The Cosmic Perspective

Bennett Donahