknoi, A. “Your Astrology Defense Kit.” *Sky & Telescope* (August 1989): 146.

Copernicus and Galileo

Gingerich, O. “Galileo and the Phases of Venus.” *Sky & Telescope* (December 1984): 520.

Gingerich, O. “How Galileo Changed the Rules of Science.” *Sky & Telescope* (March 1993): 32.

Maran, S., and Marschall, L. “The Moon, the Telescope, and the Birth of the Modern World.” *Sky & Telescope* (February 2009): 28.

Sobel, D. “The Heretic’s Daughter: A Startling Correspondence Reveals a New Portrait of Galileo.” *The New Yorker* (September 13, 1999): 52.

Websites

Ancient Astronomy

Aristarchos of Samos: **http://adsabs.harvard.edu//full/seri/JRASC/0075//0000029.000.html (http://adsabs.harvard.edu//full/seri/JRASC/0075//0000029.000.html)** . By Dr. Alan Batten.

Claudius Ptolemy: **http://www-history.mcs.st-and.ac.uk/Biographies/Ptolemy.html (http://www-history.mcs.st-and.ac.uk/Biographies/Ptolemy.html)** . An interesting biography.

Hipparchus of Rhodes: **http://www-history.mcs.st-andrews.ac.uk/Biographies/Hipparchus.html (http://www-history.mcs.st-andrews.ac.uk/Biographies/Hipparchus.html)** . An interesting biography.

Astronomy and Astrology

Astrology and Science: **http://www.astrology-and-science.com/hpage.htm (http://www.astrology-and-science.com/hpage.htm)** . The best site for a serious examination of the issues with astrology and the research on whether it works.

Real Romance in the Stars: **http://www.independent.co.uk/voices/the-real-romance-in-the-stars-1527970.html (http://www.independent.co.uk/voices/the-real-romance-in-the-stars-1527970.html)** . 1995 newspaper commentary attacking astrology.

Copernicus and Galileo

Galileo Galilei: **http://www-history.mcs.st-andrews.ac.uk/Biographies/Galileo.html (http://www-history.mcs.st-andrews.ac.uk/Biographies/Galileo.html)** . A good biography with additional links.

Galileo Project: **http://galileo.rice.edu/ (http://galileo.rice.edu/)** . Rice University’s repository of information on Galileo.

Nicolaus Copernicus: **http://www-groups.dcs.st-and.ac.uk/~history/Biographies/Copernicus.html (http://www-groups.dcs.st-and.ac.uk/~history/Biographies/Copernicus.html)** . A biography including links to photos about his life.

Videos

Astronomy and Astrology

Astrology Debunked: **https://www.youtube.com/watch?v=y84HX2pMo5U (https://www.youtube.com/watch?v=y84HX2pMo5U)** . A compilation of scientists and magicians commenting skeptically on astrology (9:09).

Copernicus and Galileo

Galileo: **http://www.biography.com/people/galileo-9305220 (http://www.biography.com/people/galileo-9305220)** . A brief biography (2:51).

Galileo's Battle for the Heavens: **https://www.youtube.com/watch?v=jvlr2iMWQyc (https://www.youtube.com/watch?v=jvlr2iMWQyc)** . A NOVA episode on PBS (1:48:55)

Nicolaus Copernicus: **http://www.biography.com/people/nicolaus-copernicus-9256984 (http://www.biography.com/people/nicolaus-copernicus-9256984)** . An overview of his life and work (2:41).

COLLABORATIVE GROUP ACTIVITIES

A. With your group, consider the question with which we began this chapter. How many ways can you think of to prove to a member of the "Flat Earth Society" that our planet is, indeed, round?

B. Make a list of ways in which a belief in astrology (the notion that your life path or personality is controlled by the position of the Sun, Moon, and planets at the time of your birth) might be harmful to an individual or to society at large.

C. Have members of the group compare their experiences with the night sky. Did you see the Milky Way? Can you identify any constellations? Make a list of reasons why you think so many fewer people know the night sky today than at the time of the ancient Greeks. Discuss reasons for why a person, today, may want to be acquainted with the night sky.

D. Constellations commemorate great heroes, dangers, or events in the legends of the people who name them. Suppose we had to start from scratch today, naming the patterns of stars in the sky. Whom or what would you choose to commemorate by naming a constellation after it, him, or her and why (begin with people from history; then if you have time, include living people as well)? Can the members of your group agree on any choices?

E. Although astronomical mythology no longer holds a powerful sway over the modern imagination, we still find proof of the power of astronomical images in the number of products in the marketplace that have astronomical names. How many can your group come up with? (Think of things like Milky Way candy bars, Eclipse and Orbit gum, or Comet cleanser.)

EXERCISES

Review Questions

1. From where on Earth could you observe all of the stars during the course of a year? What fraction of the sky can be seen from the North Pole?

2. Give four ways to demonstrate that Earth is spherical.

3. Explain, according to both geocentric and heliocentric cosmologies, why we see retrograde motion of the planets.

4. In what ways did the work of Copernicus and Galileo differ from the views of the ancient Greeks and of their contemporaries?

5. What were four of Galileo’s discoveries that were important to astronomy?

6. Explain the origin of the magnitude designation for determining the brightness of stars. Why does it seem to go backward, with smaller numbers indicating brighter stars?

7. Ursa Minor contains the pole star, Polaris, and the asterism known as the Little Dipper. From most locations in the Northern Hemisphere, all of the stars in Ursa Minor are circumpolar. Does that mean these stars are also above the horizon during the day? Explain.

8. How many degrees does the Sun move per day relative to the fixed stars? How many days does it take for the Sun to return to its original location relative to the fixed stars?

9. How many degrees does the Moon move per day relative to the fixed stars? How many days does it take for the Moon to return to its original location relative to the fixed stars?

10. Explain how the zodiacal constellations are different from the other constellations.

11. The Sun was once thought to be a planet. Explain why.

12. Is the ecliptic the same thing as the celestial equator? Explain.

13. What is an asterism? Can you name an example?

14. Why did Pythagoras believe that Earth should be spherical?

15. How did Aristotle deduce that the Sun is farther away from Earth than the Moon?

16. What are two ways in which Aristotle deduced that Earth is spherical?

17. How did Hipparchus discover the wobble of Earth’s axis, known as *precession*?

18. Why did Ptolemy have to introduce multiple circles of motion for the planets instead of a single, simple circle to represent the planet’s motion around the Sun?

19. Why did Copernicus want to develop a completely new system for predicting planetary positions? Provide two reasons.

20. What two factors made it difficult, at first, for astronomers to choose between the Copernican heliocentric model and the Ptolemaic geocentric model?

21. What phases would Venus show if the geocentric model were correct?

Thought Questions

22. Describe a practical way to determine in which constellation the Sun is found at any time of the year.

23. What is a constellation as astronomers define it today? What does it mean when an astronomer says, “I saw a comet in Orion last night”?

24. Draw a picture that explains why Venus goes through phases the way the Moon does, according to the heliocentric cosmology. Does Jupiter also go through phases as seen from Earth? Why?

25. Show with a simple diagram how the lower parts of a ship disappear first as it sails away from you on a spherical Earth. Use the same diagram to show why lookouts on old sailing ships could see farther from the masthead than from the deck. Would there be any advantage to posting lookouts on the mast if Earth were flat? (Note that these nautical arguments for a spherical Earth were quite familiar to Columbus and other mariners of his time.)

26. Parallaxes of stars were not observed by ancient astronomers. How can this fact be reconciled with the heliocentric hypothesis?

27. Why do you think so many people still believe in astrology and spend money on it? What psychological needs does such a belief system satisfy?

28. Consider three cosmological perspectives—the geocentric perspective, the heliocentric perspective, and the modern perspective—in which the Sun is a minor star on the outskirts of one galaxy among billions. Discuss some of the cultural and philosophical implications of each point of view.

29. The north celestial pole appears at an altitude above the horizon that is equal to the observer's latitude. Identify Polaris, the North Star, which lies very close to the north celestial pole. Measure its altitude. (This can be done with a protractor. Alternatively, your fist, extended at arm's length, spans a distance approximately equal to 10°.) Compare this estimate with your latitude. (Note that this experiment cannot be performed easily in the Southern Hemisphere because Polaris itself is not visible in the south and no bright star is located near the south celestial pole.)

30. What were two arguments or lines of evidence in support of the geocentric model?

31. Although the Copernican system was largely correct to place the Sun at the center of all planetary motion, the model still gave inaccurate predictions for planetary positions. Explain the flaw in the Copernican model that hindered its accuracy.

32. During a retrograde loop of Mars, would you expect Mars to be brighter than usual in the sky, about average in brightness, or fainter than usual in the sky? Explain.

33. The Great Pyramid of Giza was constructed nearly 5000 years ago. Within the pyramid, archaeologists discovered a shaft leading from the central chamber out of the pyramid, oriented for favorable viewing of the bright star Thuban at that time. Thinking about Earth's precession, explain why Thuban might have been an important star to the ancient Egyptians.

34. Explain why more stars are circumpolar for observers at higher latitudes.

35. What is the altitude of the north celestial pole in the sky from your latitude? If you do not know your latitude, look it up. If you are in the Southern Hemisphere, answer this question for the south celestial pole, since the north celestial pole is not visible from your location.

36. If you were to drive to some city south of your current location, how would the altitude of the celestial pole in the sky change?

37. Hipparchus could have warned us that the dates associated with each of the natal astrology sun signs would eventually be wrong. Explain why.

38. Explain three lines of evidence that argue against the validity of astrology.

39. What did Galileo discover about the planet Jupiter that cast doubt on exclusive geocentrism?

40. What did Galileo discover about Venus that cast doubt on geocentrism?

Figuring For Yourself

41. Suppose Eratosthenes had found that, in Alexandria, at noon on the first day of summer, the line to the Sun makes an angle 30° with the vertical. What, then, would he have found for Earth's circumference?

42. Suppose Eratosthenes' results for Earth's circumference were quite accurate. If the diameter of Earth is 12,740 km, what is the length of his stadium in kilometers?

43. Suppose you are on a strange planet and observe, at night, that the stars do not rise and set, but circle parallel to the horizon. Next, you walk in a constant direction for 8000 miles, and at your new location on the planet, you find that all stars rise straight up in the east and set straight down in the west, perpendicular to the horizon. How could you determine the circumference of the planet without any further observations? What is the circumference, in miles, of the planet?

3

ORBITS AND GRAVITY

Figure 3.1 International Space Station. This space habitat and laboratory orbits Earth once every 90 minutes. (credit: modification of work by NASA)

Chapter Outline

Thinking Ahead

How would you find a new planet at the outskirts of our solar system that is too dim to be seen with the unaided eye and is so far away that it moves very slowly among the stars? This was the problem confronting astronomers during the nineteenth century as they tried to pin down a full inventory of our solar system.

If we could look down on the solar system from somewhere out in space, interpreting planetary motions would be much simpler. But the fact is, we must observe the positions of all the other planets from our own moving planet. Scientists of the Renaissance did not know the details of Earth's motions any better than the motions of the other planets. Their problem, as we saw in **Observing the Sky: The Birth of Astronomy**, was that they had to deduce the nature of all planetary motion using only their earthbound observations of the other planets' positions in the sky. To solve this complex problem more fully, better observations and better models of the planetary system were needed.

3.1 THE LAWS OF PLANETARY MOTION

Learning Objectives

By the end of this section, you will be able to:

- Describe how Tycho Brahe and Johannes Kepler contributed to our understanding of how planets move around the Sun
- Explain Kepler's three laws of planetary motion

At about the time that Galileo was beginning his experiments with falling bodies, the efforts of two other scientists dramatically advanced our understanding of the motions of the planets. These two astronomers were the observer Tycho Brahe and the mathematician Johannes Kepler. Together, they placed the speculations of Copernicus on a sound mathematical basis and paved the way for the work of Isaac Newton in the next century.

Tycho Brahe's Observatory

Three years after the publication of Copernicus' *De Revolutionibus*, Tycho Brahe was born to a family of Danish nobility. He developed an early interest in astronomy and, as a young man, made significant astronomical observations. Among these was a careful study of what we now know was an exploding star that flared up to great brilliance in the night sky. His growing reputation gained him the patronage of the Danish King Frederick II, and at the age of 30, Brahe was able to establish a fine astronomical observatory on the North Sea island of Hven (Figure 3.2). Brahe was the last and greatest of the pre-telescopic observers in Europe.

(a) (b)

Figure 3.2 Tycho Brahe (1546–1601) and Johannes Kepler (1571–1630). (a) A stylized engraving shows Tycho Brahe using his instruments to measure the altitude of celestial objects above the horizon. The large curved instrument in the foreground allowed him to measure precise angles in the sky. Note that the scene includes hints of the grandeur of Brahe's observatory at Hven. (b) Kepler was a German mathematician and astronomer. His discovery of the basic laws that describe planetary motion placed the heliocentric cosmology of Copernicus on a firm mathematical basis.

At Hven, Brahe made a continuous record of the positions of the Sun, Moon, and planets for almost 20 years. His extensive and precise observations enabled him to note that the positions of the planets varied from those given in published tables, which were based on the work of Ptolemy. These data were extremely valuable, but Brahe didn't have the ability to analyze them and develop a better model than what Ptolemy had published. He was further inhibited because he was an extravagant and cantankerous fellow, and he accumulated enemies among government officials. When his patron, Frederick II, died in 1597, Brahe lost his political base and decided to leave Denmark. He took up residence in Prague, where he became court astronomer to Emperor Rudolf of Bohemia. There, in the year before his death, Brahe found a most able young mathematician, Johannes Kepler, to assist him in analyzing his extensive planetary data.

Johannes Kepler

Johannes Kepler was born into a poor family in the German province of Württemberg and lived much of his life amid the turmoil of the Thirty Years' War (see **Figure 3.2**). He attended university at Tubingen and studied for a theological career. There, he learned the principles of the Copernican system and became converted to the heliocentric hypothesis. Eventually, Kepler went to Prague to serve as an assistant to Brahe, who set him to work trying to find a satisfactory theory of planetary motion—one that was compatible with the long series of observations made at Hven. Brahe was reluctant to provide Kepler with much material at any one time for fear that Kepler would discover the secrets of the universal motion by himself, thereby robbing Brahe of some of the glory. Only after Brahe's death in 1601 did Kepler get full possession of the priceless records. Their study occupied most of Kepler's time for more than 20 years.

Through his analysis of the motions of the planets, Kepler developed a series of principles, now known as *Kepler's three laws,* which described the behavior of planets based on their paths through space. The first two laws of planetary motion were published in 1609 in *The New Astronomy*. Their discovery was a profound step in the development of modern science.

The First Two Laws of Planetary Motion

The path of an object through space is called its **orbit**. Kepler initially assumed that the orbits of planets were circles, but doing so did not allow him to find orbits that were consistent with Brahe's observations. Working with the data for Mars, he eventually discovered that the orbit of that planet had the shape of a somewhat flattened circle, or **ellipse**. Next to the circle, the ellipse is the simplest kind of closed curve, belonging to a family of curves known as *conic sections* (**Figure 3.3**).

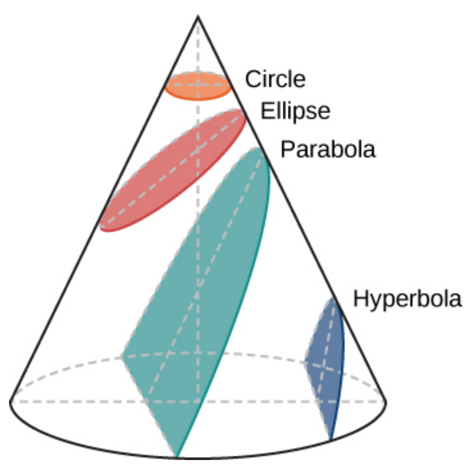


Figure 3.3 Conic Sections. The circle, ellipse, parabola, and hyperbola are all formed by the intersection of a plane with a cone. This is why such curves are called conic sections.

You might recall from math classes that in a circle, the center is a special point. The distance from the center to anywhere on the circle is exactly the same. In an ellipse, the sum of the distance from two special points inside the ellipse to any point on the ellipse is always the same. These two points inside the ellipse are called its foci (singular: **focus**), a word invented for this purpose by Kepler.

This property suggests a simple way to draw an ellipse (Figure 3.4). We wrap the ends of a loop of string around two tacks pushed through a sheet of paper into a drawing board, so that the string is slack. If we push a pencil against the string, making the string taut, and then slide the pencil against the string all around the tacks, the curve that results is an ellipse. At any point where the pencil may be, the sum of the distances from the pencil to the two tacks is a constant length—the length of the string. The tacks are at the two foci of the ellipse.

The widest diameter of the ellipse is called its **major axis**. Half this distance—that is, the distance from the center of the ellipse to one end—is the **semimajor axis**, which is usually used to specify the size of the ellipse. For example, the semimajor axis of the orbit of Mars, which is also the planet's average distance from the Sun, is 228 million kilometers.

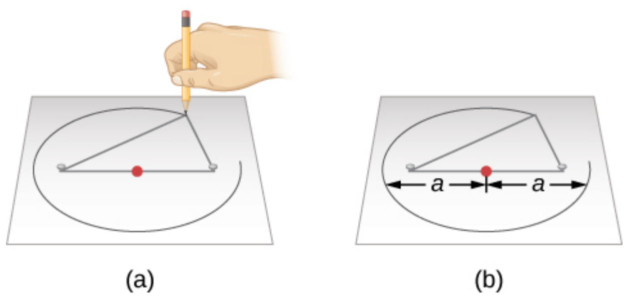


Figure 3.4 Drawing an Ellipse. (a) We can construct an ellipse by pushing two tacks (the white objects) into a piece of paper on a drawing board, and then looping a string around the tacks. Each tack represents a focus of the ellipse, with one of the tacks being the Sun. Stretch the string tight using a pencil, and then move the pencil around the tacks. The length of the string remains the same, so that the sum of the distances from any point on the ellipse to the foci is always constant. (b) In this illustration, each semimajor axis is denoted by a. The distance $2a$ is called the major axis of the ellipse.

The shape (roundness) of an ellipse depends on how close together the two foci are, compared with the major axis. The ratio of the distance between the foci to the length of the major axis is called the **eccentricity** of the ellipse.

If the foci (or tacks) are moved to the same location, then the distance between the foci would be zero. This means that the eccentricity is zero and the ellipse is just a circle; thus, a circle can be called an ellipse of zero eccentricity. In a circle, the semimajor axis would be the radius.

Next, we can make ellipses of various elongations (or extended lengths) by varying the spacing of the tacks (as long as they are not farther apart than the length of the string). The greater the eccentricity, the more elongated is the ellipse, up to a maximum eccentricity of 1.0, when the ellipse becomes "flat," the other extreme from a circle.

The size and shape of an ellipse are completely specified by its semimajor axis and its eccentricity. Using Brahe's data, Kepler found that Mars has an elliptical orbit, with the Sun at one focus (the other focus is empty). The eccentricity of the orbit of Mars is only about 0.1; its orbit, drawn to scale, would be practically indistinguishable from a circle, but the difference turned out to be critical for understanding planetary motions.

Kepler generalized this result in his first law and said that *the orbits of all the planets are ellipses*. Here was a decisive moment in the history of human thought: it was not necessary to have only circles in order to have an acceptable cosmos. The universe could be a bit more complex than the Greek philosophers had wanted it to be.

Kepler's second law deals with the speed with which each planet moves along its ellipse, also known as its **orbital speed**. Working with Brahe's observations of Mars, Kepler discovered that the planet speeds up as it comes closer to the Sun and slows down as it pulls away from the Sun. He expressed the precise form of this relationship by imagining that the Sun and Mars are connected by a straight, elastic line. When Mars is closer to the Sun (positions 1 and 2 in Figure 3.5), the elastic line is not stretched as much, and the planet moves rapidly. Farther from the Sun, as in positions 3 and 4, the line is stretched a lot, and the planet does not move so fast. As Mars travels in its elliptical orbit around the Sun, the elastic line sweeps out areas of the ellipse as it moves (the colored regions in our figure). Kepler found that in equal intervals of time (t), the areas swept out in space by this imaginary line are always equal; that is, the area of the region B from 1 to 2 is the same as that of region A from 3 to 4.

If a planet moves in a circular orbit, the elastic line is always stretched the same amount and the planet moves at a constant speed around its orbit. But, as Kepler discovered, in most orbits that speed of a planet orbiting its star (or moon orbiting its planet) tends to vary because the orbit is elliptical.

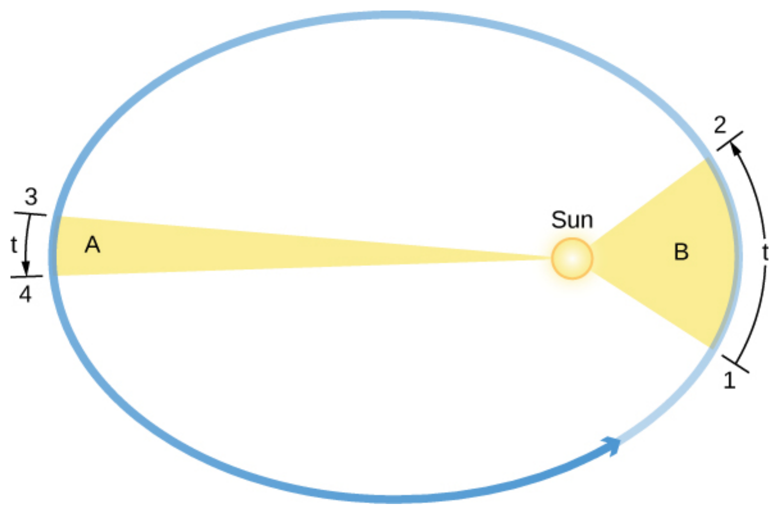


Figure 3.5 Kepler's Second Law: The Law of Equal Areas. The orbital speed of a planet traveling around the Sun (the circular object inside the ellipse) varies in such a way that in equal intervals of time (t), a line between the Sun and a planet sweeps out equal areas (A and B). Note that the eccentricities of the planets' orbits in our solar system are substantially less than shown here.

Kepler's Third Law

Kepler's first two laws of planetary motion describe the shape of a planet's orbit and allow us to calculate the speed of its motion at any point in the orbit. Kepler was pleased to have discovered such fundamental rules, but they did not satisfy his quest to fully understand planetary motions. He wanted to know why the orbits of the planets were spaced as they are and to find a mathematical pattern in their movements—a "harmony of the spheres" as he called it. For many years he worked to discover mathematical relationships governing planetary spacing and the time each planet took to go around the Sun.

In 1619, Kepler discovered a basic relationship to relate the planets' orbits to their relative distances from the Sun. We define a planet's **orbital period**, (***P***), as the time it takes a planet to travel once around the Sun. Also, recall that a planet's semimajor axis, *a,* is equal to its average distance from the Sun. The relationship, now known as *Kepler's third law*, says that a planet's orbital period squared is proportional to the semimajor axis of its orbit cubed, or

$$P^2 \propto a^3$$

When *P* (the orbital period) is measured in years, and *a* is expressed in a quantity known as an **astronomical unit (AU)**, the two sides of the formula are not only proportional but equal. One AU is the average distance between Earth and the Sun and is approximately equal to 1.5 × 10^8 kilometers. In these units,

$$P^2 = a^3$$

Kepler's third law applies to all objects orbiting the Sun, including Earth, and provides a means for calculating their relative distances from the Sun from the time they take to orbit. Let's look at a specific example to illustrate how useful Kepler's third law is.

For instance, suppose you time how long Mars takes to go around the Sun (in Earth years). Kepler's third law can then be used to calculate Mars' average distance from the Sun. Mars' orbital period (1.88 Earth years) squared, or P^2, is 1.88^2 = 3.53, and according to the equation for Kepler's third law, this equals the cube of its semimajor axis, or a^3. So what number must be cubed to give 3.53? The answer is 1.52 (since 1.52 × 1.52 × 1.52 = 3.53). Thus, Mars' semimajor axis in astronomical units must be 1.52 AU. In other words, to go around the Sun in a little less than two years, Mars must be about 50% (half again) as far from the Sun as Earth is.

EXAMPLE 3.1

Calculating Periods

Imagine an object is traveling around the Sun. What would be the orbital period of the object if its orbit has a semimajor axis of 50 AU?

Solution

From Kepler's third law, we know that (when we use units of years and AU)

$$P^2 = a^3$$

If the object's orbit has a semimajor axis of 50 AU (a = 50), we can cube 50 and then take the square root of the result to get P:

$$\begin{aligned} P &= \sqrt{a^3} \\ P &= \sqrt{50 \times 50 \times 50} = \sqrt{125{,}000} = 353.6 \text{ years} \end{aligned}$$

Therefore, the orbital period of the object is about 350 years. This would place our hypothetical object beyond the orbit of Pluto.

Check Your Learning

What would be the orbital period of an asteroid (a rocky chunk between Mars and Jupiter) with a semimajor axis of 3 AU?

Answer:

$$P = \sqrt{3 \times 3 \times 3} = \sqrt{27} = 5.2 \text{ years}$$

Kepler's three laws of planetary motion can be summarized as follows:

- **Kepler's first law**: Each planet moves around the Sun in an orbit that is an ellipse, with the Sun at one focus of the ellipse.
- **Kepler's second law**: The straight line joining a planet and the Sun sweeps out equal areas in space in equal intervals of time.

- **Kepler's third law**: The square of a planet's orbital period is directly proportional to the cube of the semimajor axis of its orbit.

Kepler's three laws provide a precise geometric description of planetary motion within the framework of the Copernican system. With these tools, it was possible to calculate planetary positions with greatly improved precision. Still, Kepler's laws are purely descriptive: they do not help us understand what forces of nature constrain the planets to follow this particular set of rules. That step was left to Isaac Newton.

EXAMPLE 3.2

Applying Kepler's Third Law

Using the orbital periods and semimajor axes for Venus and Earth that are provided here, calculate P^2 and a^3, and verify that they obey Kepler's third law. Venus' orbital period is 0.62 year, and its semimajor axis is 0.72 AU. Earth's orbital period is 1.00 year, and its semimajor axis is 1.00 AU.

Solution

We can use the equation for Kepler's third law, $P^2 \propto a^3$. For Venus, $P^2 = 0.62 \times 0.62 = 0.38$ and $a^3 = 0.72 \times 0.72 \times 0.72 = 0.37$ (rounding numbers sometimes causes minor discrepancies like this). The square of the orbital period (0.38) approximates the cube of the semimajor axis (0.37). Therefore, Venus obeys Kepler's third law. For Earth, $P^2 = 1.00 \times 1.00 = 1.00$ and $a^3 = 1.00 \times 1.00 \times 1.00 = 1.00$. The square of the orbital period (1.00) approximates (in this case, equals) the cube of the semimajor axis (1.00). Therefore, Earth obeys Kepler's third law.

Check Your Learning

Using the orbital periods and semimajor axes for Saturn and Jupiter that are provided here, calculate P^2 and a^3, and verify that they obey Kepler's third law. Saturn's orbital period is 29.46 years, and its semimajor axis is 9.54 AU. Jupiter's orbital period is 11.86 years, and its semimajor axis is 5.20 AU.

Answer:

For Saturn, $P^2 = 29.46 \times 29.46 = 867.9$ and $a^3 = 9.54 \times 9.54 \times 9.54 = 868.3$. The square of the orbital period (867.9) approximates the cube of the semimajor axis (868.3). Therefore, Saturn obeys Kepler's third law.

LINK TO LEARNING

In honor of the scientist who first devised the laws that govern the motions of planets, the team that built the first spacecraft to search for planets orbiting other stars decided to name the probe "Kepler." To learn more about Johannes Kepler's life and his laws of planetary motion, as well as lots of information on the Kepler Mission, visit **NASA's Kepler website (https://openstaxcollege.org/l/30nasakepmiss)** and follow the links that interest you.

3.2 NEWTON'S GREAT SYNTHESIS

Learning Objectives

By the end of this section, you will be able to:

- Describe Newton's three laws of motion
- Explain how Newton's three laws of motion relate to momentum
- Define mass, volume, and density and how they differ
- Define angular momentum

It was the genius of Isaac Newton that found a conceptual framework that completely explained the observations and rules assembled by Galileo, Brahe, Kepler, and others. Newton was born in Lincolnshire, England, in the year after Galileo's death (**Figure 3.6**). Against the advice of his mother, who wanted him to stay home and help with the family farm, he entered Trinity College at Cambridge in 1661 and eight years later was appointed professor of mathematics. Among Newton's contemporaries in England were architect Christopher Wren, authors Aphra Behn and Daniel Defoe, and composer G. F. Handel.

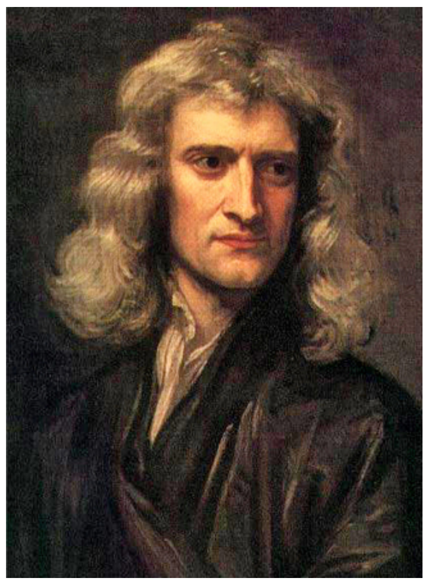


Figure 3.6 Isaac Newton (1643–1727), 1689 Portrait by Sir Godfrey Kneller. Isaac Newton's work on the laws of motion, gravity, optics, and mathematics laid the foundations for much of physical science.

Newton's Laws of Motion

As a young man in college, Newton became interested in natural philosophy, as science was then called. He worked out some of his first ideas on machines and optics during the plague years of 1665 and 1666, when students were sent home from college. Newton, a moody and often difficult man, continued to work on his ideas in private, even inventing new mathematical tools to help him deal with the complexities involved. Eventually, his friend Edmund Halley (profiled in **Comets and Asteroids: Debris of the Solar System**) prevailed on him to collect and publish the results of his remarkable investigations on motion and gravity. The result was a volume that set out the underlying system of the physical world, *Philosophiae Naturalis Principia Mathematica*. The *Principia*, as the book is generally known, was published at Halley's expense in 1687.

At the very beginning of the *Principia*, Newton proposes three laws that would govern the motions of all objects:

- **Newton’s first law**: Every object will continue to be in a state of rest or move at a constant speed in a straight line unless it is compelled to change by an outside force.
- **Newton’s second law**: The change of motion of a body is proportional to and in the direction of the force acting on it.
- **Newton’s third law**: For every action there is an equal and opposite reaction (*or:* the mutual actions of two bodies upon each other are always equal and act in opposite directions).

In the original Latin, the three laws contain only 59 words, but those few words set the stage for modern science. Let us examine them more carefully.

Interpretation of Newton’s Laws

Newton’s first law is a restatement of one of Galileo’s discoveries, called the *conservation of momentum*. The law states that in the absence of any outside influence, there is a measure of a body’s motion, called its **momentum**, that remains unchanged. You may have heard the term momentum used in everyday expressions, such as “This bill in Congress has a lot of momentum; it’s going to be hard to stop.”

Newton’s first law is sometimes called the *law of inertia*, where inertia is the tendency of objects (and legislatures) to keep doing what they are already doing. In other words, a stationary object stays put, and a moving object keeps moving unless some force intervenes.

Let’s define the precise meaning of momentum—it depends on three factors: (1) speed—how fast a body moves (zero if it is stationary), (2) the direction of its motion, and (3) its mass—a measure of the amount of matter in a body, which we will discuss later. Scientists use the term **velocity** to describe the speed and direction of motion. For example, 20 kilometers per hour due south is velocity, whereas 20 kilometers per hour just by itself is speed. Momentum then can be defined as an object’s mass times its velocity.

It’s not so easy to see this rule in action in the everyday world because of the many forces acting on a body at any one time. One important force is friction, which generally slows things down. If you roll a ball along the sidewalk, it eventually comes to a stop because the sidewalk exerts a rubbing force on the ball. But in the space between the stars, where there is so little matter that friction is insignificant, objects can in fact continue to move (to coast) indefinitely.

The momentum of a body can change only under the action of an outside influence. Newton’s second law expresses *force* in terms of its ability to change momentum with time. A force (a push or a pull) has both size and direction. When a force is applied to a body, the momentum changes in the direction of the applied force. This means that a force is required to change either the speed or the direction of a body, or both—that is, to start it moving, to speed it up, to slow it down, to stop it, or to change its direction.

As you learned in **Observing the Sky: The Birth of Astronomy**, the rate of change in an object’s velocity is called *acceleration*. Newton showed that the acceleration of a body was proportional to the force being applied to it. Suppose that after a long period of reading, you push an astronomy book away from you on a long, smooth table. (We use a smooth table so we can ignore friction.) If you push the book steadily, it will continue to speed up as long as you are pushing it. The harder you push the book, the larger its acceleration will be. How much a force will accelerate an object is also determined by the object’s mass. If you kept pushing a pen with the same force with which you pushed the textbook, the pen—having less mass—would be accelerated to a greater speed.

Newton’s third law is perhaps the most profound of the rules he discovered. Basically, it is a generalization of the first law, but it also gives us a way to define mass. If we consider a system of two or more objects isolated from outside influences, Newton’s first law says that the total momentum of the objects should remain constant. Therefore, any change of momentum within the system must be balanced by another change that is equal and opposite so that the momentum of the entire system is not changed.

This means that forces in nature do not occur alone: we find that in each situation there is always a *pair* of forces that are equal to and opposite each other. If a force is exerted on an object, it must be exerted by something else, and the object will exert an equal and opposite force back on that something. We can look at a simple example to demonstrate this.

Suppose that a daredevil astronomy student—and avid skateboarder—wants to jump from his second-story dorm window onto his board below (we don’t recommend trying this!). The force pulling him down after jumping (as we will see in the next section) is the force of gravity between him and Earth. Both he and Earth must experience the same total change of momentum because of the influence of these mutual forces. So, both the student and Earth are accelerated by each other’s pull. However, the student does much more of the moving. Because Earth has enormously greater mass, it can experience the same change of momentum by accelerating only a very small amount. Things fall toward Earth all the time, but the acceleration of our planet as a result is far too small to be measured.

A more obvious example of the mutual nature of forces between objects is familiar to all who have batted a baseball. The recoil you feel as you swing your bat shows that the ball exerts a force on it during the impact, just as the bat does on the ball. Similarly, when a rifle you are bracing on your shoulder is discharged, the force pushing the bullet out of the muzzle is equal to the force pushing backward upon the gun and your shoulder.

This is the principle behind jet engines and rockets: the force that discharges the exhaust gases from the rear of the rocket is accompanied by the force that pushes the rocket forward. The exhaust gases need not push against air or Earth; a rocket actually operates best in a vacuum (**Figure 3.7**).

Figure 3.7 Demonstrating Newton’s Third Law. The U.S. Space Shuttle (here launching *Discovery*), powered by three fuel engines burning liquid oxygen and liquid hydrogen, with two solid fuel boosters, demonstrates Newton’s third law. (credit: modification of work by NASA)

LINK TO LEARNING

For more about Isaac Newton’s life and work, check out this **timeline page (https://openstaxcollege.org/l/30IsaacNewTime)** with snapshots from his career, produced by the British Broadcasting Corporation (BBC).

Mass, Volume, and Density

Before we go on to discuss Newton's other work, we want to take a brief look at some terms that will be important to sort out clearly. We begin with *mass,* which is a measure of the amount of material within an object.

The *volume* of an object is the measure of the physical space it occupies. Volume is measured in cubic units, such as cubic centimeters or liters. The volume is the "size" of an object. A penny and an inflated balloon may both have the same mass, but they have very different volumes. The reason is that they also have very different *densities*, which is a measure of how much mass there is per unit volume. Specifically, **density** is the mass divided by the volume. Note that in everyday language we often use "heavy" and "light" as indications of density (rather than weight) as, for instance, when we say that iron is heavy or that whipped cream is light.

The units of density that will be used in this book are grams per cubic centimeter (g/cm^3).[1] If a block of some material has a mass of 300 grams and a volume of 100 cm^3, its density is 3 g/cm^3. Familiar materials span a considerable range in density, from artificial materials such as plastic insulating foam (less than 0.1 g/cm^3) to gold (19.3 g/cm^3). Table 3.1 gives the densities of some familiar materials. In the astronomical universe, much more remarkable densities can be found, all the way from a comet's tail (10^{-16} g/cm^3) to a collapsed "star corpse" called a neutron star (10^{15} g/cm^3).

Densities of Common Materials

Material	Density (g/cm^3)
Gold	19.3
Lead	11.3
Iron	7.9
Earth (bulk)	5.5
Rock (typical)	2.5
Water	1
Wood (typical)	0.8
Insulating foam	0.1
Silica gel	0.02

Table 3.1

To sum up, mass is *how much*, volume is *how big*, and density is *how tightly packed*.

1 Generally we use standard metric (or SI) units in this book. The proper metric unit of density in that system is kg/m^3. But to most people, g/cm^3 provides a more meaningful unit because the density of water is exactly 1 g/cm^3, and this is useful information for comparison. Density expressed in g/cm^3 is sometimes called specific density or specific weight.

LINK TO LEARNING

You can play with a **simple animation (https://openstaxcollege.org/l/30phetsimdenmas)** demonstrating the relationship between the concepts of density, mass, and volume, and find out why objects like wood float in water.

Angular Momentum

A concept that is a bit more complex, but important for understanding many astronomical objects, is **angular momentum**, which is a measure of the rotation of a body as it revolves around some fixed point (an example is a planet orbiting the Sun). The angular momentum of an object is defined as the product of its mass, its velocity, and its distance from the fixed point around which it revolves.

If these three quantities remain constant—that is, if the motion of a particular object takes place at a constant velocity at a fixed distance from the spin center—then the angular momentum is also a constant. Kepler's second law is a consequence of the *conservation of angular momentum*. As a planet approaches the Sun on its elliptical orbit and the distance to the spin center decreases, the planet speeds up to conserve the angular momentum. Similarly, when the planet is farther from the Sun, it moves more slowly.

The conservation of angular momentum is illustrated by figure skaters, who bring their arms and legs in to spin more rapidly, and extend their arms and legs to slow down (**Figure 3.8**). You can duplicate this yourself on a well-oiled swivel stool by starting yourself spinning slowly with your arms extended and then pulling your arms in. Another example of the conservation of angular momentum is a shrinking cloud of dust or a star collapsing on itself (both are situations that you will learn about as you read on). As material moves to a lesser distance from the spin center, the speed of the material increases to conserve angular momentum.

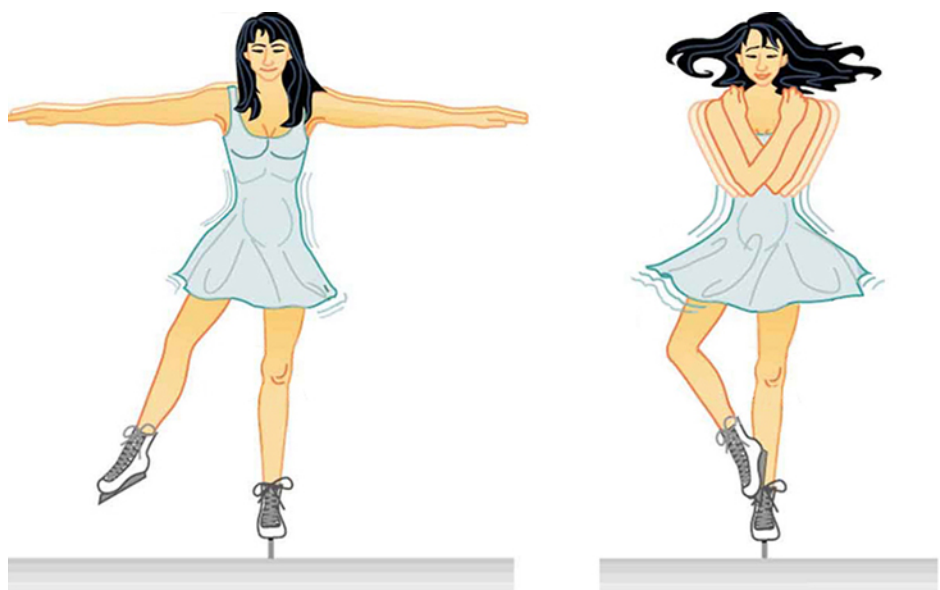


Figure 3.8 Conservation of Angular Momentum. When a spinning figure skater brings in her arms, their distance from her spin center is smaller, so her speed increases. When her arms are out, their distance from the spin center is greater, so she slows down.

3.3 NEWTON'S UNIVERSAL LAW OF GRAVITATION

Learning Objectives

By the end of this section, you will be able to:

- Explain what determines the strength of gravity
- Describe how Newton's universal law of gravitation extends our understanding of Kepler's laws

Newton's laws of motion show that objects at rest will stay at rest and those in motion will continue moving uniformly in a straight line unless acted upon by a force. Thus, it is the *straight line* that defines the most natural state of motion. But the planets move in ellipses, not straight lines; therefore, some force must be bending their paths. That force, Newton proposed, was **gravity**.

In Newton's time, gravity was something associated with Earth alone. Everyday experience shows us that Earth exerts a gravitational force upon objects at its surface. If you drop something, it accelerates toward Earth as it falls. Newton's insight was that Earth's gravity might extend as far as the Moon and produce the force required to curve the Moon's path from a straight line and keep it in its orbit. He further hypothesized that gravity is not limited to Earth, but that there is a general force of attraction between all material bodies. If so, the attractive force between the Sun and each of the planets could keep them in their orbits. (This may seem part of our everyday thinking today, but it was a remarkable insight in Newton's time.)

Once Newton boldly hypothesized that there was a universal attraction among all bodies everywhere in space, he had to determine the exact nature of the attraction. The precise mathematical description of that gravitational force had to dictate that the planets move exactly as Kepler had described them to (as expressed in Kepler's three laws). Also, that gravitational force had to predict the correct behavior of falling bodies on Earth, as observed by Galileo. How must the force of gravity depend on distance in order for these conditions to be met?

The answer to this question required mathematical tools that had not yet been developed, but this did not deter Isaac Newton, who invented what we today call calculus to deal with this problem. Eventually he was able to conclude that the magnitude of the force of gravity must decrease with increasing distance between the Sun and a planet (or between any two objects) in proportion to the inverse square of their separation. In other words, if a planet were twice as far from the Sun, the force would be $(1/2)^2$, or 1/4 as large. Put the planet three times farther away, and the force is $(1/3)^2$, or 1/9 as large.

Newton also concluded that the gravitational attraction between two bodies must be proportional to their masses. The more mass an object has, the stronger the pull of its gravitational force. The gravitational attraction between any two objects is therefore given by one of the most famous equations in all of science:

$$F_{\text{gravity}} = G\frac{M_1 M_2}{R^2}$$

where F_{gravity} is the gravitational force between two objects, M_1 and M_2 are the masses of the two objects, and R is their separation. G is a constant number known as the *universal gravitational constant*, and the equation itself symbolically summarizes Newton's *universal law of gravitation*. With such a force and the laws of motion, Newton was able to show mathematically that the only orbits permitted were exactly those described by Kepler's laws.

Newton's universal law of gravitation works for the planets, but is it really universal? The gravitational theory should also predict the observed acceleration of the Moon toward Earth as it orbits Earth, as well as of any object (say, an apple) dropped near Earth's surface. The falling of an apple is something we can measure quite easily, but can we use it to predict the motions of the Moon?

Recall that according to Newton's second law, forces cause acceleration. Newton's universal law of gravitation says that the force acting upon (and therefore the acceleration of) an object toward Earth should be inversely proportional to the square of its distance from the center of Earth. Objects like apples at the surface of Earth, at a distance of one Earth-radius from the center of Earth, are observed to accelerate downward at 9.8 meters per second per second (9.8 m/s^2).

It is this force of gravity on the surface of Earth that gives us our sense of *weight.* Unlike your mass, which would remain the same on any planet or moon, your weight depends on the local force of gravity. So you would weigh less on Mars and the Moon than on Earth, even though there is no change in your mass. (Which means you would still have to go easy on the desserts in the college cafeteria when you got back!)

The Moon is 60 Earth radii away from the center of Earth. If gravity (and the acceleration it causes) gets weaker with distance squared, the acceleration the Moon experiences should be a lot less than for the apple. The acceleration should be $(1/60)^2$ = 1/3600 (or 3600 times less—about 0.00272 m/s^2. This is precisely the observed acceleration of the Moon in its orbit. (As we shall see, the Moon does not fall *to* Earth with this acceleration, but falls *around* Earth.) Imagine the thrill Newton must have felt to realize he had discovered, and verified, a law that holds for Earth, apples, the Moon, and, as far as he knew, everything in the universe.

EXAMPLE 3.3

Calculating Weight

By what factor would a person's weight at the surface of Earth change if Earth had its present mass but eight times its present volume?

Solution

With eight times the volume, Earth's radius would double. This means the gravitational force at the surface would reduce by a factor of $(1/2)^2$ = 1/4, so a person would weigh only one-fourth as much.

Check Your Learning

By what factor would a person's weight at the surface of Earth change if Earth had its present size but only one-third its present mass?

Answer:

With one-third its present mass, the gravitational force at the surface would reduce by a factor of 1/3, so a person would weight only one-third as much.

Gravity is a "built-in" property of mass. Whenever there are masses in the universe, they will interact via the force of gravitational attraction. The more mass there is, the greater the force of attraction. Here on Earth, the largest concentration of mass is, of course, the planet we stand on, and its pull dominates the gravitational interactions we experience. But everything with mass attracts everything else with mass anywhere in the universe.

Newton's law also implies that gravity never becomes zero. It quickly gets weaker with distance, but it continues to act to some degree no matter how far away you get. The pull of the Sun is stronger at Mercury than at Pluto, but it can be felt far beyond Pluto, where astronomers have good evidence that it continuously makes enormous numbers of smaller icy bodies move around huge orbits. And the Sun's gravitational pull joins with the pull of billions of others stars to create the gravitational pull of our Milky Way Galaxy. That force, in turn, can make other smaller galaxies orbit around the Milky Way, and so on.

Why is it then, you may ask, that the astronauts aboard the Space Shuttle appear to have no gravitational forces acting on them when we see images on television of the astronauts and objects floating in the spacecraft? After all, the astronauts in the shuttle are only a few hundred kilometers above the surface of Earth, which is not a significant distance compared to the size of Earth, so gravity is certainly not a great deal weaker that much farther away. The astronauts feel "weightless" (meaning that they don't feel the gravitational force acting on them) for the same reason that passengers in an elevator whose cable has broken or in an airplane whose engines no longer work feel weightless: they are falling (**Figure 3.9**).[2]

Figure 3.9 Astronauts in Free Fall. While in space, astronauts are falling freely, so they experience "weightlessness." Clockwise from top left: Tracy Caldwell Dyson (NASA), Naoko Yamzaki (JAXA), Dorothy Metcalf-Lindenburger (NASA), and Stephanie Wilson (NASA). (credit: NASA)

When *falling*, they are in free fall and accelerate at the same rate as everything around them, including their spacecraft or a camera with which they are taking photographs of Earth. When doing so, astronauts experience no additional forces and therefore feel "weightless." Unlike the falling elevator passengers, however, the astronauts are falling *around* Earth, not *to* Earth; as a result they will continue to fall and are said to be "in orbit" around Earth (see the next section for more about orbits).

Orbital Motion and Mass

Kepler's laws describe the orbits of the objects whose motions are described by Newton's laws of motion and

2 In the film *Apollo 13*, the scenes in which the astronauts were "weightless" were actually filmed in a falling airplane. As you might imagine, the plane fell for only short periods before the engines engaged again.

the law of gravity. Knowing that gravity is the force that attracts planets toward the Sun, however, allowed Newton to rethink Kepler's third law. Recall that Kepler had found a relationship between the orbital period of a planet's revolution and its distance from the Sun. But Newton's formulation introduces the additional factor of the masses of the Sun (M_1) and the planet (M_2), both expressed in units of the Sun's mass. Newton's universal law of gravitation can be used to show mathematically that this relationship is actually

$$a^3 = \left(M_1 + M_2\right) \times P^2$$

where a is the semimajor axis and P is the orbital period.

How did Kepler miss this factor? In units of the Sun's mass, the mass of the Sun is 1, and in units of the Sun's mass, the mass of a typical planet is a negligibly small factor. This means that the sum of the Sun's mass and a planet's mass, ($M_1 + M_2$), is very, very close to 1. This makes Newton's formula appear almost the same as Kepler's; the tiny mass of the planets compared to the Sun is the reason that Kepler did not realize that both masses had to be included in the calculation. There are many situations in astronomy, however, in which we *do* need to include the two mass terms—for example, when two stars or two galaxies orbit each other.

Including the mass term allows us to use this formula in a new way. If we can measure the motions (distances and orbital periods) of objects acting under their mutual gravity, then the formula will permit us to deduce their masses. For example, we can calculate the mass of the Sun by using the distances and orbital periods of the planets, or the mass of Jupiter by noting the motions of its moons.

Indeed, Newton's reformulation of Kepler's third law is one of the most powerful concepts in astronomy. Our ability to deduce the masses of objects from their motions is key to understanding the nature and evolution of many astronomical bodies. We will use this law repeatedly throughout this text in calculations that range from the orbits of comets to the interactions of galaxies.

EXAMPLE 3.4

Calculating the Effects of Gravity

A planet like Earth is found orbiting its star at a distance of 1 AU in 0.71 Earth-year. Can you use Newton's version of Kepler's third law to find the mass of the star? (Remember that compared to the mass of a star, the mass of an earthlike planet can be considered negligible.)

Solution

In the formula $a^3 = (M_1 + M_2) \times P^2$, the factor $M_1 + M_2$ would now be approximately equal to M_1 (the mass of the star), since the planet's mass is so small by comparison. Then the formula becomes $a^3 = M_1 \times P^2$, and we can solve for M_1:

$$M_1 = \frac{a^3}{P^2}$$

Since $a = 1$, $a^3 = 1$, so

$$M_1 = \frac{1}{P^2} = \frac{1}{0.71^2} = \frac{1}{0.5} = 2$$

So the mass of the star is twice the mass of our Sun. (Remember that this way of expressing the law has units in terms of Earth and the Sun, so masses are expressed in units of the mass of our Sun.)

Check Your Learning

Suppose a star with twice the mass of our Sun had an earthlike planet that took 4 years to orbit the star. At what distance (semimajor axis) would this planet orbit its star?

Answer:

Again, we can neglect the mass of the planet. So $M_1 = 2$ and $P = 4$ years. The formula is $a^3 = M_1 \times P^2$, so $a^3 = 2 \times 4^2 = 2 \times 16 = 32$. So a is the cube root of 32. To find this, you can just ask Google, “What is the cube root of 32?” and get the answer 3.2 AU.

LINK TO LEARNING

You might like to try a **simulation (https://openstaxcollege.org/l/30phetsimsunear)** that lets you move the Sun, Earth, Moon, and space station to see the effects of changing their distances on their gravitational forces and orbital paths. You can even turn off gravity and see what happens.

3.4 ORBITS IN THE SOLAR SYSTEM

Learning Objectives

By the end of this section, you will be able to:

- Compare the orbital characteristics of the planets in the solar system
- Compare the orbital characteristics of asteroids and comets in the solar system

Recall that the path of an object under the influence of gravity through space is called its orbit, whether that object is a spacecraft, planet, star, or galaxy. An orbit, once determined, allows the future positions of the object to be calculated.

Two points in any orbit in our solar system have been given special names. The place where the planet is closest to the Sun (*helios* in Greek) and moves the fastest is called the **perihelion** of its orbit, and the place where it is farthest away and moves the most slowly is the **aphelion**. For the Moon or a satellite orbiting Earth (*gee* in Greek), the corresponding terms are **perigee** and **apogee**. (In this book, we use the word *moon* for a natural object that goes around a planet and the word **satellite** to mean a human-made object that revolves around a planet.)

Orbits of the Planets

Today, Newton’s work enables us to calculate and predict the orbits of the planets with marvelous precision. We know eight planets, beginning with Mercury closest to the Sun and extending outward to Neptune. The average orbital data for the planets are summarized in Table 3.2. (Ceres is the largest of the *asteroids,* now considered a dwarf planet.)

According to Kepler’s laws, Mercury must have the shortest orbital period (88 Earth-days); thus, it has the highest orbital speed, averaging 48 kilometers per second. At the opposite extreme, Neptune has a period of

165 years and an average orbital speed of just 5 kilometers per second.

All the planets have orbits of rather low eccentricity. The most eccentric orbit is that of Mercury (0.21); the rest have eccentricities smaller than 0.1. It is fortunate that among the rest, Mars has an eccentricity greater than that of many of the other planets. Otherwise the pre-telescopic observations of Brahe would not have been sufficient for Kepler to deduce that its orbit had the shape of an ellipse rather than a circle.

The planetary orbits are also confined close to a common plane, which is near the plane of Earth's orbit (called the ecliptic). The strange orbit of the dwarf planet Pluto is inclined about 17° to the ecliptic, and that of the dwarf planet Eris (orbiting even farther away from the Sun than Pluto) by 44°, but all the major planets lie within 10° of the common plane of the solar system.

LINK TO LEARNING

You can use an **orbital simulator (https://openstaxcollege.org/l/30phetorbsim)** to design your own mini solar system with up to four bodies. Adjust masses, velocities, and positions of the planets, and see what happens to their orbits as a result.

Orbits of Asteroids and Comets

In addition to the eight planets, there are many smaller objects in the solar system. Some of these are moons (natural satellites) that orbit all the planets except Mercury and Venus. In addition, there are two classes of smaller objects in heliocentric orbits: *asteroids* and *comets*. Both asteroids and comets are believed to be small chunks of material left over from the formation process of the solar system.

In general, asteroids have orbits with smaller semimajor axes than do comets (**Figure 3.10**). The majority of them lie between 2.2 and 3.3 AU, in the region known as the **asteroid belt** (see **Comets and Asteroids: Debris of the Solar System**). As you can see in **Table 3.2**, the asteroid belt (represented by its largest member, Ceres) is in the middle of a gap between the orbits of Mars and Jupiter. It is because these two planets are so far apart that stable orbits of small bodies can exist in the region between them.

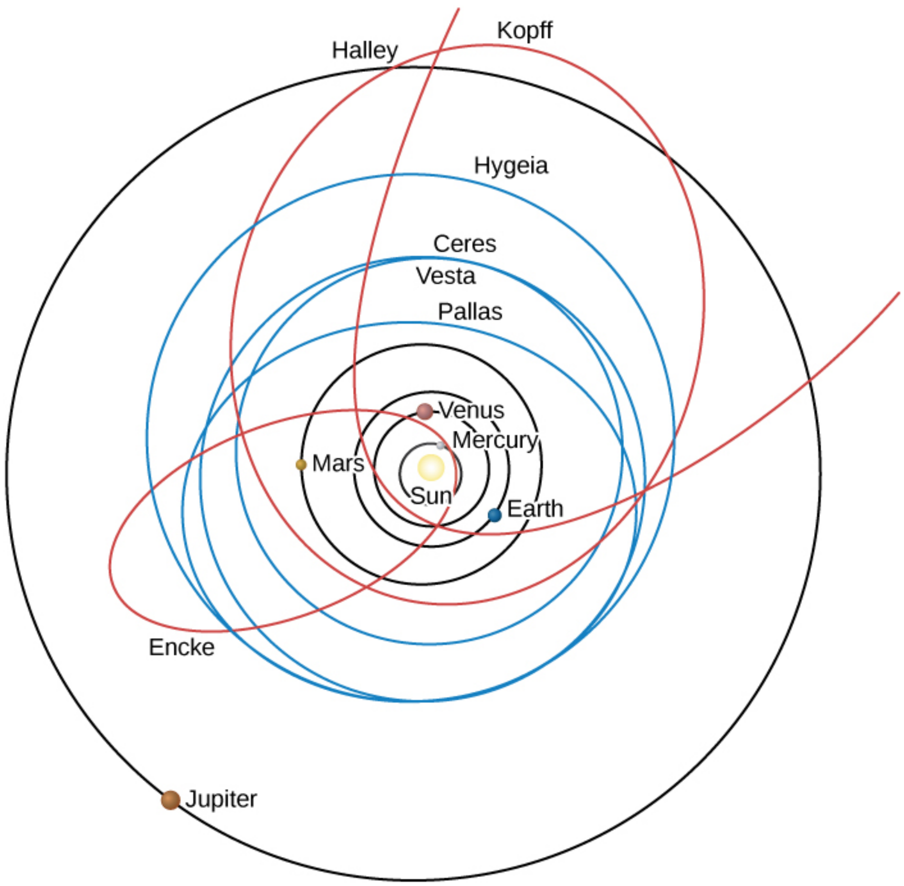


Figure 3.10 Solar System Orbits. We see the orbits of typical comets and asteroids compared with those of the planets Mercury, Venus, Earth, Mars, and Jupiter (black circles). Shown in red are three comets: Halley, Kopff, and Encke. In blue are the four largest asteroids: Ceres, Pallas, Vesta, and Hygeia.

Orbital Data for the Planets

Planet	Semimajor Axis (AU)	Period (y)	Eccentricity
Mercury	0.39	0.24	0.21
Venus	0.72	0.6	0.01
Earth	1	1.00	0.02
Mars	1.52	1.88	0.09
(Ceres)	2.77	4.6	0.08
Jupiter	5.20	11.86	0.05
Saturn	9.54	29.46	0.06
Uranus	19.19	84.01	0.05

Table 3.2

Orbital Data for the Planets

Planet	Semimajor Axis (AU)	Period (y)	Eccentricity
Neptune	30.06	164.82	0.01

Table 3.2

Comets generally have orbits of larger size and greater eccentricity than those of the asteroids. Typically, the eccentricity of their orbits is 0.8 or higher. According to Kepler’s second law, therefore, they spend most of their time far from the Sun, moving very slowly. As they approach perihelion, the comets speed up and whip through the inner parts of their orbits more rapidly.

3.5 MOTIONS OF SATELLITES AND SPACECRAFT

Learning Objectives

By the end of this section, you will be able to:

- Explain how an object (such as a satellite) can be put into orbit around Earth
- Explain how an object (such as a planetary probe) can escape from orbit

Newton’s universal law of gravitation and Kepler’s laws describe the motions of Earth satellites and interplanetary spacecraft as well as the planets. Sputnik, the first artificial Earth satellite, was launched by what was then called the Soviet Union on October 4, 1957. Since that time, thousands of satellites have been placed into orbit around Earth, and spacecraft have also orbited the Moon, Venus, Mars, Jupiter, Saturn, and a number of asteroids and comets.

Once an artificial satellite is in orbit, its behavior is no different from that of a natural satellite, such as our Moon. If the satellite is high enough to be free of atmospheric friction, it will remain in orbit forever. However, although there is no difficulty in maintaining a satellite once it is in orbit, a great deal of energy is required to lift the spacecraft off Earth and accelerate it to orbital speed.

To illustrate how a satellite is launched, imagine a gun firing a bullet horizontally from the top of a high mountain, as in **Figure 3.11**, which has been adapted from a similar diagram by Newton. Imagine, further, that the friction of the air could be removed and that nothing gets in the bullet’s way. Then the only force that acts on the bullet after it leaves the muzzle is the gravitational force between the bullet and Earth.

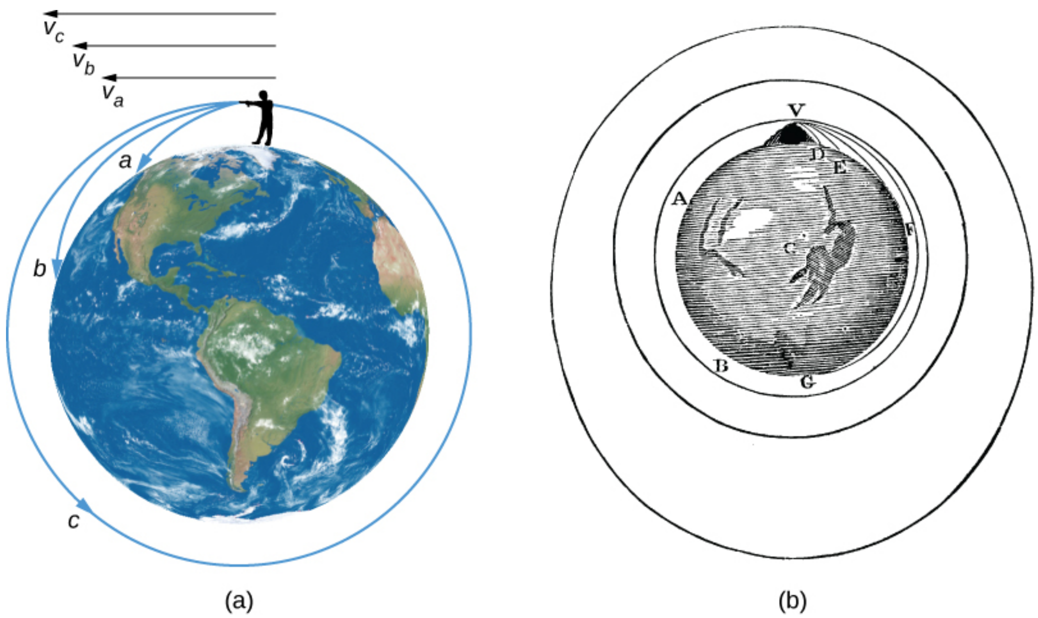


Figure 3.11 Firing a Bullet into Orbit. (a) For paths *a* and *b*, the velocity is not enough to prevent gravity from pulling the bullet back to Earth; in case *c*, the velocity allows the bullet to fall completely around Earth. (b) This diagram by Newton in his *De Mundi Systemate*, 1731 edition, illustrates the same concept shown in (a).

If the bullet is fired with a velocity we can call v_a, the gravitational force acting upon it pulls it downward toward Earth, where it strikes the ground at point *a*. However, if it is given a higher muzzle velocity, v_b, its higher speed carries it farther before it hits the ground at point *b*.

If our bullet is given a high enough muzzle velocity, v_c, the curved surface of Earth causes the ground to remain the same distance from the bullet so that the bullet falls *around* Earth in a complete circle. The speed needed to do this—called the circular satellite velocity—is about 8 kilometers per second, or about 17,500 miles per hour in more familiar units.

Each year, more than 50 new satellites are launched into orbit by such nations as Russia, the United States, China, Japan, India, and Israel, as well as by the European Space Agency (ESA), a consortium of European nations (**Figure 3.12**). Today, these satellites are used for weather tracking, ecology, global positioning systems, communications, and military purposes, to name a few uses. Most satellites are launched into low Earth orbit, since this requires the minimum launch energy. At the orbital speed of 8 kilometers per second, they circle the planet in about 90 minutes. Some of the very low Earth orbits are not indefinitely stable because, as Earth's atmosphere swells from time to time, a frictional drag is generated by the atmosphere on these satellites, eventually leading to a loss of energy and "decay" of the orbit.

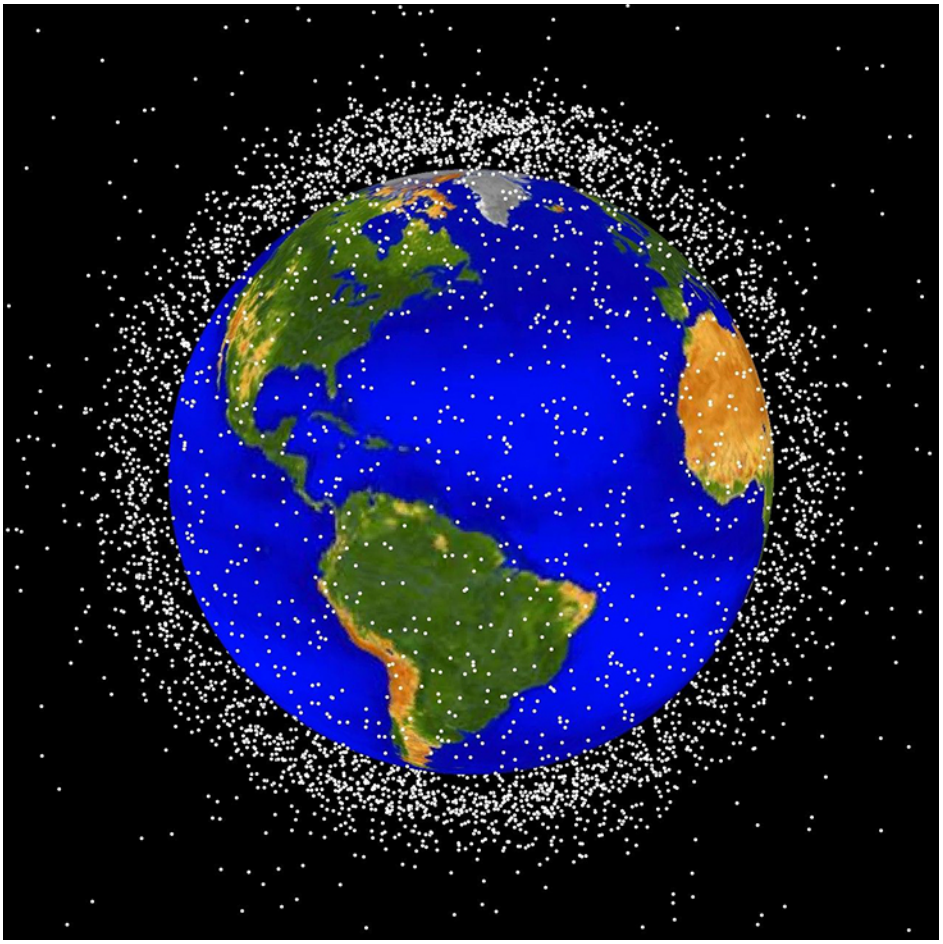


Figure 3.12 Satellites in Earth Orbit. This figure shows the larger pieces of orbital debris that are being tracked by NASA in Earth's orbit. (credit: NASA/JSC)

Interplanetary Spacecraft

The exploration of the solar system has been carried out largely by robot spacecraft sent to the other planets. To escape Earth, these craft must achieve **escape speed**, the speed needed to move away from Earth forever, which is about 11 kilometers per second (about 25,000 miles per hour). After escaping Earth, these craft coast to their targets, subject only to minor trajectory adjustments provided by small thruster rockets on board. In interplanetary flight, these spacecraft follow orbits around the Sun that are modified only when they pass near one of the planets.

As it comes close to its target, a spacecraft is deflected by the planet's gravitational force into a modified orbit, either gaining or losing energy in the process. Spacecraft controllers have actually been able to use a planet's gravity to redirect a flyby spacecraft to a second target. For example, Voyager 2 used a series of gravity-assisted encounters to yield successive flybys of Jupiter (1979), Saturn (1980), Uranus (1986), and Neptune (1989). The Galileo spacecraft, launched in 1989, flew past Venus once and Earth twice to gain the energy required to reach its ultimate goal of orbiting Jupiter.

If we wish to orbit a planet, we must slow the spacecraft with a rocket when the spacecraft is near its destination, allowing it to be captured into an elliptical orbit. Additional rocket thrust is required to bring a vehicle down from orbit for a landing on the surface. Finally, if a return trip to Earth is planned, the landed payload must include enough propulsive power to repeat the entire process in reverse.

3.6 GRAVITY WITH MORE THAN TWO BODIES

Learning Objectives

By the end of this section, you will be able to:

- Explain how the gravitational interactions of many bodies can causes perturbations in their motions
- Explain how the planet Neptune was discovered

Until now, we have considered the Sun and a planet (or a planet and one of its moons) as nothing more than a pair of bodies revolving around each other. In fact, all the planets exert gravitational forces upon one another as well. These interplanetary attractions cause slight variations from the orbits than would be expected if the gravitational forces between planets were neglected. The motion of a body that is under the gravitational influence of two or more other bodies is very complicated and can be calculated properly only with large computers. Fortunately, astronomers have such computers at their disposal in universities and government research institutes.

The Interactions of Many Bodies

As an example, suppose you have a cluster of a thousand stars all orbiting a common center (such clusters are quite common, as we shall see in **Star Clusters**). If we know the exact position of each star at any given instant, we can calculate the combined gravitational force of the entire group on any one member of the cluster. Knowing the force on the star in question, we can therefore find how it will accelerate. If we know how it was moving to begin with, we can then calculate how it will move in the next instant of time, thus tracking its motion.

However, the problem is complicated by the fact that the other stars are also moving and thus changing the effect they will have on our star. Therefore, we must simultaneously calculate the acceleration of each star produced by the combination of the gravitational attractions of all the others in order to track the motions of all of them, and hence of any one. Such complex calculations have been carried out with modern computers to track the evolution of hypothetical clusters of stars with up to a million members (**Figure 3.13**).

Figure 3.13 Modern Computing Power. These supercomputers at NASA's Ames Research Center are capable of tracking the motions of more than a million objects under their mutual gravitation. (credit: NASA Ames Research Center/Tom Trower)

Within the solar system, the problem of computing the orbits of planets and spacecraft is somewhat simpler. We have seen that Kepler's laws, which do not take into account the gravitational effects of the other planets on an orbit, really work quite well. This is because these additional influences are very small in comparison with the dominant gravitational attraction of the Sun. Under such circumstances, it is possible to treat the effects of other bodies as small **perturbations** (or disturbances). During the eighteenth and nineteenth centuries, mathematicians developed many elegant techniques for calculating perturbations, permitting them to predict very precisely the positions of the planets. Such calculations eventually led to the prediction and discovery of a new planet in 1846.

The Discovery of Neptune

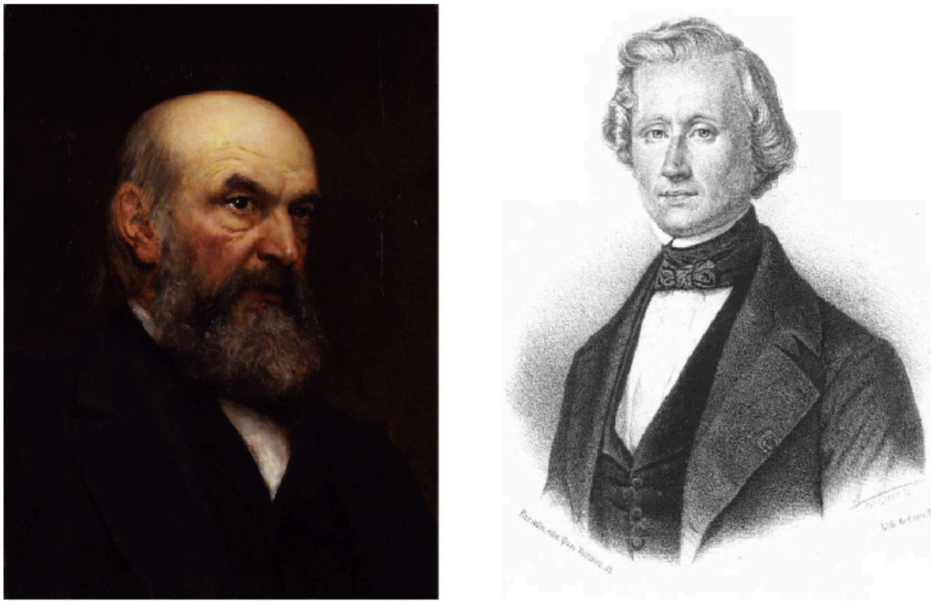
The discovery of the eighth planet, Neptune, was one of the high points in the development of gravitational theory. In 1781, William Herschel, a musician and amateur astronomer, accidentally discovered the seventh planet, Uranus. It happens that Uranus had been observed a century before, but in none of those earlier sightings was it recognized as a planet; rather, it was simply recorded as a star. Herschel's discovery showed that there could be planets in the solar system too dim to be visible to the unaided eye, but ready to be discovered with a telescope if we just knew where to look.

By 1790, an orbit had been calculated for Uranus using observations of its motion in the decade following its discovery. Even after allowance was made for the perturbing effects of Jupiter and Saturn, however, it was found that Uranus did not move on an orbit that exactly fit the earlier observations of it made since 1690. By 1840, the discrepancy between the positions observed for Uranus and those predicted from its computed orbit amounted to about 0.03°—an angle barely discernable to the unaided eye but still larger than the probable errors in the orbital calculations. In other words, Uranus just did not seem to move on the orbit predicted from Newtonian theory.

In 1843, John Couch Adams, a young Englishman who had just completed his studies at Cambridge, began a detailed mathematical analysis of the irregularities in the motion of Uranus to see whether they might be produced by the pull of an unknown planet. He hypothesized a planet more distant from the Sun than Uranus, and then determined the mass and orbit it had to have to account for the departures in Uranus' orbit. In October 1845, Adams delivered his results to George Airy, the British Astronomer Royal, informing him where in the sky to find the new planet. We now know that Adams' predicted position for the new body was correct to within 2°, but for a variety of reasons, Airy did not follow up right away.

Meanwhile, French mathematician Urbain Jean Joseph Le Verrier, unaware of Adams or his work, attacked the same problem and published its solution in June 1846. Airy, noting that Le Verrier's predicted position for the unknown planet agreed to within 1° with that of Adams, suggested to James Challis, Director of the Cambridge Observatory, that he begin a search for the new object. The Cambridge astronomer, having no up-to-date star charts of the Aquarius region of the sky where the planet was predicted to be, proceeded by recording the positions of all the faint stars he could observe with his telescope in that location. It was Challis' plan to repeat such plots at intervals of several days, in the hope that the planet would distinguish itself from a star by its motion. Unfortunately, he was negligent in examining his observations; although he had actually seen the planet, he did not recognize it.

About a month later, Le Verrier suggested to Johann Galle, an astronomer at the Berlin Observatory, that he look for the planet. Galle received Le Verrier's letter on September 23, 1846, and, possessing new charts of the Aquarius region, found and identified the planet that very night. It was less than a degree from the position Le Verrier predicted. The discovery of the eighth planet, now known as Neptune (the Latin name for the god of the sea), was a major triumph for gravitational theory for it dramatically confirmed the generality of Newton's laws. The honor for the discovery is properly shared by the two mathematicians, Adams and Le Verrier (**Figure 3.14**).



(a) (b)

Figure 3.14 Mathematicians Who Discovered a Planet. (a) John Couch Adams (1819–1892) and (b) Urbain J. J. Le Verrier (1811–1877) share the credit for discovering the planet Neptune.

We should note that the discovery of Neptune was not a complete surprise to astronomers, who had long suspected the existence of the planet based on the “disobedient” motion of Uranus. On September 10, 1846, two weeks before Neptune was actually found, John Herschel, son of the discoverer of Uranus, remarked in a speech before the British Association, “We see [the new planet] as Columbus saw America from the shores of Spain. Its movements have been felt trembling along the far-reaching line of our analysis with a certainty hardly inferior to ocular demonstration.”

This discovery was a major step forward in combining Newtonian theory with painstaking observations. Such work continues in our own times with the discovery of planets around other stars.

LINK TO LEARNING

For the fuller story of how Neptune was predicted and found (and the effect of the discovery on the search for Pluto), you can read **this page (https://openstaxcollege.org/l/30nepplumatdis)** on the mathematical discovery of planets.

MAKING CONNECTIONS

Astronomy and the Poets

When Copernicus, Kepler, Galileo, and Newton formulated the fundamental rules that underlie everything in the physical world, they changed much more than the face of science. For some, they gave humanity the courage to let go of old superstitions and see the world as rational and manageable; for others, they upset comforting, ordered ways that had served humanity for centuries, leaving only a dry, "mechanical clockwork" universe in their wake.

Poets of the time reacted to such changes in their work and debated whether the new world picture was an appealing or frightening one. John Donne (1573–1631), in a poem called "Anatomy of the World," laments the passing of the old certainties:

> The new Philosophy [science] calls all in doubt,
> The element of fire is quite put out;
> The Sun is lost, and th' earth, and no man's wit
> Can well direct him where to look for it.

(Here the "element of fire" refers also to the sphere of fire, which medieval thought placed between Earth and the Moon.)

By the next century, however, poets like Alexander Pope were celebrating Newton and the Newtonian world view. Pope's famous couplet, written upon Newton's death, goes

> Nature, and nature's laws lay hid in night.
> God said, Let Newton be! And all was light.

In his 1733 poem, *An Essay on Man*, Pope delights in the complexity of the new views of the world, incomplete though they are:

> Of man, what see we, but his station here,
> From which to reason, to which refer? . . .
> He, who thro' vast immensity can pierce,
> See worlds on worlds compose one universe,
> Observe how system into system runs,
> What other planets circle other suns,
> What vary'd being peoples every star,
> May tell why Heav'n has made us as we are . . .
> All nature is but art, unknown to thee;
> All chance, direction, which thou canst not see;
> All discord, harmony not understood;
> All partial evil, universal good:
> And, in spite of pride, in erring reason's spite,
> One truth is clear, whatever is, is right.

Poets and philosophers continued to debate whether humanity was exalted or debased by the new views of science. The nineteenth-century poet Arthur Hugh Clough (1819–1861) cries out in his poem "The New Sinai":

> And as old from Sinai's top God said that God is one,
> By science strict so speaks He now to tell us, there is None!
> Earth goes by chemic forces; Heaven's a Mécanique Celeste!
> And heart and mind of humankind a watchwork as the rest!

(A “mécanique celeste” is a clockwork model to demonstrate celestial motions.)

The twentieth-century poet Robinson Jeffers (whose brother was an astronomer) saw it differently in a poem called “Star Swirls”:

> There is nothing like astronomy to pull the stuff out of man.
> His stupid dreams and red-rooster importance:
> Let him count the star-swirls.

CHAPTER 3 REVIEW

KEY TERMS

angular momentum the measure of the motion of a rotating object in terms of its speed and how widely the object's mass is distributed around its axis

aphelion the point in its orbit where a planet (or other orbiting object) is farthest from the Sun

apogee the point in its orbit where an Earth satellite is farthest from Earth

asteroid belt the region of the solar system between the orbits of Mars and Jupiter in which most asteroids are located; the main belt, where the orbits are generally the most stable, extends from 2.2 to 3.3 AU from the Sun

astronomical unit (AU) the unit of length defined as the average distance between Earth and the Sun; this distance is about 1.5×10^8 kilometers

density the ratio of the mass of an object to its volume

eccentricity in an ellipse, the ratio of the distance between the foci to the major axis

ellipse a closed curve for which the sum of the distances from any point on the ellipse to two points inside (called the foci) is always the same

escape speed the speed a body must achieve to break away from the gravity of another body

focus (plural: foci) one of two fixed points inside an ellipse from which the sum of the distances to any point on the ellipse is constant

gravity the mutual attraction of material bodies or particles

Kepler's first law each planet moves around the Sun in an orbit that is an ellipse, with the Sun at one focus of the ellipse

Kepler's second law the straight line joining a planet and the Sun sweeps out equal areas in space in equal intervals of time

Kepler's third law the square of a planet's orbital period is directly proportional to the cube of the semimajor axis of its orbit

major axis the maximum diameter of an ellipse

momentum the measure of the amount of motion of a body; the momentum of a body is the product of its mass and velocity; in the absence of an unbalanced force, momentum is conserved

Newton's first law every object will continue to be in a state of rest or move at a constant speed in a straight line unless it is compelled to change by an outside force

Newton's second law the change of motion of a body is proportional to and in the direction of the force acting on it

Newton's third law for every action there is an equal and opposite reaction (*or:* the mutual actions of two bodies upon each other are always equal and act in opposite directions)

orbit the path of an object that is in revolution about another object or point

orbital period (*P*) the time it takes an object to travel once around the Sun

orbital speed the speed at which an object (usually a planet) orbits around the mass of another object; in the case of a planet, the speed at which each planet moves along its ellipse

perigee the point in its orbit where an Earth satellite is closest to Earth

perihelion the point in its orbit where a planet (or other orbiting object) is nearest to the Sun

perturbation a small disturbing effect on the motion or orbit of a body produced by a third body

satellite an object that revolves around a planet

semimajor axis half of the major axis of a conic section, such as an ellipse

velocity the speed and direction a body is moving—for example, 44 kilometers per second toward the north galactic pole

SUMMARY

3.1 The Laws of Planetary Motion

Tycho Brahe's accurate observations of planetary positions provided the data used by Johannes Kepler to derive his three fundamental laws of planetary motion. Kepler's laws describe the behavior of planets in their orbits as follows: (1) planetary orbits are ellipses with the Sun at one focus; (2) in equal intervals, a planet's orbit sweeps out equal areas; and (3) the relationship between the orbital period (*P*) and the semimajor axis (*a*) of an orbit is given by $P^2 = a^3$ (when *a* is in units of AU and *P* is in units of Earth years).

3.2 Newton's Great Synthesis

In his *Principia*, Isaac Newton established the three laws that govern the motion of objects: (1) objects continue to be at rest or move with a constant velocity unless acted upon by an outside force; (2) an outside force causes an acceleration (and changes the momentum) for an object; and (3) for every action there is an equal and opposite reaction. Momentum is a measure of the motion of an object and depends on both its mass and its velocity. Angular momentum is a measure of the motion of a spinning or revolving object and depends on its mass, velocity, and distance from the point around which it revolves. The density of an object is its mass divided by its volume.

3.3 Newton's Universal Law of Gravitation

Gravity, the attractive force between all masses, is what keeps the planets in orbit. Newton's universal law of gravitation relates the gravitational force to mass and distance:

$$F_{\text{gravity}} = G\frac{M_1 M_2}{R^2}$$

The force of gravity is what gives us our sense of weight. Unlike mass, which is constant, weight can vary depending on the force of gravity (or acceleration) you feel. When Kepler's laws are reexamined in the light of Newton's gravitational law, it becomes clear that the masses of both objects are important for the third law, which becomes $a^3 = (M_1 + M_2) \times P^2$. Mutual gravitational effects permit us to calculate the masses of astronomical objects, from comets to galaxies.

3.4 Orbits in the Solar System

The closest point in a satellite orbit around Earth is its perigee, and the farthest point is its apogee (corresponding to perihelion and aphelion for an orbit around the Sun). The planets follow orbits around the Sun that are nearly circular and in the same plane. Most asteroids are found between Mars and Jupiter in the asteroid belt, whereas comets generally follow orbits of high eccentricity.

3.5 Motions of Satellites and Spacecraft

The orbit of an artificial satellite depends on the circumstances of its launch. The circular satellite velocity needed to orbit Earth's surface is 8 kilometers per second, and the escape speed from our planet is 11 kilometers per second. There are many possible interplanetary trajectories, including those that use gravity-assisted flybys of one object to redirect the spacecraft toward its next target.

3.6 Gravity with More Than Two Bodies

Calculating the gravitational interaction of more than two objects is complicated and requires large computers. If one object (like the Sun in our solar system) dominates gravitationally, it is possible to calculate the effects of a second object in terms of small perturbations. This approach was used by John Couch Adams and Urbain Le Verrier to predict the position of Neptune from its perturbations of the orbit of Uranus and thus discover a new planet mathematically.

FOR FURTHER EXPLORATION

Articles

Brahe and Kepler

Christianson, G. "The Celestial Palace of Tycho Brahe." *Scientific American* (February 1961): 118.

Gingerich, O. "Johannes Kepler and the Rudolphine Tables." *Sky & Telescope* (December 1971): 328. Brief article on Kepler's work.

Wilson, C. "How Did Kepler Discover His First Two Laws?" *Scientific American* (March 1972): 92.

Newton

Christianson, G. "Newton's *Principia*: A Retrospective." *Sky & Telescope* (July 1987): 18.

Cohen, I. "Newton's Discovery of Gravity." *Scientific American* (March 1981): 166.

Gingerich, O. "Newton, Halley, and the Comet." *Sky & Telescope* (March 1986): 230.

Sullivant, R. "When the Apple Falls." *Astronomy* (April 1998): 55. Brief overview.

The Discovery of Neptune

Sheehan, W., et al. "The Case of the Pilfered Planet: Did the British Steal Neptune?" *Scientific American* (December 2004): 92.

Websites

Brahe and Kepler

Johannes Kepler: His Life, His Laws, and Time: **http://kepler.nasa.gov/Mission/JohannesKepler/ (http://kepler.nasa.gov/Mission/JohannesKepler/)** . From NASA's Kepler mission.

Johannes Kepler: **http://www.britannica.com/biography/Johannes-Kepler (http://www.britannica.com/**

biography/Johannes-Kepler) . Encyclopedia Britannica article.

Johannes Kepler: http://www-history.mcs.st-andrews.ac.uk/Biographies/Kepler.html (http://www-history.mcs.st-andrews.ac.uk/Biographies/Kepler.html) . MacTutor article with additional links.

Noble Dane: Images of Tycho Brahe: http://www.mhs.ox.ac.uk/tycho/index.htm (http://www.mhs.ox.ac.uk/tycho/index.htm) . A virtual museum exhibit from Oxford.

Newton

Sir Isaac Newton: http://www-groups.dcs.st-and.ac.uk/~history//Biographies/Newton.html (http://www-groups.dcs.st-and.ac.uk/~history//Biographies/Newton.html) . MacTutor article with additional links.

Sir Isaac Newton: http://www.luminarium.org/sevenlit/newton/newtonbio.htm (http://www.luminarium.org/sevenlit/newton/newtonbio.htm) . Newton Biography at the Luminarium.

The Discovery of Neptune

Adams, Airy, and the Discovery of Neptune: http://www.mikeoates.org/lassell/adams-airy.htm (http://www.mikeoates.org/lassell/adams-airy.htm) . A defense of Airy's role by historian Alan Chapman.

Mathematical Discovery of Planets: http://www-groups.dcs.st-and.ac.uk/~history/HistTopics/Neptune_and_Pluto.html (http://www-groups.dcs.st-and.ac.uk/~history/HistTopics/Neptune_and_Pluto.html) . MacTutor article.

Videos

Brahe and Kepler

"Harmony of the Worlds." This third episode of Carl Sagan's TV series *Cosmos* focuses on Kepler and his life and work.

Tycho Brahe, Johannes Kepler, and Planetary Motion: https://www.youtube.com/watch?v=x3ALuycrCwI (https://www.youtube.com/watch?v=x3ALuycrCwI) . German-produced video, in English (14:27).

Newton

Beyond the Big Bang: Sir Isaac Newton's Law of Gravity: http://www.history.com/topics/enlightenment/videos/beyond-the-big-bang-sir-isaac-newtons-law-of-gravity (http://www.history.com/topics/enlightenment/videos/beyond-the-big-bang-sir-isaac-newtons-law-of-gravity) . From the History Channel (4:35).

Sir Isaac Newton versus Bill Nye: Epic Rap Battles of History: https://www.youtube.com/watch?v=8yis7GzlXNM (https://www.youtube.com/watch?v=8yis7GzlXNM) . (2:47).

The Discovery of Neptune

Richard Feynman: On the Discovery of Neptune: https://www.youtube.com/watch?v=FgXQffVgZRs (https://www.youtube.com/watch?v=FgXQffVgZRs) . A brief black-and-white Caltech lecture (4:33).

COLLABORATIVE GROUP ACTIVITIES

A. An eccentric, but very rich, alumnus of your college makes a bet with the dean that if you drop a baseball and a bowling ball from the tallest building on campus, the bowling ball would hit the ground first. Have your group discuss whether you would make a side bet that the alumnus is right. How would you decide who is right?

B. Suppose someone in your astronomy class was unhappy about his or her weight. Where could a person go to weigh one-fourth as much as he or she does now? Would changing the unhappy person's weight have any effect on his or her mass?

C. When the Apollo astronauts landed on the Moon, some commentators commented that it ruined the mystery and "poetry" of the Moon forever (and that lovers could never gaze at the full moon in the same way again). Others felt that knowing more about the Moon could only enhance its interest to us as we see it from Earth. How do the various members of your group feel? Why?

D. Figure 3.12 shows a swarm of satellites in orbit around Earth. What do you think all these satellites do? How many categories of functions for Earth satellites can your group come up with?

E. The Making Connections feature box **Astronomy and the Poets** discusses how poets included the most recent astronomical knowledge in their poetry. Is this still happening today? Can your group members come up with any poems or songs that you know that deal with astronomy or outer space? If not, perhaps you could find some online, or by asking friends or roommates who are into poetry or music.

EXERCISES

Review Questions

1. State Kepler's three laws in your own words.
2. Why did Kepler need Tycho Brahe's data to formulate his laws?
3. Which has more mass: an armful of feathers or an armful of lead? Which has more volume: a kilogram of feathers or a kilogram of lead? Which has higher density: a kilogram of feathers or a kilogram of lead?
4. Explain how Kepler was able to find a relationship (his third law) between the orbital periods and distances of the planets that did not depend on the masses of the planets or the Sun.
5. Write out Newton's three laws of motion in terms of what happens with the momentum of objects.
6. Which major planet has the largest . . .
   - **A.** semimajor axis?
   - **B.** average orbital speed around the Sun?
   - **C.** orbital period around the Sun?
   - **D.** eccentricity?
7. Why do we say that Neptune was the first planet to be discovered through the use of mathematics?
8. Why was Brahe reluctant to provide Kepler with all his data at one time?
9. According to Kepler's second law, where in a planet's orbit would it be moving fastest? Where would it be moving slowest?
10. The gas pedal, the brakes, and the steering wheel all have the ability to accelerate a car—how?
11. Explain how a rocket can propel itself using Newton's third law.

12. A certain material has a mass of 565 g while occupying 50 cm^3 of space. What is this material? (Hint: Use **Table 3.1**.)

13. To calculate the momentum of an object, which properties of an object do you need to know?

14. To calculate the angular momentum of an object, which properties of an object do you need to know?

15. What was the great insight Newton had regarding Earth’s gravity that allowed him to develop the universal law of gravitation?

16. Which of these properties of an object best quantifies its inertia: velocity, acceleration, volume, mass, or temperature?

17. Pluto’s orbit is more eccentric than any of the major planets. What does that mean?

18. Why is Tycho Brahe often called “the greatest naked-eye astronomer” of all time?

Thought Questions

19. Is it possible to escape the force of gravity by going into orbit around Earth? How does the force of gravity in the International Space Station (orbiting an average of 400 km above Earth’s surface) compare with that on the ground?

20. What is the momentum of an object whose velocity is zero? How does Newton’s first law of motion include the case of an object at rest?

21. Evil space aliens drop you and your fellow astronomy student 1 km apart out in space, very far from any star or planet. Discuss the effects of gravity on each of you.

22. A body moves in a perfectly circular path at constant speed. Are there forces acting in such a system? How do you know?

23. As friction with our atmosphere causes a satellite to spiral inward, closer to Earth, its orbital speed increases. Why?

24. Use a history book, an encyclopedia, or the internet to find out what else was happening in England during Newton’s lifetime and discuss what trends of the time might have contributed to his accomplishments and the rapid acceptance of his work.

25. Two asteroids begin to gravitationally attract one another. If one asteroid has twice the mass of the other, which one experiences the greater force? Which one experiences the greater acceleration?

26. How does the mass of an astronaut change when she travels from Earth to the Moon? How does her weight change?

27. If there is gravity where the International Space Station (ISS) is located above Earth, why doesn’t the space station get pulled back down to Earth?

28. Compare the density, weight, mass, and volume of a pound of gold to a pound of iron on the surface of Earth.

29. If identical spacecraft were orbiting Mars and Earth at identical radii (distances), which spacecraft would be moving faster? Why?

Figuring For Yourself

30. By what factor would a person’s weight be increased if Earth had 10 times its present mass, but the same volume?

31. Suppose astronomers find an earthlike planet that is twice the size of Earth (that is, its radius is twice that of Earth's). What must be the mass of this planet such that the gravitational force (F_{gravity}) at the surface would be identical to Earth's?

32. What is the semimajor axis of a circle of diameter 24 cm? What is its eccentricity?

33. If 24 g of material fills a cube 2 cm on a side, what is the density of the material?

34. If 128 g of material is in the shape of a brick 2 cm wide, 4 cm high, and 8 cm long, what is the density of the material?

35. If the major axis of an ellipse is 16 cm, what is the semimajor axis? If the eccentricity is 0.8, would this ellipse be best described as mostly circular or very elongated?

36. What is the average distance from the Sun (in astronomical units) of an asteroid with an orbital period of 8 years?

37. What is the average distance from the Sun (in astronomical units) of a planet with an orbital period of 45.66 years?

38. In 1996, astronomers discovered an icy object beyond Pluto that was given the designation 1996 TL 66. It has a semimajor axis of 84 AU. What is its orbital period according to Kepler's third law?

4 EARTH, MOON, AND SKY

Figure 4.1 Southern Summer. As captured with a fish-eye lens aboard the Atlantis Space Shuttle on December 9, 1993, Earth hangs above the Hubble Space Telescope as it is repaired. The reddish continent is Australia, its size and shape distorted by the special lens. Because the seasons in the Southern Hemisphere are opposite those in the Northern Hemisphere, it is summer in Australia on this December day. (credit: modification of work by NASA)

Chapter Outline

Thinking Ahead

If Earth's orbit is nearly a perfect circle (as we saw in earlier chapters), why is it hotter in summer and colder in winter in many places around the globe? And why are the seasons in Australia or Peru the opposite of those in the United States or Europe?

The story is told that Galileo, as he left the Hall of the Inquisition following his retraction of the doctrine that Earth rotates and revolves about the Sun, said under his breath, "But nevertheless it moves." Historians are not sure whether the story is true, but certainly Galileo knew that Earth was in motion, whatever church authorities said.

It is the motions of Earth that produce the seasons and give us our measures of time and date. The Moon's motions around us provide the concept of the month and the cycle of lunar phases. In this chapter we examine some of the basic phenomena of our everyday world in their astronomical context.

4.1 EARTH AND SKY

Learning Objectives

By the end of this section, you will be able to:

- Describe how latitude and longitude are used to map Earth
- Explain how right ascension and declination are used to map the sky

In order to create an accurate map, a mapmaker needs a way to uniquely and simply identify the location of all the major features on the map, such as cities or natural landmarks. Similarly, astronomical mapmakers need a way to uniquely and simply identify the location of stars, galaxies, and other celestial objects. On Earth maps, we divide the surface of Earth into a grid, and each location on that grid can easily be found using its *latitude* and *longitude* coordinate. Astronomers have a similar system for objects on the sky. Learning about these can help us understand the apparent motion of objects in the sky from various places on Earth.

Locating Places on Earth

Let’s begin by fixing our position on the surface of planet Earth. As we discussed in **Observing the Sky: The Birth of Astronomy**, Earth’s axis of rotation defines the locations of its North and South Poles and of its equator, halfway between. Two other directions are also defined by Earth’s motions: east is the direction toward which Earth rotates, and west is its opposite. At almost any point on Earth, the four directions—north, south, east, and west—are well defined, despite the fact that our planet is round rather that flat. The only exceptions are exactly at the North and South Poles, where the directions east and west are ambiguous (because points exactly at the poles do not turn).

We can use these ideas to define a system of coordinates attached to our planet. Such a system, like the layout of streets and avenues in Manhattan or Salt Lake City, helps us find where we are or want to go. Coordinates on a sphere, however, are a little more complicated than those on a flat surface. We must define circles on the sphere that play the same role as the rectangular grid that you see on city maps.

A **great circle** is any circle on the surface of a sphere whose center is at the center of the sphere. For example, Earth’s equator is a great circle on Earth’s surface, halfway between the North and South Poles. We can also imagine a series of great circles that pass through both the North and South Poles. Each of this circles is called a **meridian**; they are each perpendicular to the equator, crossing it at right angles.

Any point on the surface of Earth will have a meridian passing through it (**Figure 4.2**). The meridian specifies the east-west location, or longitude, of the place. By international agreement (and it took many meetings for the world’s countries to agree), longitude is defined as the number of degrees of arc along the equator between your meridian and the one passing through Greenwich, England, which has been designated as the Prime Meridian. The longitude of the Prime Meridian is defined as 0°.

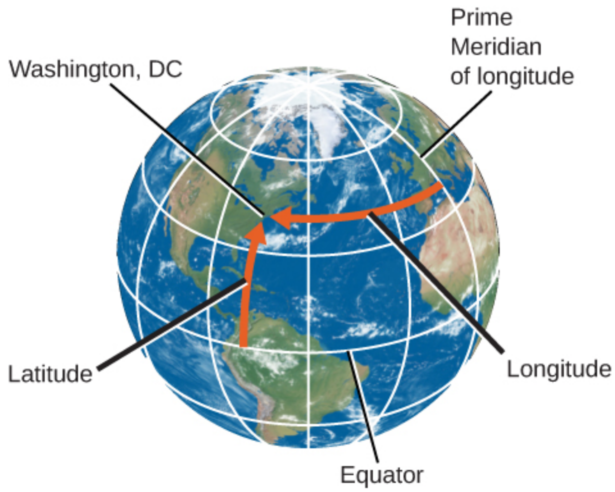


Figure 4.2 Latitude and Longitude of Washington, DC. We use latitude and longitude to find cities like Washington, DC, on a globe. Latitude is the number of degrees north or south of the equator, and longitude is the number of degrees east or west of the Prime Meridian. Washington, DC's coordinates are 38° N and 77° W.

Why Greenwich, you might ask? Every country wanted 0° longitude to pass through its own capital. Greenwich, the site of the old Royal Observatory (**Figure 4.3**), was selected because it was between continental Europe and the United States, and because it was the site for much of the development of the method to measure longitude at sea. Longitudes are measured either to the east or to the west of the Greenwich meridian from 0° to 180°. As an example, the longitude of the clock-house benchmark of the U.S. Naval Observatory in Washington, DC, is 77.066° W.

Figure 4.3 Royal Observatory in Greenwich, England. At the internationally agreed-upon zero point of longitude at the Royal Observatory Greenwich, tourists can stand and straddle the exact line where longitude "begins."(credit left: modification of work by "pdbreen"/Flickr; credit right: modification of work by Ben Sutherland)

Your latitude (or north-south location) is the number of degrees of arc you are away from the equator along your meridian. Latitudes are measured either north or south of the equator from 0° to 90°. (The latitude of the equator is 0°.) As an example, the latitude of the previously mentioned Naval Observatory benchmark is 38.921° N. The latitude of the South Pole is 90° S, and the latitude of the North Pole is 90° N.

Locating Places in the Sky

Positions in the sky are measured in a way that is very similar to the way we measure positions on the surface of Earth. Instead of latitude and longitude, however, astronomers use coordinates called **declination** and **right ascension**. To denote positions of objects in the sky, it is often convenient to make use of the fictitious celestial sphere. We saw in **Observing the Sky: The Birth of Astronomy** that the sky appears to rotate about points above the North and South Poles of Earth—points in the sky called the north celestial pole and the south celestial pole. Halfway between the celestial poles, and thus 90° from each pole, is the *celestial equator,* a great circle on the celestial sphere that is in the same plane as Earth's equator. We can use these markers in the sky to set up a system of celestial coordinates.

Declination on the celestial sphere is measured the same way that latitude is measured on the sphere of Earth: from the celestial equator toward the north (positive) or south (negative). So Polaris, the star near the north celestial pole, has a declination of almost +90°.

Right ascension (RA) is like longitude, except that instead of Greenwich, the arbitrarily chosen point where we start counting is the *vernal equinox*, a point in the sky where the *ecliptic* (the Sun's path) crosses the celestial equator. RA can be expressed either in units of angle (degrees) or in units of time. This is because the celestial sphere appears to turn around Earth once a day as our planet turns on its axis. Thus the 360° of RA that it takes to go once around the celestial sphere can just as well be set equal to 24 hours. Then each 15° of arc is equal to 1 hour of time. For example, the approximate celestial coordinates of the bright star Capella are RA 5h = 75° and declination +50°.

One way to visualize these circles in the sky is to imagine Earth as a transparent sphere with the terrestrial coordinates (latitude and longitude) painted on it with dark paint. Imagine the celestial sphere around us as a giant ball, painted white on the inside. Then imagine yourself at the center of Earth, with a bright light bulb in the middle, looking out through its transparent surface to the sky. The terrestrial poles, equator, and meridians will be projected as dark shadows on the celestial sphere, giving us the system of coordinates in the sky.

LINK TO LEARNING

You can explore a variety of basic animations about coordinates and motions in the sky at this **interactive site (https://openstaxcollege.org/l/30anicoormot)** from ClassAction. Click on the "Animations" tab for a list of options. If you choose the second option in the menu, you can play with the celestial sphere and see RA and declination defined visually.

The Turning Earth

Why do many stars rise and set each night? Why, in other words, does the night sky seem to turn? We have seen that the apparent rotation of the celestial sphere could be accounted for either by a daily rotation of the sky around a stationary Earth or by the rotation of Earth itself. Since the seventeenth century, it has been generally accepted that it is Earth that turns, but not until the nineteenth century did the French physicist Jean Foucault provide an unambiguous demonstration of this rotation. In 1851, he suspended a 60-meter pendulum weighing about 25 kilograms from the dome of the Pantheon in Paris and started the pendulum swinging evenly. If Earth had not been turning, there would have been no alteration of the pendulum's plane of oscillation, and so it would have continued tracing the same path. Yet after a few minutes Foucault could see that the pendulum's plane of motion was turning. Foucault explained that it was not the pendulum that was shifting, but rather Earth that was turning beneath it (**Figure 4.4**). You can now find such pendulums in many science centers and planetariums around the world.

Figure 4.4 Foucault's Pendulum. As Earth turns, the plane of oscillation of the Foucault pendulum shifts gradually so that over the course of 12 hours, all the targets in the circle at the edge of the wooden platform are knocked over in sequence. (credit: Manuel M. Vicente)

Can you think of other pieces of evidence that indicate that it is Earth and not the sky that is turning? (See **Collaborative Group Activity A** at the end of this chapter.)

4.2 THE SEASONS

Learning Objectives

By the end of this section, you will be able to:

- Describe how the tilt of Earth's axis causes the seasons
- Explain how seasonal differences on Earth vary with latitude

One of the fundamental facts of life at Earth's midlatitudes, where most of this book's readers live, is that there are significant variations in the heat we receive from the Sun during the course of the year. We thus divide the year into *seasons*, each with its different amount of sunlight. The difference between seasons gets more pronounced the farther north or south from the equator we travel, and the seasons in the Southern Hemisphere are the opposite of what we find on the northern half of Earth. With these observed facts in mind, let us ask what causes the seasons.

Many people have believed that the seasons were the result of the changing distance between Earth and the Sun. This sounds reasonable at first: it should be colder when Earth is farther from the Sun. But the facts don't bear out this hypothesis. Although Earth's orbit around the Sun is an ellipse, its distance from the Sun varies by only about 3%. That's not enough to cause significant variations in the Sun's heating. To make matters worse for people in North America who hold this hypothesis, Earth is actually closest to the Sun in January, when the Northern Hemisphere is in the middle of winter. And if distance were the governing factor, why would the two hemispheres have opposite seasons? As we shall show, the seasons are actually caused by the 23.5° tilt of Earth's axis.

The Seasons and Sunshine

Figure 4.5 shows Earth's annual path around the Sun, with Earth's axis tilted by 23.5°. Note that our axis continues to point the same direction in the sky throughout the year. As Earth travels around the Sun, in June the Northern Hemisphere "leans into" the Sun and is more directly illuminated. In December, the situation is reversed: the Southern Hemisphere leans into the Sun, and the Northern Hemisphere leans away. In September and March, Earth leans "sideways"—neither into the Sun nor away from it—so the two hemispheres are equally favored with sunshine.

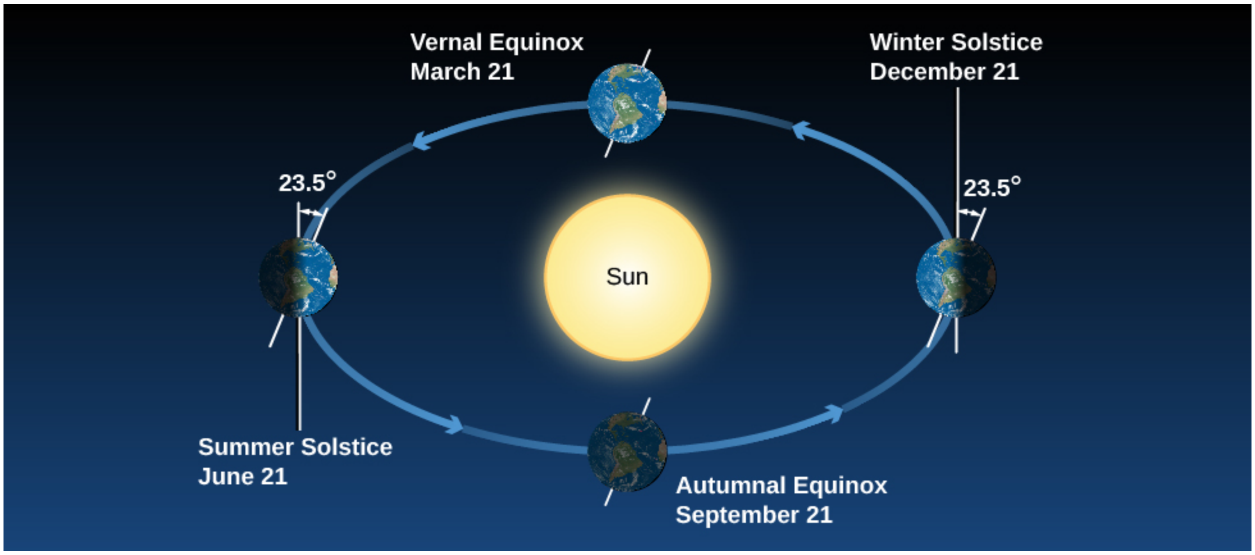


Figure 4.5 Seasons. We see Earth at different seasons as it circles the Sun. In June, the Northern Hemisphere "leans into" the Sun, and those in the North experience summer and have longer days. In December, during winter in the Northern Hemisphere, the Southern Hemisphere "leans into" the Sun and is illuminated more directly. In spring and autumn, the two hemispheres receive more equal shares of sunlight.[1]

How does the Sun's favoring one hemisphere translate into making it warmer for us down on the surface of Earth? There are two effects we need to consider. When we lean into the Sun, sunlight hits us at a more direct angle and is more effective at heating Earth's surface (**Figure 4.6**). You can get a similar effect by shining a flashlight onto a wall. If you shine the flashlight straight on, you get an intense spot of light on the wall. But if you hold the flashlight at an angle (if the wall "leans out" of the beam), then the spot of light is more spread out. Like the straight-on light, the sunlight in June is more direct and intense in the Northern Hemisphere, and hence more effective at heating.

1 Note that the dates indicated for the solstices and equinoxes are approximate; depending on the year, they may occur a day or two earlier or later.

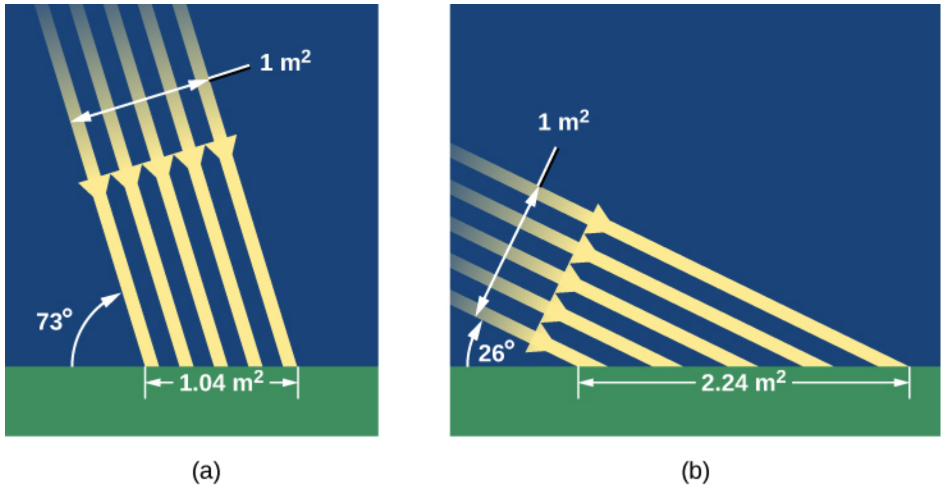


Figure 4.6 The Sun’s Rays in Summer and Winter. (a) In summer, the Sun appears high in the sky and its rays hit Earth more directly, spreading out less. (b) In winter, the Sun is low in the sky and its rays spread out over a much wider area, becoming less effective at heating the ground.

The second effect has to do with the length of time the Sun spends above the horizon (Figure 4.7). Even if you’ve never thought about astronomy before, we’re sure you have observed that the hours of daylight increase in summer and decrease in winter. Let’s see why this happens.

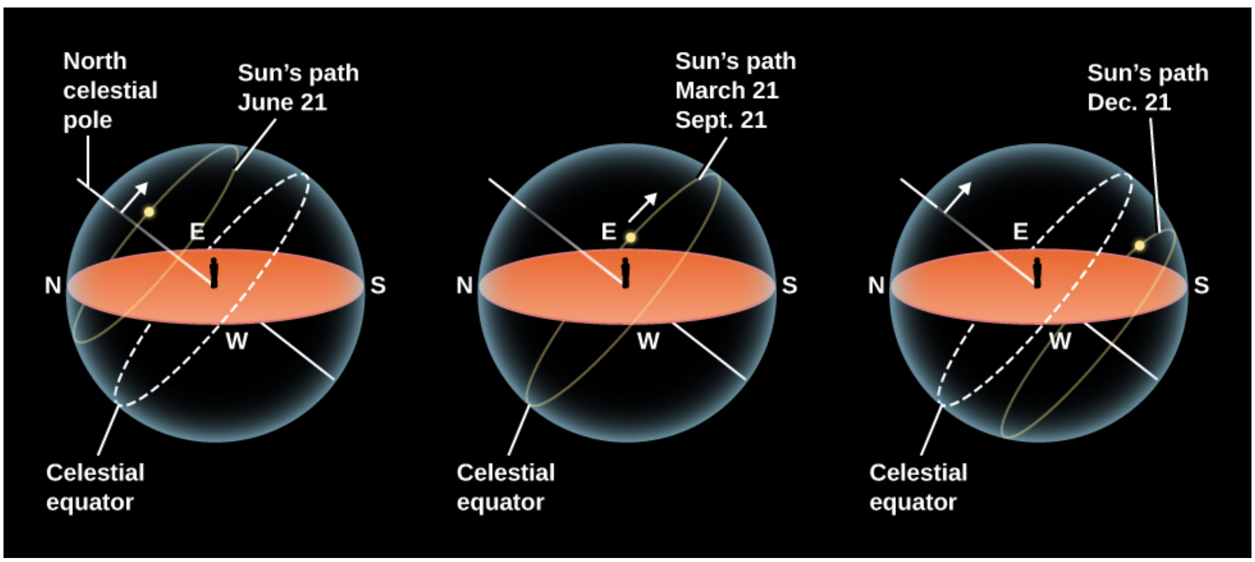


Figure 4.7 The Sun’s Path in the Sky for Different Seasons. On June 21, the Sun rises north of east and sets north of west. For observers in the Northern Hemisphere of Earth, the Sun spends about 15 hours above the horizon in the United States, meaning more hours of daylight. On December 21, the Sun rises south of east and sets south of west. It spends 9 hours above the horizon in the United States, which means fewer hours of daylight and more hours of night in northern lands (and a strong need for people to hold celebrations to cheer themselves up). On March 21 and September 21, the Sun spends equal amounts of time above and below the horizon in both hemispheres.

As we saw in Observing the Sky: The Birth of Astronomy, an equivalent way to look at our path around the Sun each year is to pretend that the Sun moves around Earth (on a circle called the ecliptic). Because Earth’s axis is tilted, the ecliptic is tilted by about 23.5° relative to the celestial equator (review Figure 2.7). As a result, where we see the Sun in the sky changes as the year wears on.

In June, the Sun is north of the celestial equator and spends more time with those who live in the Northern Hemisphere. It rises high in the sky and is above the horizon in the United States for as long as 15 hours. Thus, the Sun not only heats us with more direct rays, but it also has more time to do it each day. (Notice in Figure 4.7

that the Northern Hemisphere's gain is the Southern Hemisphere's loss. There the June Sun is low in the sky, meaning fewer daylight hours. In Chile, for example, June is a colder, darker time of year.) In December, when the Sun is south of the celestial equator, the situation is reversed.

Let's look at what the Sun's illumination on Earth looks like at some specific dates of the year, when these effects are at their maximum. On or about June 21 (the date we who live in the Northern Hemisphere call the *summer solstice* or sometimes the first day of summer), the Sun shines down most directly upon the Northern Hemisphere of Earth. It appears about 23° north of the equator, and thus, on that date, it passes through the zenith of places on Earth that are at 23° N latitude. The situation is shown in detail in **Figure 4.8**. To a person at 23° N (near Hawaii, for example), the Sun is directly overhead at noon. This latitude, where the Sun can appear at the zenith at noon on the first day of summer, is called the *Tropic of Cancer*.

We also see in **Figure 4.8** that the Sun's rays shine down all around the North Pole at the solstice. As Earth turns on its axis, the North Pole is continuously illuminated by the Sun; all places within 23° of the pole have sunshine for 24 hours. The Sun is as far north on this date as it can get; thus, 90° – 23° (or 67° N) is the southernmost latitude where the Sun can be seen for a full 24-hour period (sometimes called the "land of the midnight Sun"). That circle of latitude is called the *Arctic Circle*.

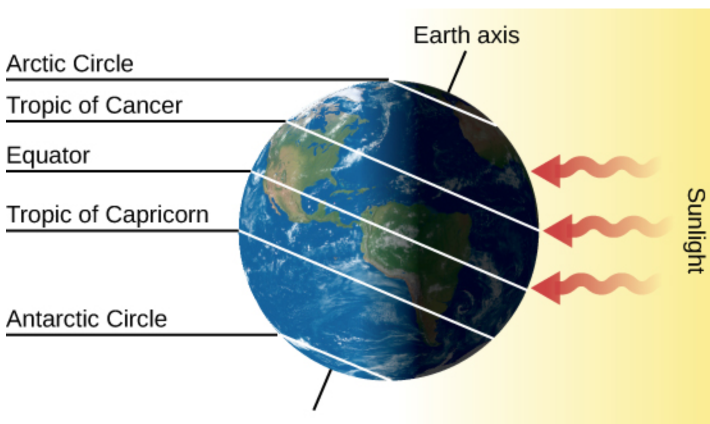


Figure 4.8 Earth on June 21. This is the date of the summer solstice in the Northern Hemisphere. Note that as Earth turns on its axis (the line connecting the North and South Poles), the North Pole is in constant sunlight while the South Pole is veiled in 24 hours of darkness. The Sun is at the zenith for observers on the Tropic of Cancer.

Many early cultures scheduled special events around the summer solstice to celebrate the longest days and thank their gods for making the weather warm. This required people to keep track of the lengths of the days and the northward trek of the Sun in order to know the right day for the "party." (You can do the same thing by watching for several weeks, from the same observation point, where the Sun rises or sets relative to a fixed landmark. In spring, the Sun will rise farther and farther north of east, and set farther and farther north of west, reaching the maximum around the summer solstice.)

Now look at the South Pole in **Figure 4.8**. On June 21, all places within 23° of the South Pole—that is, south of what we call the *Antarctic Circle*—do not see the Sun at all for 24 hours.

The situation is reversed 6 months later, about December 21 (the date of the *winter solstice*, or the first day of winter in the Northern Hemisphere), as shown in **Figure 4.9**. Now it is the Arctic Circle that has the 24-hour night and the Antarctic Circle that has the midnight Sun. At latitude 23° S, called the *Tropic of Capricorn*, the Sun passes through the zenith at noon. Days are longer in the Southern Hemisphere and shorter in the north. In the United States and Southern Europe, there may be only 9 or 10 hours of sunshine during the day. It is winter in the Northern Hemisphere and summer in the Southern Hemisphere.

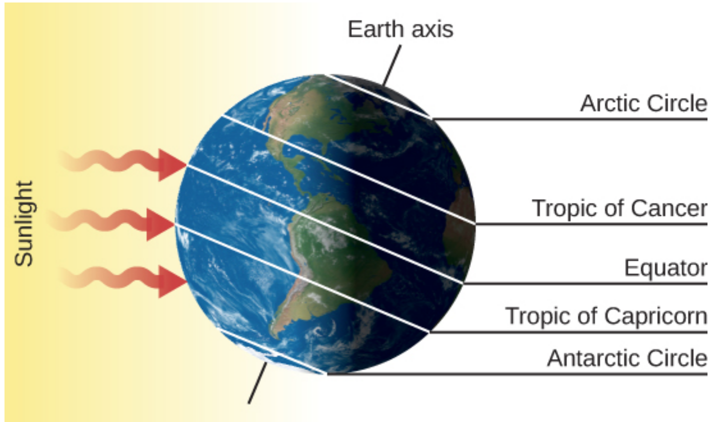


Figure 4.9 Earth on December 21. This is the date of the winter solstice in the Northern Hemisphere. Now the North Pole is in darkness for 24 hours and the South Pole is illuminated. The Sun is at the zenith for observers on the Tropic of Capricorn and thus is low in the sky for the residents of the Northern Hemisphere.

EXAMPLE 4.1

Seasonal Variations

As you can see in Figure 4.8, the Tropic of Cancer is the latitude for which the Sun is directly overhead on the summer solstice. At this time, the Sun is at a declination of 23° N of the celestial equator, and the corresponding latitude on Earth is 23° N of the equator. If Earth were tilted a bit less, then the Tropic of Cancer would be at a lower latitude, closer to the equator.

The Arctic Circle marks the southernmost latitude for which the day length is 24 hours on the day of the summer solstice. This is located at 90° – 23° = 67° N of Earth's equator. If Earth were tilted a bit less, then the Arctic Circle would move farther North. In the limit at which Earth is not tilted at all (its axis is perpendicular to the ecliptic), the Tropic of Cancer would be right on Earth's equator, and the Arctic Circle would simply be the North Pole. Suppose the tilt of Earth's axis were tilted only 5°. What would be the effect on the seasons and the locations of the Tropic of Cancer and Arctic Circle?

Solution

If Earth were tilted less, the seasons would be less extreme. The variation in day length and direct sunlight would be very small over the course of a year, and the Sun's daily path in the sky would not vary much. If Earth were tilted by 5°, the Sun's position on the day of the summer solstice would be 5° N of the celestial equator, so the Tropic of Cancer would be at the corresponding latitude on Earth of 5° N of the Equator. The Arctic Circle would be located at 90° – 5° = 85° N of the equator.

Check Your Learning

Suppose the tilt of Earth's axis were 16°. What, then, would be the difference in latitude between the Arctic Circle and the Tropic of Cancer? What would be the effect on the seasons compared with that produced by the actual tilt of 23°?

Answer:

The Tropic of Cancer is at a latitude equal to Earth's tilt, so in this case, it would be at 16° N latitude. The

Arctic Circle is at a latitude equal to 90° minus Earth's tilt, or 90° – 16° = 74°. The difference between these two latitudes is 74° – 16° = 58°. Since the tilt of Earth is less, there would be less variation in the tilt of Earth and less variation in the Sun's paths throughout the year, so there would be milder seasonal changes.

LINK TO LEARNING

You can see an **animation (https://openstaxcollege.org/l/30anisunpath)** of the Sun's path during the seasons alongside a time-lapse view of light and shadow from a camera set up on the University of Nebraska campus.

Many cultures that developed some distance north of the equator have a celebration around December 21 to help people deal with the depressing lack of sunlight and the often dangerously cold temperatures. Originally, this was often a time for huddling with family and friends, for sharing the reserves of food and drink, and for rituals asking the gods to return the light and heat and turn the cycle of the seasons around. Many cultures constructed elaborate devices for anticipating when the shortest day of the year was coming. Stonehenge in England, built long before the invention of writing, is probably one such device. In our own time, we continue the winter solstice tradition with various holiday celebrations around that December date.

Halfway between the solstices, on about March 21 and September 21, the Sun is on the celestial equator. From Earth, it appears above our planet's equator and favors neither hemisphere. Every place on Earth then receives roughly 12 hours of sunshine and 12 hours of night. The points where the Sun crosses the celestial equator are called the *vernal* (spring) and *autumnal* (fall) *equinoxes*.

The Seasons at Different Latitudes

The seasonal effects are different at different latitudes on Earth. Near the equator, for instance, all seasons are much the same. Every day of the year, the Sun is up half the time, so there are approximately 12 hours of sunshine and 12 hours of night. Local residents define the seasons by the amount of rain (wet season and dry season) rather than by the amount of sunlight. As we travel north or south, the seasons become more pronounced, until we reach extreme cases in the Arctic and Antarctic.

At the North Pole, all celestial objects that are north of the celestial equator are always above the horizon and, as Earth turns, circle around parallel to it. The Sun is north of the celestial equator from about March 21 to September 21, so at the North Pole, the Sun rises when it reaches the vernal equinox and sets when it reaches the autumnal equinox. Each year there are 6 months of sunshine at each pole, followed by 6 months of darkness.

EXAMPLE 4.2

The Position of the Sun in the Sky

The Sun's coordinates on the celestial sphere range from a declination of 23° N of the celestial equator (or +23°) to a declination 23° S of the celestial equator (or –23°). So, the Sun's altitude at noon, when it crosses the meridian, varies by a total of 46°. What is the altitude of the Sun at noon on March 21, as seen from a place on Earth's equator? What is its altitude on June 21, as seen from a place on Earth's equator?

Solution

On Earth's equator, the celestial equator passes through the zenith. On March 21, the Sun is crossing the celestial equator, so it should be found at the zenith (90°) at noon. On June 21, the Sun is 23° N of the celestial equator, so it will be 23° away from the zenith at noon. The altitude above the horizon will be 23° less than the altitude of the zenith (90°), so it is 90° – 23° = 67° above the horizon.

Check Your Learning

What is the altitude of the Sun at noon on December 21, as seen from a place on the Tropic of Cancer?

Answer:

On the day of the winter solstice, the Sun is located about 23° S of the celestial equator. From the Tropic of Cancer, a latitude of 23° N, the zenith would be a declination of 23° N. The difference in declination between zenith and the position of the Sun is 46°, so the Sun would be 46° away from the zenith. That means it would be at an altitude of 90° – 46° = 44°.

Clarifications about the Real World

In our discussions so far, we have been describing the rising and setting of the Sun and stars as they would appear if Earth had little or no atmosphere. In reality, however, the atmosphere has the curious effect of allowing us to see a little way "over the horizon." This effect is a result of *refraction*, the bending of light passing through air or water, something we will discuss in **Astronomical Instruments**. Because of this atmospheric refraction (and the fact that the Sun is not a point of light but a disk), the Sun appears to rise earlier and to set later than it would if no atmosphere were present.

In addition, the atmosphere scatters light and provides some twilight illumination even when the Sun is below the horizon. Astronomers define morning twilight as beginning when the Sun is 18° below the horizon, and evening twilight extends until the Sun sinks more than 18° below the horizon.

These atmospheric effects require small corrections in many of our statements about the seasons. At the equinoxes, for example, the Sun appears to be above the horizon for a few minutes longer than 12 hours, and below the horizon for fewer than 12 hours. These effects are most dramatic at Earth's poles, where the Sun actually can be seen more than a week before it reaches the celestial equator.

You probably know that the summer solstice (June 21) is not the warmest day of the year, even if it is the longest. The hottest months in the Northern Hemisphere are July and August. This is because our weather involves the air and water covering Earth's surface, and these large reservoirs do not heat up instantaneously. You have probably observed this effect for yourself; for example, a pond does not get warm the moment the Sun rises but is warmest late in the afternoon, after it has had time to absorb the Sun's heat. In the same way, Earth gets warmer after it has had a chance to absorb the extra sunlight that is the Sun's summer gift to us. And the coldest times of winter are a month or more after the winter solstice.

4.3 KEEPING TIME

Learning Objectives

By the end of this section, you will be able to:

- Explain the difference between the solar day and the sidereal day
- Explain mean solar time and the reason for time zones

The measurement of time is based on the rotation of Earth. Throughout most of human history, time has been reckoned by positions of the Sun and stars in the sky. Only recently have mechanical and electronic clocks taken over this function in regulating our lives.

The Length of the Day

The most fundamental astronomical unit of time is the day, measured in terms of the rotation of Earth. There is, however, more than one way to define the day. Usually, we think of it as the rotation period of Earth with respect to the Sun, called the **solar day**. After all, for most people sunrise is more important than the rising time of Arcturus or some other star, so we set our clocks to some version of Sun-time. However, astronomers also use a **sidereal day**, which is defined in terms of the rotation period of Earth with respect to the stars.

A solar day is slightly longer than a sidereal day because (as you can see from Figure 4.10) Earth not only turns but also moves along its path around the Sun in a day. Suppose we start when Earth's orbital position is at day 1, with both the Sun and some distant star (located in the direction indicated by the long white arrow pointing left), directly in line with the zenith for the observer on Earth. When Earth has completed one rotation with respect to the distant star and is at day 2, the long arrow again points to the same distant star. However, notice that because of the movement of Earth along its orbit from day 1 to 2, the Sun has not yet reached a position above the observer. To complete a solar day, Earth must rotate an additional amount, equal to 1/365 of a full turn. The time required for this extra rotation is 1/365 of a day, or about 4 minutes. So the solar day is about 4 minutes longer than the sidereal day.

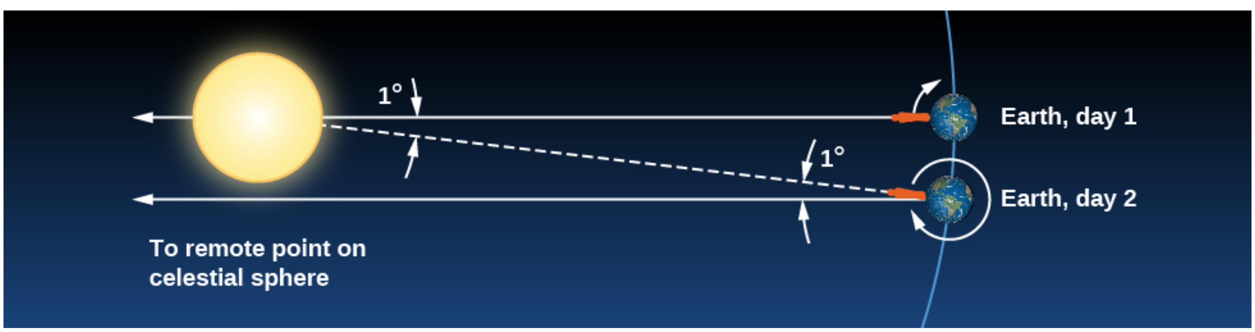


Figure 4.10 Difference Between a Sidereal Day and a Solar Day. This is a top view, looking down as Earth orbits the Sun. Because Earth moves around the Sun (roughly 1° per day), after one complete rotation of Earth relative to the stars, we do not see the Sun in the same position.

Because our ordinary clocks are set to solar time, stars rise 4 minutes earlier each day. Astronomers prefer sidereal time for planning their observations because in that system, a star rises at the same time every day.

EXAMPLE 4.3

Sidereal Time and Solar Time

The Sun makes a complete circle in the sky approximately every 24 hours, while the stars make a complete circle in the sky in 4 minutes less time, or 23 hours and 56 minutes. This causes the positions of the stars at a given time of day or night to change slightly each day. Since stars rise 4 minutes earlier each day, that works out to about 2 hours per month (4 minutes × 30 = 120 minutes or 2 hours). So, if a particular constellation rises at sunset during the winter, you can be sure that by the summer, it will rise about 12 hours earlier, with the sunrise, and it will not be so easily visible in the night sky. Let’s say that tonight the bright star Sirius rises at 7:00 p.m. from a given location so that by midnight, it is very high in the sky. At what time will Sirius rise in three months?

Solution

In three months’ time, Sirius will be rising earlier by:

$$90 \text{ days} \times \frac{4 \text{ minutes}}{\text{day}} = 360 \text{ minutes or } 6 \text{ hours}$$

It will rise at about 1:00 p.m. and be high in the sky at around sunset instead of midnight. Sirius is the brightest star in the constellation of Canis Major (the big dog). So, some other constellation will be prominently visible high in the sky at this later date.

Check Your Learning

If a star rises at 8:30 p.m. tonight, approximately what time will it rise two months from now?

Answer:

In two months, the star will rise:

$$60 \text{ days} \times \frac{4 \text{ minutes}}{\text{day}} = 240 \text{ minutes or } 4 \text{ hours earlier.}$$

This means it will rise at 4:30 p.m.

Apparent Solar Time

We can define **apparent solar time** as time reckoned by the actual position of the Sun in the sky (or, during the night, its position below the horizon). This is the kind of time indicated by sundials, and it probably represents the earliest measure of time used by ancient civilizations. Today, we adopt the middle of the night as the starting point of the day and measure time in hours elapsed since midnight.

During the first half of the day, the Sun has not yet reached the meridian (the great circle in the sky that passes through our zenith). We designate those hours as before midday (*ante meridiem*, or a.m.), before the Sun reaches the local meridian. We customarily start numbering the hours after noon over again and designate them by p.m. (*post meridiem*), after the Sun reaches the local meridian.

Although apparent solar time seems simple, it is not really very convenient to use. The exact length of an apparent solar day varies slightly during the year. The eastward progress of the Sun in its annual journey around the sky is not uniform because the speed of Earth varies slightly in its elliptical orbit. Another complication is that Earth’s axis of rotation is not perpendicular to the plane of its revolution. Thus, apparent solar time does not advance at a uniform rate. After the invention of mechanical clocks that run at a uniform rate, it became necessary to abandon the apparent solar day as the fundamental unit of time.

Mean Solar Time and Standard Time

Instead, we can consider the **mean solar time**, which is based on the average value of the solar day over the course of the year. A mean solar day contains exactly 24 hours and is what we use in our everyday timekeeping. Although mean solar time has the advantage of progressing at a uniform rate, it is still inconvenient for practical use because it is determined by the position of the Sun. For example, noon occurs when the Sun is highest in the sky on the meridian (but not necessarily at the zenith). But because we live on a round Earth, the exact time of noon is different as you change your longitude by moving east or west.

If mean solar time were strictly observed, people traveling east or west would have to reset their watches continually as the longitude changed, just to read the local mean time correctly. For instance, a commuter traveling from Oyster Bay on Long Island to New York City would have to adjust the time on the trip through the East River tunnel because Oyster Bay time is actually about 1.6 minutes more advanced than that of Manhattan. (Imagine an airplane trip in which an obnoxious flight attendant gets on the intercom every minute, saying, “Please reset your watch for local mean time.”)

Until near the end of the nineteenth century, every city and town in the United States kept its own local mean time. With the development of railroads and the telegraph, however, the need for some kind of standardization became evident. In 1883, the United States was divided into four standard time zones (now six, including Hawaii and Alaska), each with one system of time within that zone.

By 1900, most of the world was using the system of 24 standardized global time zones. Within each zone, all places keep the same *standard time*, with the local mean solar time of a standard line of longitude running more or less through the middle of each zone. Now travelers reset their watches only when the time change has amounted to a full hour. Pacific standard time is 3 hours earlier than eastern standard time, a fact that becomes painfully obvious in California when someone on the East Coast forgets and calls you at 5:00 a.m.

Globally, almost all countries have adopted one or more standard time zones, although one of the largest nations, India, has settled on a half-zone, being 5.5 hours from Greenwich standard. Also, China officially uses only one time zone, so all the clocks in that country keep the same time. In Tibet, for example, the Sun rises while the clocks (which keep Beijing time) say it is midmorning already.

Daylight saving time is simply the local standard time of the place plus 1 hour. It has been adopted for spring and summer use in most states in the United States, as well as in many countries, to prolong the sunlight into evening hours, on the apparent theory that it is easier to change the time by government action than it would be for individuals or businesses to adjust their own schedules to produce the same effect. It does not, of course, “save” any daylight at all—because the amount of sunlight is not determined by what we do with our clocks—and its observance is a point of legislative debate in some states.

The International Date Line

The fact that time is always advancing as you move toward the east presents a problem. Suppose you travel eastward around the world. You pass into a new time zone, on the average, about every 15° of longitude you travel, and each time you dutifully set your watch ahead an hour. By the time you have completed your trip, you have set your watch ahead a full 24 hours and thus gained a day over those who stayed at home.

The solution to this dilemma is the **International Date Line**, set by international agreement to run approximately along the 180° meridian of longitude. The date line runs down the middle of the Pacific Ocean, although it jogs a bit in a few places to avoid cutting through groups of islands and through Alaska (**Figure**

4.11). By convention, at the date line, the date of the calendar is changed by one day. Crossing the date line from west to east, thus advancing your time, you compensate by decreasing the date; crossing from east to west, you increase the date by one day. To maintain our planet on a rational system of timekeeping, we simply must accept that the date will differ in different cities at the same time. A good example is the date when the Imperial Japanese Navy bombed Pearl Harbor in Hawaii, known in the United States as Sunday, December 7, 1941, but taught to Japanese students as Monday, December 8.

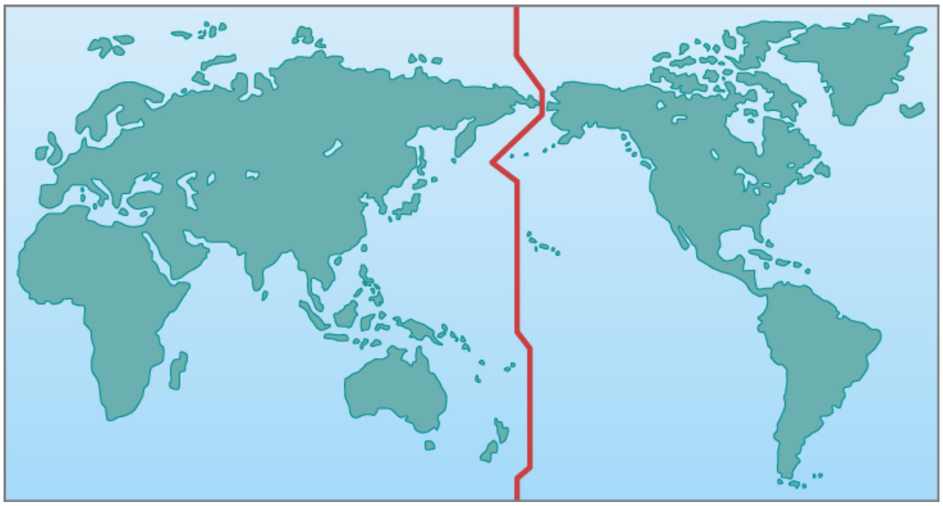


Figure 4.11 Where the Date Changes. The International Date Line is an arbitrarily drawn line on Earth where the date changes. So that neighbors do not have different days, the line is located where Earth's surface is mostly water.

4.4 THE CALENDAR

Learning Objectives

By the end of this section, you will be able to:

- Understand how calendars varied among different cultures
- Explain the origins of our modern calendar

"What's today's date?" is one of the most common questions you can ask (usually when signing a document or worrying about whether you should have started studying for your next astronomy exam). Long before the era of digital watches, smartphones, and fitness bands that tell the date, people used calendars to help measure the passage of time.

The Challenge of the Calendar

There are two traditional functions of any calendar. First, it must keep track of time over the course of long spans, allowing people to anticipate the cycle of the seasons and to honor special religious or personal anniversaries. Second, to be useful to a large number of people, a calendar must use natural time intervals that everyone can agree on—those defined by the motions of Earth, the Moon, and sometimes even the planets. The natural units of our calendar are the *day*, based on the period of rotation of Earth; the *month*, based on the cycle of the Moon's phases (see later in this chapter) about Earth; and the year, based on the period of revolution of Earth about the Sun. Difficulties have resulted from the fact that these three periods are not commensurable; that's a fancy way of saying that one does not divide evenly into any of the others.

The rotation period of Earth is, by definition, 1.0000 day (and here the solar day is used, since that is the basis of human experience). The period required by the Moon to complete its cycle of phases, called the *month*, is

29.5306 days. The basic period of revolution of Earth, called the *tropical year*, is 365.2422 days. The ratios of these numbers are not convenient for calculations. This is the historic challenge of the calendar, dealt with in various ways by different cultures.

Early Calendars

Even the earliest cultures were concerned with the keeping of time and the calendar. Some interesting examples include monuments left by Bronze Age people in northwestern Europe, especially the British Isles. The best preserved of the monuments is Stonehenge, about 13 kilometers from Salisbury in southwest England (**Figure 4.12**). It is a complex array of stones, ditches, and holes arranged in concentric circles. Carbon dating and other studies show that Stonehenge was built during three periods ranging from about 2800 to 1500 BCE. Some of the stones are aligned with the directions of the Sun and Moon during their risings and settings at critical times of the year (such as the summer and winter solstices), and it is generally believed that at least one function of the monument was connected with the keeping of a calendar.

Figure 4.12 Stonehenge. The ancient monument known as Stonehenge was used to keep track of the motions of the Sun and Moon. (credit: modification of work by Adriano Aurelio Araujo)

The Maya in Central America, who thrived more than a thousand years ago, were also concerned with the keeping of time. Their calendar was as sophisticated as, and perhaps more complex than, contemporary calendars in Europe. The Maya did not attempt to correlate their calendar accurately with the length of the year or lunar month. Rather, their calendar was a system for keeping track of the passage of days and for counting time far into the past or future. Among other purposes, it was useful for predicting astronomical events, such as the position of Venus in the sky (**Figure 4.13**).

Figure 4.13 El Caracol. This Mayan observatory at Chichen Itza in the Yucatan, Mexico, dates from around the year 1000. (credit: “wiredtourist.com”/Flickr)

The ancient Chinese developed an especially complex calendar, largely limited to a few privileged hereditary court astronomer-astrologers. In addition to the motions of Earth and the Moon, they were able to fit in the approximately 12-year cycle of Jupiter, which was central to their system of astrology. The Chinese still preserve some aspects of this system in their cycle of 12 “years”—the Year of the Dragon, the Year of the Pig, and so on—that are defined by the position of Jupiter in the zodiac.

Our Western calendar derives from a long history of timekeeping beginning with the Sumerians, dating back to at least the second millennium BCE, and continuing with the Egyptians and the Greeks around the eighth century BCE. These calendars led, eventually, to the *Julian calendar*, introduced by Julius Caesar, which approximated the year at 365.25 days, fairly close to the actual value of 365.2422. The Romans achieved this approximation by declaring years to have 365 days each, with the exception of every fourth year. The *leap year* was to have one extra day, bringing its length to 366 days, and thus making the average length of the year in the Julian calendar 365.25 days.

In this calendar, the Romans had dropped the almost impossible task of trying to base their calendar on the Moon as well as the Sun, although a vestige of older lunar systems can be seen in the fact that our months have an average length of about 30 days. However, lunar calendars remained in use in other cultures, and Islamic calendars, for example, are still primarily lunar rather than solar.

The Gregorian Calendar

Although the Julian calendar (which was adopted by the early Christian Church) represented a great advance, its average year still differed from the true year by about 11 minutes, an amount that accumulates over the centuries to an appreciable error. By 1582, that 11 minutes per year had added up to the point where the first day of spring was occurring on March 11, instead of March 21. If the trend were allowed to continue, eventually the Christian celebration of Easter would be occurring in early winter. Pope Gregory XIII, a contemporary of Galileo, felt it necessary to institute further calendar reform.

The Gregorian calendar reform consisted of two steps. First, 10 days had to be dropped out of the calendar to bring the vernal equinox back to March 21; by proclamation, the day following October 4, 1582, became October 15. The second feature of the new Gregorian calendar was a change in the rule for leap year, making the average length of the year more closely approximate the tropical year. Gregory decreed that three of every four century years—all leap years under the Julian calendar—would be common years henceforth. The rule was that only century years divisible by 400 would be leap years. Thus, 1700, 1800, and 1900—all divisible by 4 but not by 400—were not leap years in the Gregorian calendar. On the other hand, the years 1600 and 2000, both divisible by 400, were leap years. The average length of this Gregorian year, 365.2425 mean solar days, is correct to about 1 day in 3300 years.

The Catholic countries immediately put the Gregorian reform into effect, but countries of the Eastern Church and most Protestant countries did not adopt it until much later. It was 1752 when England and the American colonies finally made the change. By parliamentary decree, September 2, 1752, was followed by September 14. Although special laws were passed to prevent such abuses as landlords collecting a full month's rent for September, there were still riots, and people demanded their 12 days back. Russia did not abandon the Julian calendar until the time of the Bolshevik revolution. The Russians then had to omit 13 days to come into step with the rest of the world. The anniversary of the October Revolution (old calendar) of 1917, bringing the communists to power, thus ended up being celebrated in November (new calendar), a difference that is perhaps not so important since the fall of communism.

4.5 PHASES AND MOTIONS OF THE MOON

Learning Objectives

By the end of this section, you will be able to:

- Explain the cause of the lunar phases
- Understand how the Moon rotates and revolves around Earth

After the Sun, the Moon is the brightest and most obvious object in the sky. Unlike the Sun, it does not shine under its own power, but merely glows with reflected sunlight. If you were to follow its progress in the sky for a month, you would observe a cycle of **phases** (different appearances), with the Moon starting dark and getting more and more illuminated by sunlight over the course of about two weeks. After the Moon's disk becomes fully bright, it begins to fade, returning to dark about two weeks later.

These changes fascinated and mystified many early cultures, which came up with marvelous stories and legends to explain the cycle of the Moon. Even in the modern world, many people don't understand what causes the phases, thinking that they are somehow related to the shadow of Earth. Let us see how the phases can be explained by the motion of the Moon relative to the bright light source in the solar system, the Sun.

Lunar Phases

Although we know that the Sun moves 1/12 of its path around the sky each month, for purposes of explaining the phases, we can assume that the Sun's light comes from roughly the same direction during the course of a four-week lunar cycle. The Moon, on the other hand, moves completely around Earth in that time. As we watch the Moon from our vantage point on Earth, how much of its face we see illuminated by sunlight depends on the angle the Sun makes with the Moon.

Here is a simple experiment to show you what we mean: stand about 6 feet in front of a bright electric light in a completely dark room (or outdoors at night) and hold in your hand a small round object such as a tennis ball or an orange. Your head can then represent Earth, the light represents the Sun, and the ball the Moon. Move the ball around your head (making sure you don't cause an eclipse by blocking the light with your head). You will see phases just like those of the Moon on the ball. (Another good way to get acquainted with the phases and motions of the Moon is to follow our satellite in the sky for a month or two, recording its shape, its direction from the Sun, and when it rises and sets.)

Let's examine the Moon's cycle of phases using **Figure 4.14**, which depicts the Moon's behavior for the entire month. The trick to this figure is that you must imagine yourself standing on Earth, facing the Moon in each of its phases. So, for the position labeled “New,” you are on the right side of Earth and it’s the middle of the day; for the position “Full,” you are on the left side of Earth in the middle of the night. Note that in every position on Figure 4.14, the Moon is half illuminated and half dark (as a ball in sunlight should be). The difference at each position has to do with what part of the Moon faces Earth.

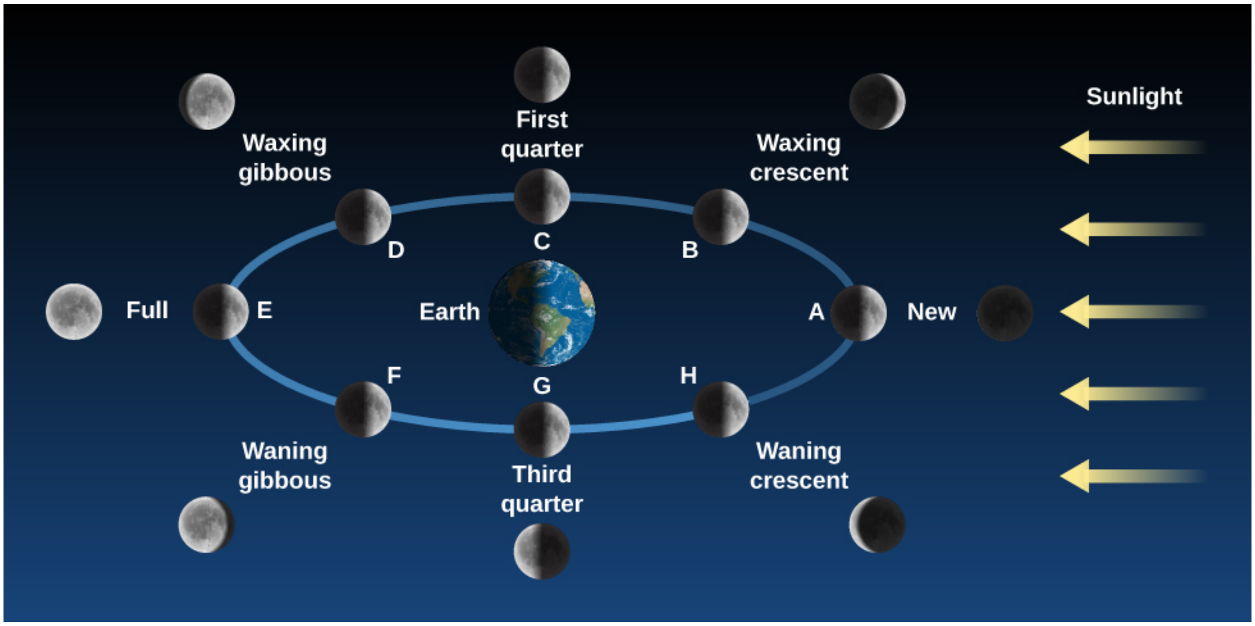


Figure 4.14 Phases of the Moon. The appearance of the Moon changes over the course of a complete monthly cycle. The pictures of the Moon on the white circle show the perspective from space, with the Sun off to the right in a fixed position. The outer images show how the Moon appears to you in the sky from each point in the orbit. Imagine yourself standing on Earth, facing the Moon at each stage. In the position “New,” for example, you are facing the Moon from the right side of Earth in the middle of the day. (Note that the distance of the Moon from Earth is not to scale in this diagram: the Moon is roughly 30 Earth-diameters away from us.) (credit: modification of work by NASA)

The Moon is said to be *new* when it is in the same general direction in the sky as the Sun (position A). Here, its illuminated (bright) side is turned away from us and its dark side is turned toward us. You might say that the Sun is shining on the “wrong ” side of the Moon from our perspective. In this phase the Moon is invisible to us; its dark, rocky surface does not give off any light of its own. Because the new moon is in the same part of the sky as the Sun, it rises at sunrise and sets at sunset.

But the Moon does not remain in this phase long because it moves eastward each day in its monthly path around us. Since it takes about 30 days to orbit Earth and there are 360° in a circle, the Moon will move about 12° in the sky each day (or about 24 times its own diameter). A day or two after the new phase, the thin *crescent* first appears, as we begin to see a small part of the Moon’s illuminated hemisphere. It has moved into a position where it now reflects a little sunlight toward us along one side. The bright crescent increases in size on successive days as the Moon moves farther and farther around the sky away from the direction of the Sun (position B). Because the Moon is moving eastward away from the Sun, it rises later and later each day (like a student during summer vacation).

After about one week, the Moon is one-quarter of the way around its orbit (position C) and so we say it is at the *first quarter* phase. Half of the Moon’s illuminated side is visible to Earth observers. Because of its eastward motion, the Moon now lags about one-quarter of the day behind the Sun, rising around noon and setting around midnight.

During the week after the first quarter phase, we see more and more of the Moon’s illuminated hemisphere (position D), a phase that is called *waxing* (or growing) gibbous (from the Latin *gibbus*, meaning hump). Eventually, the Moon arrives at position E in our figure, where it and the Sun are opposite each other in the sky.

The side of the Moon turned toward the Sun is also turned toward Earth, and we have the *full* phase.

When the Moon is full, it is opposite the Sun in the sky. The Moon does the opposite of what the Sun does, rising at sunset and setting at sunrise. Note what that means in practice: the completely illuminated (and thus very noticeable) Moon rises just as it gets dark, remains in the sky all night long, and sets as the Sun's first rays are seen at dawn. Its illumination throughout the night helps lovers on a romantic stroll and students finding their way back to their dorms after a long night in the library or an off-campus party.

And when is the full moon highest in the sky and most noticeable? At midnight, a time made famous in generations of horror novels and films. (Note how the behavior of a vampire like Dracula parallels the behavior of the full Moon: Dracula rises at sunset, does his worst mischief at midnight, and must be back down in his coffin by sunrise. The old legends were a way of personifying the behavior of the Moon, which was a much more dramatic part of people's lives in the days before electric lights and television.)

Folklore has it that more crazy behavior is seen during the time of the full moon (the Moon even gives a name to crazy behavior—"lunacy"). But, in fact, statistical tests of this "hypothesis" involving thousands of records from hospital emergency rooms and police files do not reveal any correlation of human behavior with the phases of the Moon. For example, homicides occur at the same rate during the new moon or the crescent moon as during the full moon. Most investigators believe that the real story is not that more crazy behavior happens on nights with a full moon, but rather that we are more likely to notice or remember such behavior with the aid of a bright celestial light that is up all night long.

During the two weeks following the full moon, the Moon goes through the same phases again in reverse order (points F, G, and H in **Figure 4.14**), returning to new phase after about 29.5 days. About a week after the full moon, for example, the Moon is at *third quarter*, meaning that it is three-quarters of the way around (not that it is three-quarters illuminated—in fact, half of the visible side of the Moon is again dark). At this phase, the Moon is now rising around midnight and setting around noon.

Note that there is one thing quite misleading about **Figure 4.14**. If you look at the Moon in position E, although it is full in theory, it appears as if its illumination would in fact be blocked by a big fat Earth, and hence we would not see anything on the Moon except Earth's shadow. In reality, the Moon is nowhere near as close to Earth (nor is its path so identical with the Sun's in the sky) as this diagram (and the diagrams in most textbooks) might lead you to believe.

The Moon is actually 30 *Earth-diameters* away from us; **Science and the Universe: A Brief Tour** contains a diagram that shows the two objects to scale. And, since the Moon's orbit is tilted relative to the path of the Sun in the sky, Earth's shadow misses the Moon most months. That's why we regularly get treated to a full moon. The times when Earth's shadow does fall on the Moon are called lunar eclipses and are discussed in **Eclipses of the Sun and Moon**.

MAKING CONNECTIONS

Astronomy and the Days of the Week

The week seems independent of celestial motions, although its length may have been based on the time between quarter phases of the Moon. In Western culture, the seven days of the week are named after the seven "wanderers" that the ancients saw in the sky: the Sun, the Moon, and the five planets visible to the unaided eye (Mercury, Venus, Mars, Jupiter, and Saturn).

In English, we can easily recognize the names Sun-day (Sunday), Moon-day (Monday), and Saturn-day (Saturday), but the other days are named after the Norse equivalents of the Roman gods that gave their names to the planets. In languages more directly related to Latin, the correspondences are clearer. Wednesday, Mercury's day, for example, is *mercoledi* in Italian, *mercredi* in French, and *miércoles* in Spanish. Mars gives its name to Tuesday (*martes* in Spanish), Jupiter or Jove to Thursday (*giovedi* in Italian), and Venus to Friday (*vendredi* in French).

There is no reason that the week has to have seven days rather than five or eight. It is interesting to speculate that if we had lived in a planetary system where more planets were visible without a telescope, the Beatles could have been right and we might well have had "Eight Days a Week."

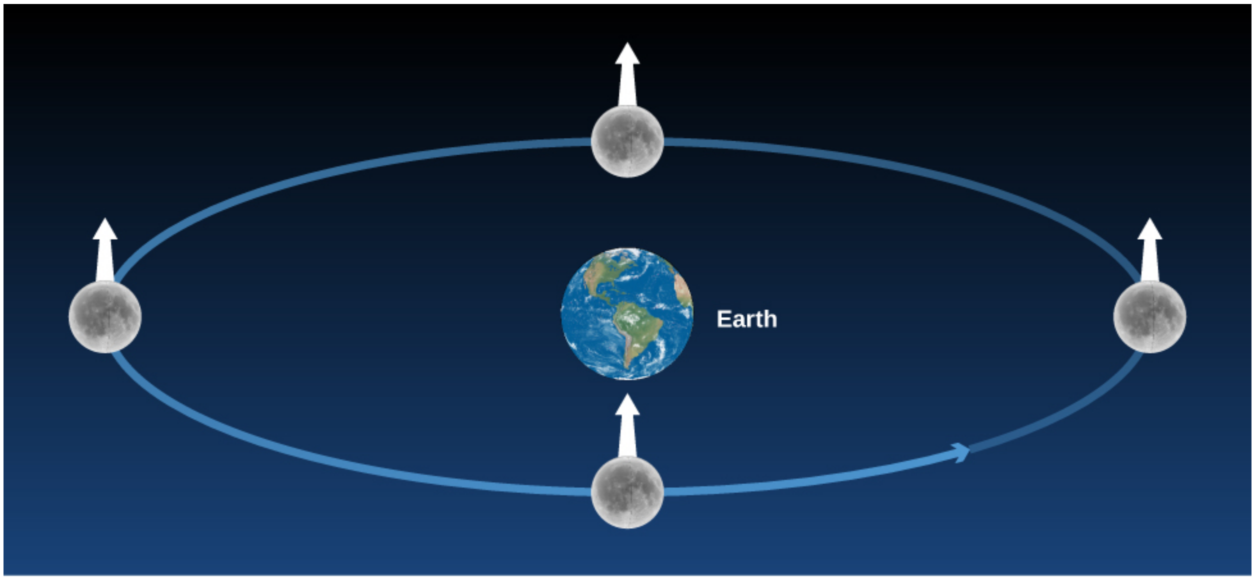
LINK TO LEARNING

View **this animation (https://openstaxcollege.org/l/30phamoonearth)** to see the phases of the Moon as it orbits Earth and as Earth orbits the Sun.

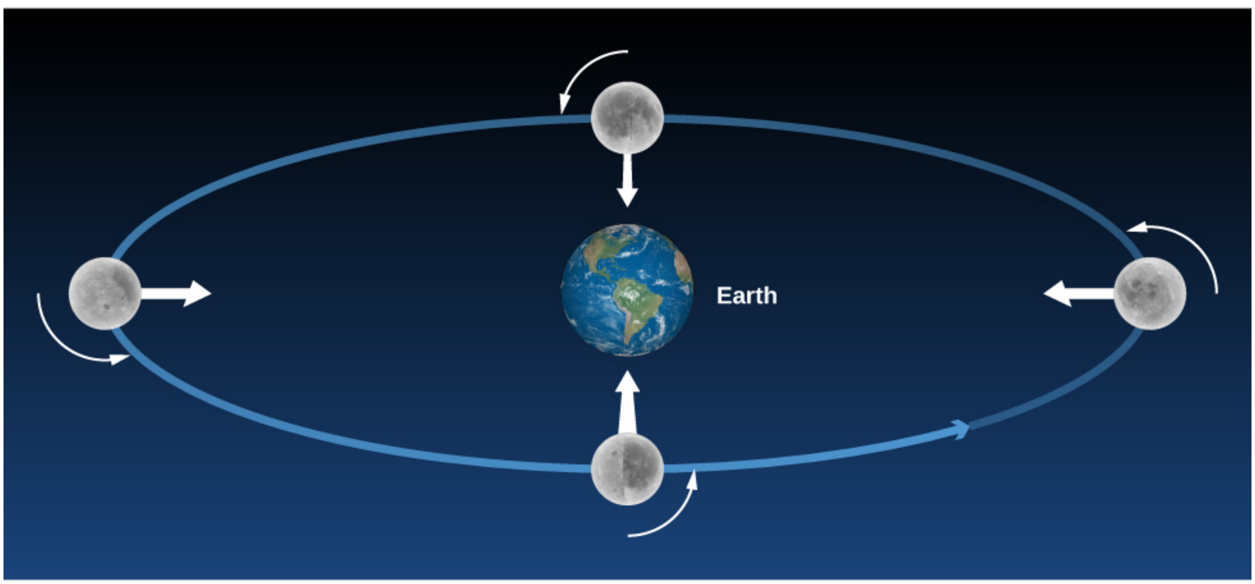
The Moon's Revolution and Rotation

The Moon's sidereal period—that is, the period of its revolution about Earth measured with respect to the stars—is a little over 27 days: the **sidereal month** is 27.3217 days to be exact. The time interval in which the phases repeat—say, from full to full—is the **solar month**, 29.5306 days. The difference results from Earth's motion around the Sun. The Moon must make more than a complete turn around the moving Earth to get back to the same phase with respect to the Sun. As we saw, the Moon changes its position on the celestial sphere rather rapidly: even during a single evening, the Moon creeps visibly eastward among the stars, traveling its own width in a little less than 1 hour. The delay in moonrise from one day to the next caused by this eastward motion averages about 50 minutes.

The Moon *rotates* on its axis in exactly the same time that it takes to *revolve* about Earth. As a consequence, the Moon always keeps the same face turned toward Earth (**Figure 4.15**). You can simulate this yourself by "orbiting" your roommate or another volunteer. Start by facing your roommate. If you make one rotation (spin) with your shoulders in the exact same time that you revolve around him or her, you will continue to face your roommate during the whole "orbit." As we will see in coming chapters, our Moon is not the only world that exhibits this behavior, which scientists call **synchronous rotation**.



(a)



(b)

Figure 4.15 The Moon without and with Rotation. In this figure, we stuck a white arrow into a fixed point on the Moon to keep track of its sides. (a) If the Moon did not rotate as it orbited Earth, it would present all of its sides to our view; hence the white arrow would point directly toward Earth only in the bottom position on the diagram. (b) Actually, the Moon rotates in the same period that it revolves, so we always see the same side (the white arrow keeps pointing to Earth).

The differences in the Moon's appearance from one night to the next are due to changing illumination by the Sun, not to its own rotation. You sometimes hear the back side of the Moon (the side we never see) called the "dark side." This is a misunderstanding of the real situation: which side is light and which is dark changes as the Moon moves around Earth. The back side is dark no more frequently than the front side. Since the Moon rotates, the Sun rises and sets on all sides of the Moon. With apologies to Pink Floyd, there is simply no regular "Dark Side of the Moon."

4.6 OCEAN TIDES AND THE MOON

Learning Objectives

By the end of this section, you will be able to:

- Describe what causes tides on Earth
- Explain why the amplitude of tides changes during the course of a month

Anyone living near the sea is familiar with the twice-daily rising and falling of the **tides**. Early in history, it was clear that tides must be related to the Moon because the daily delay in high tide is the same as the daily delay in the Moon's rising. A satisfactory explanation of the tides, however, awaited the theory of gravity, supplied by Newton.

The Pull of the Moon on Earth

The gravitational forces exerted by the Moon at several points on Earth are illustrated in Figure 4.16. These forces differ slightly from one another because Earth is not a point, but has a certain size: all parts are not equally distant from the Moon, nor are they all in exactly the same direction from the Moon. Moreover, Earth is not perfectly rigid. As a result, the differences among the forces of the Moon's attraction on different parts of Earth (called *differential forces*) cause Earth to distort slightly. The side of Earth nearest the Moon is attracted toward the Moon more strongly than is the center of Earth, which in turn is attracted more strongly than is the side opposite the Moon. Thus, the differential forces tend to stretch Earth slightly into a *prolate spheroid* (a football shape), with its long diameter pointed toward the Moon.

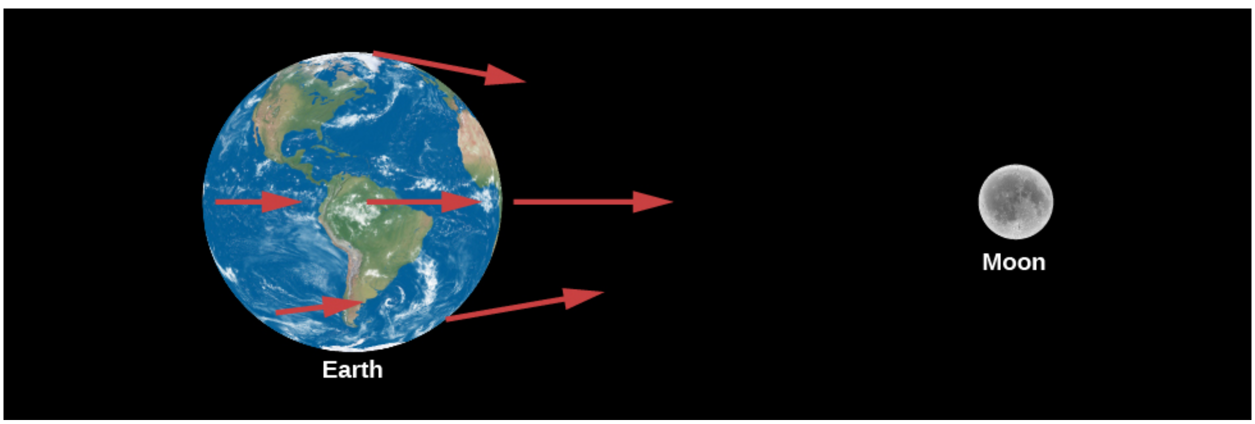


Figure 4.16 Pull of the Moon. The Moon's differential attraction is shown on different parts of Earth. (Note that the differences have been exaggerated for educational purposes.)

If Earth were made of water, it would distort until the Moon's differential forces over different parts of its surface came into balance with Earth's own gravitational forces pulling it together. Calculations show that in this case, Earth would distort from a sphere by amounts ranging up to nearly 1 meter. Measurements of the actual deformation of Earth show that the solid Earth does distort, but only about one-third as much as water would, because of the greater rigidity of Earth's interior.

Because the tidal distortion of the solid Earth amounts—at its greatest—to only about 20 centimeters, Earth does not distort enough to balance the Moon's differential forces with its own gravity. Hence, objects at Earth's surface experience tiny horizontal tugs, tending to make them slide about. These *tide-raising forces* are too insignificant to affect solid objects like astronomy students or rocks in Earth's crust, but they do affect the waters in the oceans.

The Formation of Tides

The tide-raising forces, acting over a number of hours, produce motions of the water that result in measurable tidal bulges in the oceans. Water on the side of Earth facing the Moon flows toward it, with the greatest depths roughly at the point below the Moon. On the side of Earth opposite the Moon, water also flows to produce a tidal bulge (**Figure 4.17**).

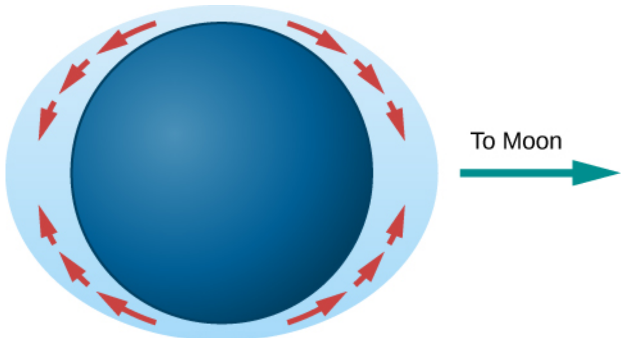


Figure 4.17 Tidal Bulges in an "Ideal" Ocean. Differences in gravity cause tidal forces that push water in the direction of tidal bulges on Earth.

LINK TO LEARNING

You can run this **animation (https://openstaxcollege.org/l/30visdemotidal)** for a visual demonstration of the tidal bulge.

Note that the tidal bulges in the oceans do not result from the Moon's compressing or expanding the water, nor from the Moon's lifting the water "away from Earth." Rather, they result from an actual flow of water over Earth's surface toward the two regions below and opposite the Moon, causing the water to pile up to greater depths at those places (**Figure 4.18**).

Figure 4.18 High and Low Tides. This is a side-by-side comparison of the Bay of Fundy in Canada at high and low tides. (credit a, b: modification of work by Dylan Kereluk)

In the idealized (and, as we shall see, oversimplified) model just described, the height of the tides would be only a few feet. The rotation of Earth would carry an observer at any given place alternately into regions of deeper and shallower water. An observer being carried toward the regions under or opposite the Moon, where the water was deepest, would say, “The tide is coming in”; when carried away from those regions, the observer would say, “The tide is going out.” During a day, the observer would be carried through two tidal bulges (one on each side of Earth) and so would experience two high tides and two low tides.

The Sun also produces tides on Earth, although it is less than half as effective as the Moon at tide raising. The actual tides we experience are a combination of the larger effect of the Moon and the smaller effect of the Sun. When the Sun and Moon are lined up (at new moon or full moon), the tides produced reinforce each other and so are greater than normal (**Figure 4.19**). These are called spring tides (the name is connected not to the season but to the idea that higher tides “spring up”). Spring tides are approximately the same, whether the Sun and Moon are on the same or opposite sides of Earth, because tidal bulges occur on both sides. When the Moon is at first quarter or last quarter (at right angles to the Sun’s direction), the tides produced by the Sun partially cancel the tides of the Moon, making them lower than usual. These are called neap tides.

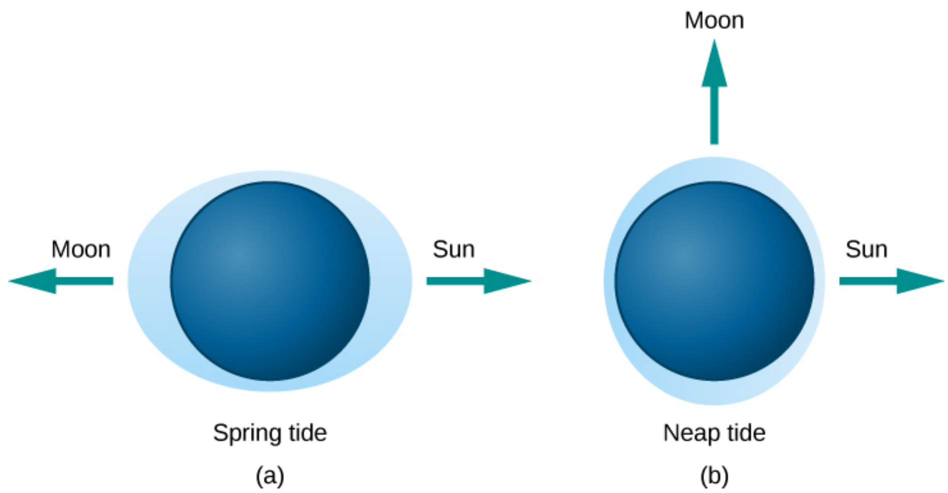


Figure 4.19 Tides Caused by Different Alignments of the Sun and Moon. (a) In spring tides, the Sun’s and Moon’s pulls reinforce each other. (b) In neap tides, the Sun and the Moon pull at right angles to each other and the resulting tides are lower than usual.

The “simple” theory of tides, described in the preceding paragraphs, would be sufficient if Earth rotated very slowly and were completely surrounded by very deep oceans. However, the presence of land masses stopping the flow of water, the friction in the oceans and between oceans and the ocean floors, the rotation of Earth, the wind, the variable depth of the ocean, and other factors all complicate the picture. This is why, in the real world, some places have very small tides while in other places huge tides become tourist attractions. If you have been in such places, you may know that “tide tables” need to be computed and published for each location; one set of tide predictions doesn’t work for the whole planet. In this introductory chapter, we won’t delve further into these complexities.

VOYAGERS IN ASTRONOMY

George Darwin and the Slowing of Earth

The rubbing of water over the face of Earth involves an enormous amount of energy. Over long periods of time, the friction of the tides is slowing down the rotation of Earth. Our day gets longer by about 0.002 second each century. That seems very small, but such tiny changes can add up over millions and billions of years.

Although Earth's spin is slowing down, the angular momentum (see **Orbits and Gravity**) in a system such as the Earth-Moon system cannot change. Thus, some other spin motion must speed up to take the extra angular momentum. The details of what happens were worked out over a century ago by George Darwin, the son of naturalist Charles Darwin. George Darwin (see **Figure 4.20**) had a strong interest in science but studied law for six years and was admitted to the bar. However, he never practiced law, returning to science instead and eventually becoming a professor at Cambridge University. He was a protégé of Lord Kelvin, one of the great physicists of the nineteenth century, and he became interested in the long-term evolution of the solar system. He specialized in making detailed (and difficult) mathematical calculations of how orbits and motions change over geologic time.

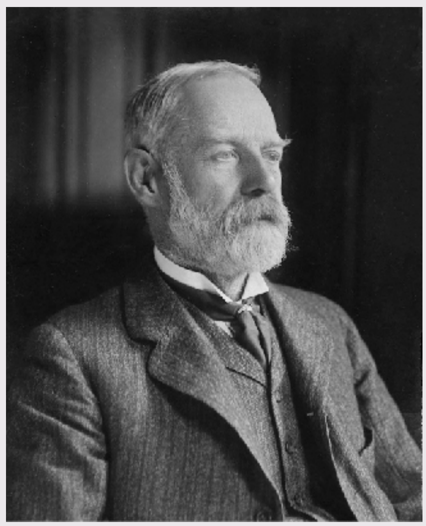


Figure 4.20 George Darwin (1845–1912). George Darwin is best known for studying Earth's spin in relation to angular momentum.

What Darwin calculated for the Earth-Moon system was that the Moon will slowly spiral outward, away from Earth. As it moves farther away, it will orbit less quickly (just as planets farther from the Sun move more slowly in their orbits). Thus, the month will get longer. Also, because the Moon will be more distant, total eclipses of the Sun will no longer be visible from Earth.

Both the day and the month will continue to get longer, although bear in mind that the effects are very gradual. Darwin's calculations were confirmed by mirrors placed on the Moon by Apollo 11 astronauts. These show that the Moon is moving away by 3.8 centimeters per year, and that ultimately—billions of years in the future—the day and the month will be the same length (about 47 of our present days). At this point the Moon will be stationary in the sky over the same spot on Earth, meaning some parts of Earth will see the Moon and its phases and other parts will never see them. This kind of alignment is already true for Pluto's moon Charon (among others). Its rotation and orbital period are the same length as a day on Pluto.

4.7 ECLIPSES OF THE SUN AND MOON

Learning Objectives

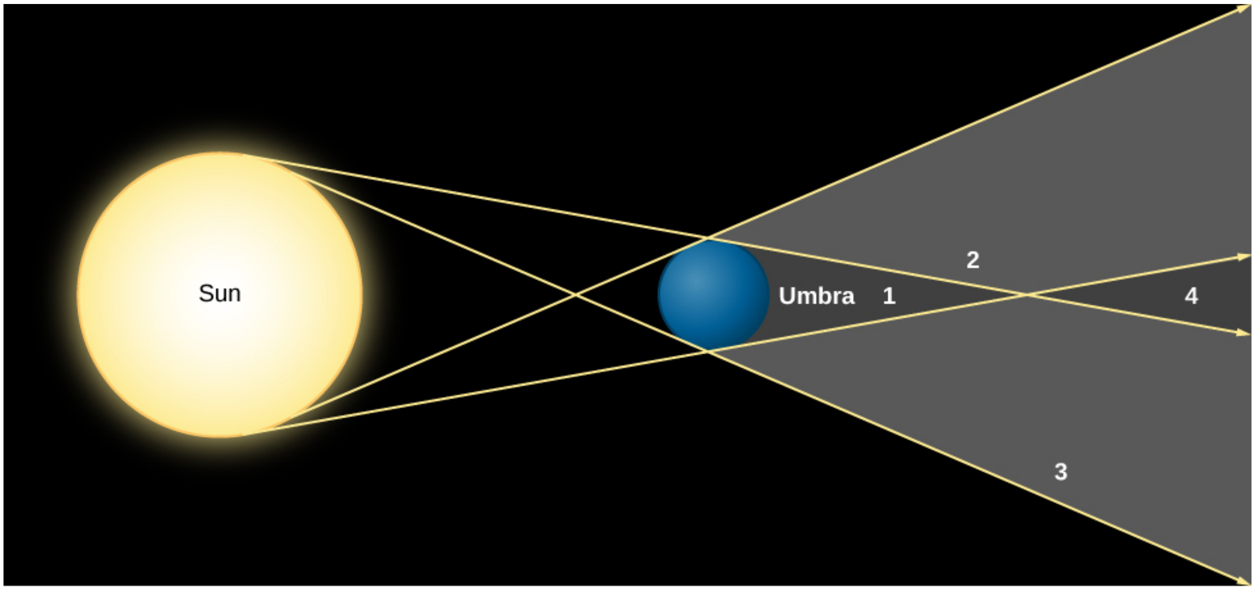
By the end of this section, you will be able to:

- Describe what causes lunar and solar eclipses
- Differentiate between a total and partial solar eclipse
- Explain why lunar eclipses are much more common than solar eclipses

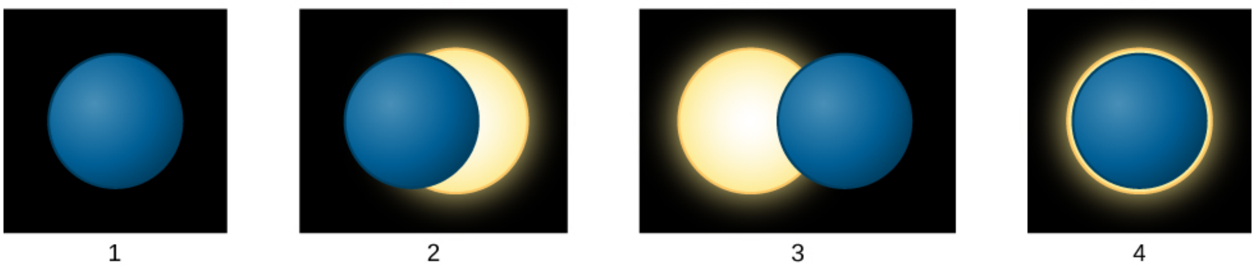
One of the coincidences of living on Earth at the present time is that the two most prominent astronomical objects, the Sun and the Moon, have nearly the same apparent size in the sky. Although the Sun is about 400 times larger in diameter than the Moon, it is also about 400 times farther away, so both the Sun and the Moon have the same angular size—about 1/2°. As a result, the Moon, as seen from Earth, can appear to cover the Sun, producing one of the most impressive events in nature.

Any solid object in the solar system casts a shadow by blocking the light of the Sun from a region behind it. This shadow in space becomes apparent whenever another object moves into it. In general, an *eclipse* occurs whenever any part of either Earth or the Moon enters the shadow of the other. When the Moon's shadow strikes Earth, people within that shadow see the Sun at least partially covered by the Moon; that is, they witness a **solar eclipse**. When the Moon passes into the shadow of Earth, people on the night side of Earth see the Moon darken in what is called a **lunar eclipse**. Let's look at how these happen in more detail.

The shadows of Earth and the Moon consist of two parts: a cone where the shadow is darkest, called the *umbra*, and a lighter, more diffuse region of darkness called the *penumbra*. As you can imagine, the most spectacular eclipses occur when an object enters the umbra. Figure 4.21 illustrates the appearance of the Moon's shadow and what the Sun and Moon would look like from different points within the shadow.



(a)



(b)

Figure 4.21 Solar Eclipse. (a) The shadow cast by a spherical body (the Moon, for example) is shown. Notice the dark umbra and the lighter penumbra. Four points in the shadow are labeled with numbers. In (b) you see what the Sun and Moon would look like in the sky at the four labeled points. At position 1, you see a total eclipse. At positions 2 and 3, the eclipse is partial. At position 4, the Moon is farther away and thus cannot cover the Sun completely; a ring of light thus shows around the Sun, creating what is called an "annular" eclipse.

If the path of the Moon in the sky were identical to the path of the Sun (the ecliptic), we might expect to see an eclipse of the Sun and the Moon each month—whenever the Moon got in front of the Sun or into the shadow of Earth. However, as we mentioned, the Moon's orbit is tilted relative to the plane of Earth's orbit about the Sun by about 5° (imagine two hula hoops with a common center, but tilted a bit). As a result, during most months, the Moon is sufficiently above or below the ecliptic plane to avoid an eclipse. But when the two paths cross (twice a year), it is then "eclipse season" and eclipses are possible.

Eclipses of the Sun

The apparent or angular sizes of both the Sun and Moon vary slightly from time to time as their distances from Earth vary. (**Figure 4.21** shows the distance of the observer varying at points A–D, but the idea is the same.) Much of the time, the Moon looks slightly smaller than the Sun and cannot cover it completely, even if the two are perfectly aligned. In this type of "annular eclipse," there is a ring of light around the dark sphere of the Moon.

However, if an eclipse of the Sun occurs when the Moon is somewhat nearer than its average distance, the Moon can completely hide the Sun, producing a *total* solar eclipse. Another way to say it is that a total eclipse of the Sun occurs at those times when the umbra of the Moon's shadow reaches the surface of Earth.

The geometry of a total solar eclipse is illustrated in **Figure 4.22**. If the Sun and Moon are properly aligned, then the Moon's darkest shadow intersects the ground at a small point on Earth's surface. Anyone on Earth within the small area covered by the tip of the Moon's shadow will, for a few minutes, be unable to see the Sun and will witness a total eclipse. At the same time, observers on a larger area of Earth's surface who are in the penumbra will see only a part of the Sun eclipsed by the Moon: we call this a *partial* solar eclipse.

Between Earth's rotation and the motion of the Moon in its orbit, the tip of the Moon's shadow sweeps eastward at about 1500 kilometers per hour along a thin band across the surface of Earth. The thin zone across Earth within which a total solar eclipse is visible (weather permitting) is called the eclipse path. Within a region about 3000 kilometers on either side of the eclipse path, a partial solar eclipse is visible. It does not take long for the Moon's shadow to sweep past a given point on Earth. The duration of totality may be only a brief instant; it can never exceed about 7 minutes.

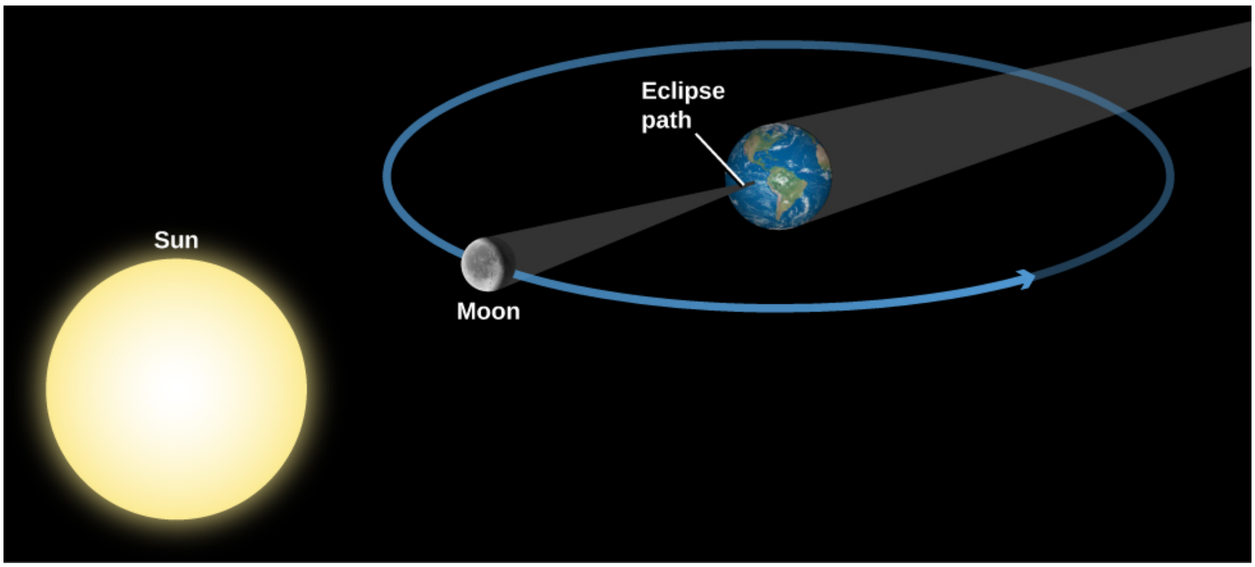


Figure 4.22 Geometry of a Total Solar Eclipse. Note that our diagram is not to scale. The Moon blocks the Sun during new moon phase as seen from some parts of Earth and casts a shadow on our planet.

Because a total eclipse of the Sun is so spectacular, it is well worth trying to see one if you can. There are some people whose hobby is "eclipse chasing" and who brag about how many they have seen in their lifetimes. Because much of Earth's surface is water, eclipse chasing can involve lengthy boat trips (and often requires air travel as well). As a result, eclipse chasing is rarely within the budget of a typical college student. Nevertheless, a list of future eclipses is given for your reference in **Appendix H**, just in case you strike it rich early. (And, as you can see in the Appendix, there will be total eclipses visible in the United States in 2017 and 2024, to which even college students may be able to afford travel.)

Appearance of a Total Eclipse

What can you see if you are lucky enough to catch a total eclipse? A solar eclipse starts when the Moon just begins to silhouette itself against the edge of the Sun's disk. A partial phase follows, during which more and more of the Sun is covered by the Moon. About an hour after the eclipse begins, the Sun becomes completely hidden behind the Moon. In the few minutes immediately before this period of totality begins, the sky noticeably darkens, some flowers close up, and chickens may go to roost. As an eerie twilight suddenly descends during the day, other animals (and people) may get disoriented. During totality, the sky is dark enough that planets become visible in the sky, and usually the brighter stars do as well.

As the bright disk of the Sun becomes entirely hidden behind the Moon, the Sun's remarkable corona flashes into view (**Figure 4.23**). The *corona* is the Sun's outer atmosphere, consisting of sparse gases that extend for millions of miles in all directions from the apparent surface of the Sun. It is ordinarily not visible because the light of the corona is feeble compared with the light from the underlying layers of the Sun. Only when the brilliant glare from the Sun's visible disk is blotted out by the Moon during a total eclipse is the pearly white corona visible. (We'll talk more about the corona in the chapter on **The Sun: A Garden-Variety Star**.)

Figure 4.23 The Sun's Corona. The corona (thin outer atmosphere) of the Sun is visible during a total solar eclipse. (It looks more extensive in photographs than it would to the unaided eye.) (credit: modification of work by Lutfar Rahman Nirjhar)

The total phase of the eclipse ends, as abruptly as it began, when the Moon begins to uncover the Sun. Gradually, the partial phases of the eclipse repeat themselves, in reverse order, until the Moon has completely uncovered the Sun. We should make one important safety point here: while the few minutes of the *total* eclipse are safe to look at, if any part of the Sun is uncovered, you must protect your eyes with safe eclipse glasses[2] or by projecting an image of the Sun (instead of looking at it directly). For more, read the **How to Observe Solar Eclipses** box in this chapter.

Eclipses of the Moon

A lunar eclipse occurs when the Moon enters the shadow of Earth. The geometry of a lunar eclipse is shown in **Figure 4.24**. Earth's dark shadow is about 1.4 million kilometers long, so at the Moon's distance (an average of 384,000 kilometers), it could cover about four full moons. Unlike a solar eclipse, which is visible only in certain local areas on Earth, a lunar eclipse is visible to everyone who can see the Moon. Because a lunar eclipse can be seen (weather permitting) from the entire night side of Earth, lunar eclipses are observed far more frequently from a given place on Earth than are solar eclipses.

2 Eclipse glasses are available in many planetarium and observatory gift stores, and also from the two main U.S. manufacturers: American Paper Optics and Rainbow Symphony.

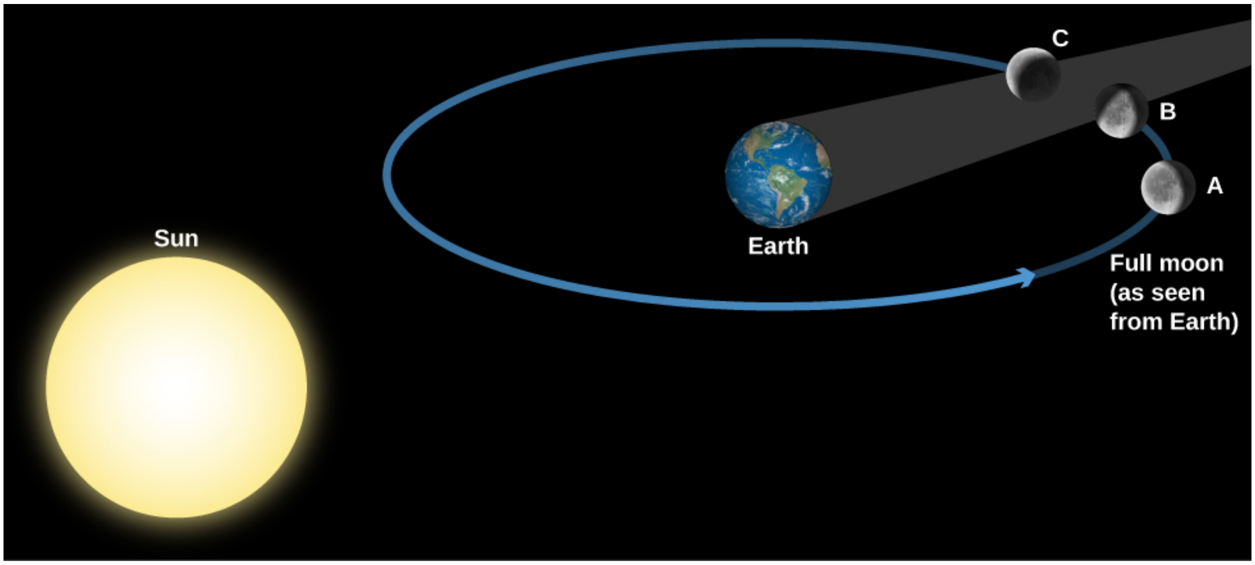


Figure 4.24 Geometry of a Lunar Eclipse. The Moon is shown moving through the different parts of Earth's shadow during a total lunar eclipse. Note that the distance the Moon moves in its orbit during the eclipse has been exaggerated here for clarity.

An eclipse of the Moon is total only if the Moon's path carries it though Earth's umbra. If the Moon does not enter the umbra completely, we have a partial eclipse of the Moon. But because Earth is larger than the Moon, its umbra is larger, so that lunar eclipses last longer than solar eclipses, as we will discuss below.

A lunar eclipse can take place only when the Sun, Earth, and Moon are in a line. The Moon is opposite the Sun, which means the Moon will be in full phase before the eclipse, making the darkening even more dramatic. About 20 minutes before the Moon reaches the dark shadow, it dims somewhat as Earth partly blocks the sunlight. As the Moon begins to dip into the shadow, the curved shape of Earth's shadow upon it soon becomes apparent.

Even when totally eclipsed, the Moon is still faintly visible, usually appearing a dull coppery red. The illumination on the eclipsed Moon is sunlight that has been bent into Earth's shadow by passing through Earth's atmosphere.

After totality, the Moon moves out of the shadow and the sequence of events is reversed. The total duration of the eclipse depends on how closely the Moon's path approaches the axis of the shadow. For an eclipse where the Moon goes through the center of Earth's shadow, each partial phase consumes at least 1 hour, and totality can last as long as 1 hour and 40 minutes. Eclipses of the Moon are much more "democratic" than solar eclipses. Since the full moon is visible on the entire night side of Earth, the lunar eclipse is visible for all those who live in that hemisphere. (Recall that a total eclipse of the Sun is visible only in a narrow path where the shadow of the umbra falls.) Total eclipses of the Moon occur, on average, about once every two or three years. A list of future total eclipses of the Moon is in **Appendix H**. In addition, since the lunar eclipse happens to a full moon, and a full moon is not dangerous to look at, everyone can look at the Moon during all the parts of the eclipse without worrying about safety.

Thanks to our understanding of gravity and motion (see **Orbits and Gravity**), eclipses can now be predicted centuries in advance. We've come a long way since humanity stood frightened by the darkening of the Sun or the Moon, fearing the displeasure of the gods. Today, we enjoy the sky show with a healthy appreciation of the majestic forces that keep our solar system running.

SEEING FOR YOURSELF

How to Observe Solar Eclipses

A total eclipse of the Sun is a spectacular sight and should not be missed. However, it is extremely dangerous to look directly at the Sun: even a brief exposure can damage your eyes. Normally, few rational people are tempted to do this because it is painful (and something your mother told you never to do!). But during the partial phases of a solar eclipse, the temptation to take a look is strong. Think before you give in. The fact that the Moon is covering part of the Sun doesn’t make the uncovered part any less dangerous to look at. Still, there are perfectly safe ways to follow the course of a solar eclipse, if you are lucky enough to be in the path of the shadow.

The easiest technique is to make a pinhole projector. Take a piece of cardboard with a small (1 millimeter) hole punched in it, and hold it several feet above a light surface, such as a concrete sidewalk or a white sheet of paper, so that the hole is “aimed” at the Sun. The hole produces a fuzzy but adequate image of the eclipsed Sun. Alternatively, if it’s the right time of year, you can let the tiny spaces between a tree’s leaves form multiple pinhole images against a wall or sidewalk. Watching hundreds of little crescent Suns dancing in the breeze can be captivating. A kitchen colander also makes an excellent pinhole projector.

Although there are safe filters for looking at the Sun directly, people have suffered eye damage by looking through improper filters, or no filter at all. For example, neutral density photographic filters are not safe because they transmit infrared radiation that can cause severe damage to the retina. Also unsafe are smoked glass, completely exposed color film, sunglasses, and many other homemade filters. Safe filters include welders’ goggles and specially designed eclipse glasses.

You should certainly look at the Sun directly when it is totally eclipsed, even through binoculars or telescopes. Unfortunately, the total phase, as we discussed, is all too brief. But if you know when it is coming and going, be sure you look, for it’s an unforgettably beautiful sight. And, despite the ancient folklore that presents eclipses as dangerous times to be outdoors, the partial phases of eclipses—as long as you are not looking directly at the Sun—are not any more dangerous than being out in sunlight.

During past eclipses, unnecessary panic has been created by uninformed public officials acting with the best intentions. There were two marvelous total eclipses in Australia in the twentieth century during which townspeople held newspapers over their heads for protection and schoolchildren cowered indoors with their heads under their desks. What a pity that all those people missed what would have been one of the most memorable experiences of their lifetimes.

On August 21, 2017, there will be a total solar eclipse visible across a large swath of the continental United States. The path the Moon’s shadow will cast is shown in **Figure 4.25**.

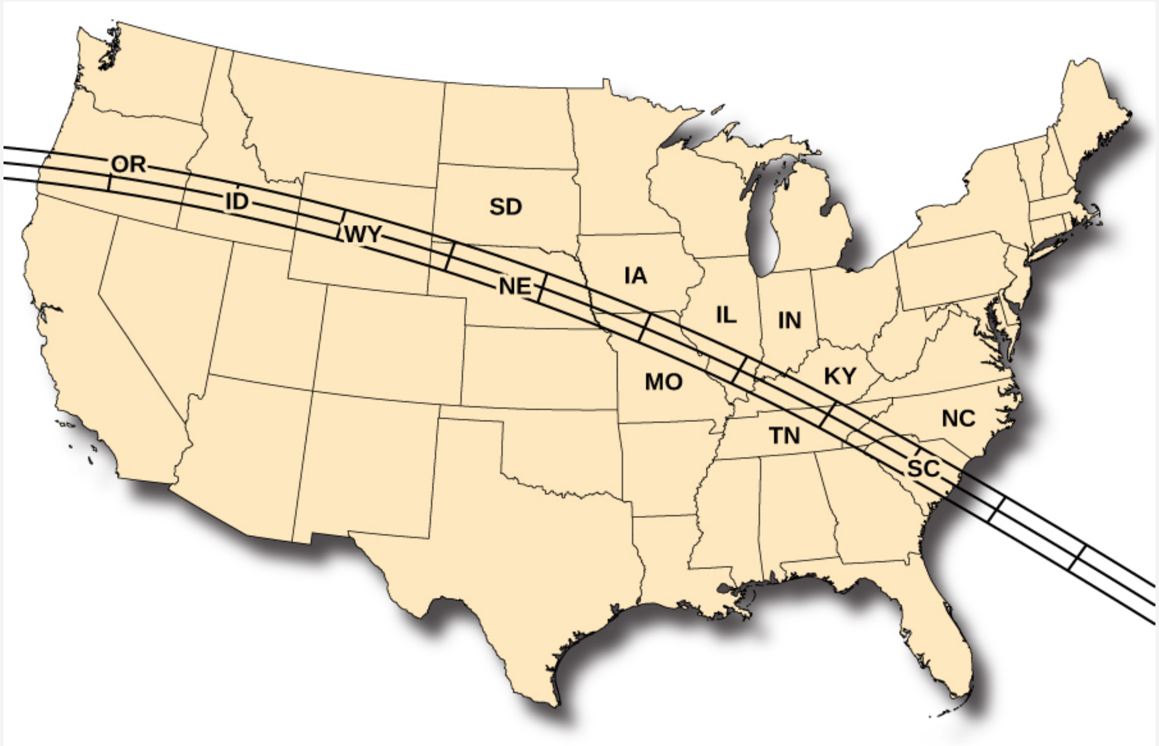


Figure 4.25 2017 Total Solar Eclipse. This map of the United States shows the path of the total solar eclipse of 2017. On August 21, 2017, the shadow will first cross onto the West Coast near Portland, Oregon, traversing the United States and exiting the East Coast in South Carolina approximately 90 minutes later, covering about 3000 miles in the process. (credit: modification of work by NASA)

Since the eclipse path is not more than a one-day drive for most people in the United States, this would be a prime opportunity to witness this extraordinary spectacle.

LINK TO LEARNING

Check out this **useful booklet (https://openstaxcollege.org/l/302017ecliboo)** about the 2017 eclipse (with specific times in different locations).

CHAPTER 4 REVIEW

KEY TERMS

apparent solar time time as measured by the position of the Sun in the sky (the time that would be indicated by a sundial)

declination the angular distance north or south of the celestial equator

great circle a circle on the surface of a sphere that is the curve of intersection of the sphere with a plane passing through its center

International Date Line an arbitrary line on the surface of Earth near longitude 180° across which the date changes by one day

lunar eclipse an eclipse of the Moon, in which the Moon moves into the shadow of Earth; lunar eclipses can occur only at the time of full moon

mean solar time time based on the rotation of Earth; mean solar time passes at a constant rate, unlike apparent solar time

meridian a great circle on the terrestrial or celestial sphere that passes through the poles

phases of the Moon the different appearance of light and dark on the Moon as seen from Earth during its monthly cycle, from new moon to full moon and back to new moon

right ascension the coordinate for measuring the east-west positions of celestial bodies; the angle measured eastward along the celestial equator from the vernal equinox to the hour circle passing through a body

sidereal day Earth's rotation period as defined by the positions of the stars in the sky; the time between successive passages of the same star through the meridian

sidereal month the period of the Moon's revolution about Earth measured with respect to the stars

solar day Earth's rotation period as defined by the position of the Sun in the sky; the time between successive passages of the Sun through the meridian

solar eclipse an eclipse of the Sun by the Moon, caused by the passage of the Moon in front of the Sun; solar eclipses can occur only at the time of the new moon

solar month the time interval in which the phases repeat—say, from full to full phase

synchronous rotation when a body (for example, the Moon) rotates at the same rate that it revolves around another body

tides alternate rising and falling of sea level caused by the difference in the strength of the Moon's gravitational pull on different parts of Earth

SUMMARY

4.1 Earth and Sky

The terrestrial system of latitude and longitude makes use of the great circles called meridians. Longitude is arbitrarily set to 0° at the Royal Observatory at Greenwich, England. An analogous celestial coordinate system is called right ascension (RA) and declination, with 0° of declination starting at the vernal equinox. These coordinate systems help us locate any object on the celestial sphere. The Foucault pendulum is a way to demonstrate that Earth is turning.

4.2 The Seasons

The familiar cycle of the seasons results from the 23.5° tilt of Earth's axis of rotation. At the summer solstice, the Sun is higher in the sky and its rays strike Earth more directly. The Sun is in the sky for more than half of the day and can heat Earth longer. At the winter solstice, the Sun is low in the sky and its rays come in at more of an angle; in addition, it is up for fewer than 12 hours, so those rays have less time to heat. At the vernal and autumnal equinoxes, the Sun is on the celestial equator and we get about 12 hours of day and night. The seasons are different at different latitudes.

4.3 Keeping Time

The basic unit of astronomical time is the day—either the solar day (reckoned by the Sun) or the sidereal day (reckoned by the stars). Apparent solar time is based on the position of the Sun in the sky, and mean solar time is based on the average value of a solar day during the year. By international agreement, we define 24 time zones around the world, each with its own standard time. The convention of the International Date Line is necessary to reconcile times on different parts of Earth.

4.4 The Calendar

The fundamental problem of the calendar is to reconcile the incommensurable lengths of the day, month, and year. Most modern calendars, beginning with the Roman (Julian) calendar of the first century BCE, neglect the problem of the month and concentrate on achieving the correct number of days in a year by using such conventions as the leap year. Today, most of the world has adopted the Gregorian calendar established in 1582 while finding ways to coexist with the older lunar calendars' system of months.

4.5 Phases and Motions of the Moon

The Moon's monthly cycle of phases results from the changing angle of its illumination by the Sun. The full moon is visible in the sky only during the night; other phases are visible during the day as well. Because its period of revolution is the same as its period of rotation, the Moon always keeps the same face toward Earth.

4.6 Ocean Tides and the Moon

The twice-daily ocean tides are primarily the result of the Moon's differential force on the material of Earth's crust and ocean. These tidal forces cause ocean water to flow into two tidal bulges on opposite sides of Earth; each day, Earth rotates through these bulges. Actual ocean tides are complicated by the additional effects of the Sun and by the shape of the coasts and ocean basins.

4.7 Eclipses of the Sun and Moon

The Sun and Moon have nearly the same angular size (about 1/2°). A solar eclipse occurs when the Moon moves between the Sun and Earth, casting its shadow on a part of Earth's surface. If the eclipse is total, the light from the bright disk of the Sun is completely blocked, and the solar atmosphere (the corona) comes into view. Solar eclipses take place rarely in any one location, but they are among the most spectacular sights in nature. A lunar eclipse takes place when the Moon moves into Earth's shadow; it is visible (weather permitting) from the entire night hemisphere of Earth.

FOR FURTHER EXPLORATION

Articles

Bakich, M. "Your Twenty-Year Solar Eclipse Planner." *Astronomy* (October 2008): 74. Describes the circumstances of upcoming total eclipses of the Sun.

Coco, M. "Not Just Another Pretty Phase." *Astronomy* (July 1994): 76. Moon phases explained.

Espenak, F., & Anderson, J. "Get Ready for America's Coast to Coast Experience." *Sky & Telescope* (February 2016): 22.

Gingerich, O. "Notes on the Gregorian Calendar Reform." *Sky & Telescope* (December 1982): 530.

Kluepfel, C. "How Accurate Is the Gregorian Calendar?" *Sky & Telescope* (November 1982): 417.

Krupp, E. "Calendar Worlds." *Sky & Telescope* (January 2001): 103. On how the days of the week got their names.

Krupp, E. "Behind the Curve." *Sky & Telescope* (September 2002): 68. On the reform of the calendar by Pope Gregory XIII.

MacRobert, A., & Sinnott, R. "Young Moon Hunting." *Sky & Telescope* (February 2005): 75. Hints for finding the Moon as soon after its new phase as possible.

Pasachoff, J. "Solar Eclipse Science: Still Going Strong." *Sky & Telescope* (February 2001): 40. On what we have learned and are still learning from eclipses.

Regas, D. "The Quest for Totality." *Sky & Telescope* (July 2012): 36. On eclipse chasing as a hobby.

Schaefer, B. "Lunar Eclipses That Changed the World." *Sky & Telescope* (December 1992): 639.

Schaefer, B. "Solar Eclipses That Changed the World." *Sky & Telescope* (May 1994): 36.

Websites

Ancient Observatories, Timeless Knowledge (Stanford Solar Center): **http://solar-center.stanford.edu/AO/ (http://solar-center.stanford.edu/AO/)** . An introduction to ancient sites where the movements of celestial objects were tracked over the years (with a special focus on tracking the Sun).

Astronomical Data Services: **http://aa.usno.navy.mil/data/index.php (http://aa.usno.navy.mil/data/index.php)** . This rich site from the U.S. Naval Observatory has information about Earth, the Moon, and the sky, with tables and online calculators.

Calendars through the Ages: **http://www.webexhibits.org/calendars/index.html (http://www.webexhibits.org/calendars/index.html)** . Like a good museum exhibit on the Web.

Calendar Zone: **http://www.calendarzone.com/ (http://www.calendarzone.com/)** . Everything you wanted to ask or know about calendars and timekeeping, with links from around the world.

Eclipse 2017 Information and Safe Viewing Instructions: **http://www.nsta.org/publications/press/extras/files/solarscience/SolarScienceInsert.pdf (http://www.nsta.org/publications/press/extras/files/solarscience/SolarScienceInsert.pdf)** .

Eclipse Maps: **http://www.eclipse-maps.com/Eclipse-Maps/Welcome.html (http://www.eclipse-maps.com/Eclipse-Maps/Welcome.html)** . Michael Zeiler specializes in presenting helpful and interactive maps of where solar eclipses will be visible

Eclipse Predictions: **http://astro.unl.edu/classaction/animations/lunarcycles/eclipsetable.html**

(http://astro.unl.edu/classaction/animations/lunarcycles/eclipsetable.html) . This visual calendar provides dates for upcoming solar and lunar eclipses through 2029.EclipseWise: **http://www.eclipsewise.com/intro.html (http://www.eclipsewise.com/intro.html)** . An introductory site on future eclipses and eclipse observing by NASA's Fred Espenak.

History of the International Date Line: **http://www.staff.science.uu.nl/~gent0113/idl/idl.htm (http://www.staff.science.uu.nl/~gent0113/idl/idl.htm)** . From R. H. van Gent at Utrecht University in the Netherlands.

Lunacy and the Full Moon: **http://www.scientificamerican.com/article/lunacy-and-the-full-moon/ (http://www.scientificamerican.com/article/lunacy-and-the-full-moon/)** . This *Scientific American* article explores whether the Moon's phase is related to strange behavior.

Moon Phase Calculator: **https://stardate.org/nightsky/moon (https://stardate.org/nightsky/moon)** . Keep track of the phases of the Moon with this calendar.

NASA Eclipse Website: **http://eclipse.gsfc.nasa.gov/eclipse.html (http://eclipse.gsfc.nasa.gov/eclipse.html)** . This site, by NASA's eclipse expert Fred Espenak, contains a wealth of information on lunar and solar eclipses, past and future, as well as observing and photography links.

Phases of the Moon Gallery and Information: **http://astropixels.com/moon/phases/phasesgallery.html (http://astropixels.com/moon/phases/phasesgallery.html)** . Photographs and descriptions presented by NASA's Fred Espenak.

Time and Date Website: **http://www.timeanddate.com/ (http://www.timeanddate.com/)** . Comprehensive resource about how we keep time on Earth; has time zone converters and many other historical and mathematical tools.

Walk through Time: The Evolution of Time Measurement through the Ages (National Institute of Standards and Technology): **http://www.nist.gov/pml/general/time/ (http://www.nist.gov/pml/general/time/)** .

Videos

Bill Nye, the Science Guy, Explains the Seasons: **https://www.youtube.com/watch?v=KUU7IyfR34o (https://www.youtube.com/watch?v=KUU7IyfR34o)** . For kids, but college students can enjoy the bad jokes, too (4:45).

Geography Lesson Idea: Time Zones: **https://www.youtube.com/watch?v=-j-SWKtWEcU (https://www.youtube.com/watch?v=-j-SWKtWEcU)** . (3:11).

How to View a Solar Eclipse: **http://www.exploratorium.edu/eclipse/how-to-view-eclipse (http://www.exploratorium.edu/eclipse/how-to-view-eclipse)** . (1:35).

Shadow of the Moon: **https://www.youtube.com/watch?v=XNcfKUJwnjM (https://www.youtube.com/watch?v=XNcfKUJwnjM)** . This NASA video explains eclipses of the Sun, with discussion and animation, focusing on a 2015 eclipse, and shows what an eclipse looks like from space (1:54).

Strangest Time Zones in the World: **https://www.youtube.com/watch?v=uW6QqcmCfm8 (https://www.youtube.com/watch?v=uW6QqcmCfm8)** . (8:38).

Understanding Lunar Eclipses: **https://www.youtube.com/watch?v=lNi5UFpales (https://www.youtube.com/watch?v=lNi5UFpales)** . This NASA video explains why there isn't an eclipse every month, with good animation (1:58).

COLLABORATIVE GROUP ACTIVITIES

A. Have your group brainstorm about other ways (besides the Foucault pendulum) you could prove that it is our Earth that is turning once a day, and not the sky turning around us. (Hint: How does the spinning of Earth affect the oceans and the atmosphere?)

B. What would the seasons on Earth be like if Earth's axis were not tilted? Discuss with your group how many things about life on Earth you think would be different.

C. After college and graduate training, members of your U.S. student group are asked to set up a school in New Zealand. Describe some ways your yearly school schedule in the Southern Hemisphere would differ from what students are used to in the Northern Hemisphere.

D. During the traditional U.S. Christmas vacation weeks, you are sent to the vicinity of the South Pole on a research expedition (depending on how well you did on your astronomy midterm, either as a research assistant or as a short-order cook!). Have your group discuss how the days and nights will be different there and how these differences might affect you during your stay.

E. Discuss with your group all the stories you have heard about the full moon and crazy behavior. Why do members of your group think people associate crazy behavior with the full moon? What other legends besides vampire stories are connected with the phases of the Moon? (Hint: Think Professor Lupin in the Harry Potter stories, for example.)

F. Your college town becomes the founding site for a strange new cult that worships the Moon. These true believers gather regularly around sunset and do a dance in which they must extend their arms in the direction of the Moon. Have your group discuss which way their arms will be pointing at sunset when the Moon is new, first quarter, full, and third quarter.

G. Changes of the seasons play a large part in our yearly plans and concerns. The seasons have inspired music, stories, poetry, art, and much groaning from students during snowstorms. Search online to come up with some examples of the seasons being celebrated or overcome in fields other than science.

H. Use the information in **Appendix H** and online to figure out when the next eclipse of the Sun or eclipse of the Moon will be visible from where your group is going to college or from where your group members live. What time of day will the eclipse be visible? Will it be a total or partial eclipse? What preparations can you make to have an enjoyable and safe eclipse experience? How do these preparations differ between a solar and lunar eclipse?

I. On Mars, a day (often called a sol) is 24 hours and 40 minutes. Since Mars takes longer to go around the Sun, a year is 668.6 sols. Mars has two tiny moons, Phobos and Deimos. Phobos, the inner moon, rises in the west and sets in the east, taking 11 hours from moonrise to the next moonrise. Using your calculators and imaginations, have your group members come up with a calendar for Mars. (After you do your own, and only after, you can search online for the many suggestions that have been made for a martian calendar over the years.)

EXERCISES

Review Questions

1. Discuss how latitude and longitude on Earth are similar to declination and right ascension in the sky.
2. What is the latitude of the North Pole? The South Pole? Why does longitude have no meaning at the North and South Poles?
3. Make a list of each main phase of the Moon, describing roughly when the Moon rises and sets for each phase. During which phase can you see the Moon in the middle of the morning? In the middle of the afternoon?
4. What are advantages and disadvantages of apparent solar time? How is the situation improved by introducing mean solar time and standard time?
5. What are the two ways that the tilt of Earth's axis causes the summers in the United States to be warmer than the winters?
6. Why is it difficult to construct a practical calendar based on the Moon's cycle of phases?
7. Explain why there are two high tides and two low tides each day. Strictly speaking, should the period during which there are two high tides be 24 hours? If not, what should the interval be?
8. What is the phase of the Moon during a total solar eclipse? During a total lunar eclipse?
9. On a globe or world map, find the nearest marked latitude line to your location. Is this an example of a great circle? Explain.
10. Explain three lines of evidence that indicate that the seasons in North America are not caused by the changing Earth-Sun distance as a result of Earth's elliptical orbit around the Sun.
11. What is the origin of the terms "a.m." and "p.m." in our timekeeping?
12. Explain the origin of the leap year. Why is it necessary?
13. Explain why the year 1800 was not a leap year, even though years divisible by four are normally considered to be leap years.
14. What fraction of the Moon's visible face is illuminated during first quarter phase? Why is this phase called first quarter?
15. Why don't lunar eclipses happen during every full moon?
16. Why does the Moon create tidal bulges on both sides of Earth instead of only on the side of Earth closest to the Moon?
17. Why do the heights of the tides change over the course of a month?
18. Explain how tidal forces are causing Earth to slow down.
19. Explain how tidal forces are causing the Moon to slowly recede from Earth.
20. Explain why the Gregorian calendar modified the nature of the leap year from its original definition in the Julian calendar.

21. The term *equinox* translates as "equal night." Explain why this translation makes sense from an astronomical point of view.

22. The term *solstice* translates as "Sun stop." Explain why this translation makes sense from an astronomical point of view.

23. Why is the warmest day of the year in the United States (or in the Northern Hemisphere temperate zone) usually in August rather than on the day of the summer solstice, in late June?

Thought Questions

24. When Earth's Northern Hemisphere is tilted toward the Sun during June, some would argue that the cause of our seasons is that the Northern Hemisphere is physically closer to the Sun than the Southern Hemisphere, and this is the primary reason the Northern Hemisphere is warmer. What argument or line of evidence could contradict this idea?

25. Where are you on Earth if you experience each of the following? (Refer to the discussion in **Observing the Sky: The Birth of Astronomy** as well as this chapter.)

- **A.** The stars rise and set perpendicular to the horizon.
- **B.** The stars circle the sky parallel to the horizon.
- **C.** The celestial equator passes through the zenith.
- **D.** In the course of a year, all stars are visible.
- **E.** The Sun rises on March 21 and does not set until September 21 (ideally).

26. In countries at far northern latitudes, the winter months tend to be so cloudy that astronomical observations are nearly impossible. Why can't good observations of the stars be made at those places during the summer months?

27. What is the phase of the Moon if it . . .

- **A.** rises at 3:00 p.m.?
- **B.** is highest in the sky at sunrise?
- **C.** sets at 10:00 a.m.?

28. A car accident occurs around midnight on the night of a full moon. The driver at fault claims he was blinded momentarily by the Moon rising on the eastern horizon. Should the police believe him?

29. The secret recipe to the ever-popular veggie burgers in the college cafeteria is hidden in a drawer in the director's office. Two students decide to break in to get their hands on it, but they want to do it a few hours before dawn on a night when there is no Moon, so they are less likely to be caught. What phases of the Moon would suit their plans?

30. Your great-great-grandfather, who often exaggerated events in his own life, once told your relatives about a terrific adventure he had on February 29, 1900. Why would this story make you suspicious?

31. One year in the future, when money is no object, you enjoy your birthday so much that you want to have another one right away. You get into your supersonic jet. Where should you and the people celebrating with you travel? From what direction should you approach? Explain.

32. Suppose you lived in the crater Copernicus on the side of the Moon facing Earth.
    - **A.** How often would the Sun rise?
    - **B.** How often would Earth set?
    - **C.** During what fraction of the time would you be able to see the stars?
33. In a lunar eclipse, does the Moon enter the shadow of Earth from the east or west side? Explain.
34. Describe what an observer at the crater Copernicus would see while the Moon is eclipsed on Earth. What would the same observer see during what would be a total solar eclipse as viewed from Earth?
35. The day on Mars is 1.026 Earth-days long. The martian year lasts 686.98 Earth-days. The two moons of Mars take 0.32 Earth-day (for Phobos) and 1.26 Earth-days (for Deimos) to circle the planet. You are given the task of coming up with a martian calendar for a new Mars colony. Would a solar or lunar calendar be better for tracking the seasons?
36. What is the right ascension and declination of the vernal equinox?
37. What is the right ascension and declination of the autumnal equinox?
38. What is the right ascension and declination of the Sun at noon on the summer solstice in the Northern Hemisphere?
39. During summer in the Northern Hemisphere, the North Pole is illuminated by the Sun 24 hours per day. During this time, the temperature often does not rise above the freezing point of water. Explain why.
40. On the day of the vernal equinox, the day length for all places on Earth is actually slightly longer than 12 hours. Explain why.
41. Regions north of the Arctic Circle are known as the "land of the midnight Sun." Explain what this means from an astronomical perspective.
42. In a part of Earth's orbit where Earth is moving faster than usual around the Sun, would the length of the sidereal day change? If so, how? Explain.
43. In a part of Earth's orbit where Earth is moving faster than usual around the Sun, would the length of the solar day change? If so, how? Explain.
44. If Sirius rises at 8:00 p.m. tonight, at what time will it rise tomorrow night, to the nearest minute? Explain.
45. What are three lines of evidence you could use to indicate that the phases of the Moon are not caused by the shadow of Earth falling on the Moon?
46. If the Moon rises at a given location at 6:00 p.m. today, about what time will it rise tomorrow night?
47. Explain why some solar eclipses are total and some are annular.
48. Why do lunar eclipses typically last much longer than solar eclipses?

Figuring For Yourself

49. Suppose Earth took exactly 300.0 days to go around the Sun, and everything else (the day, the month) was the same. What kind of calendar would we have? How would this affect the seasons?
50. Consider a calendar based entirely on the day and the month (the Moon's period from full phase to full phase). How many days are there in a month? Can you figure out a scheme analogous to leap year to make this calendar work?

51. If a star rises at 8:30 p.m. tonight, approximately what time will it rise two months from now?

52. What is the altitude of the Sun at noon on December 22, as seen from a place on the Tropic of Cancer?

53. Show that the Gregorian calendar will be in error by 1 day in about 3300 years.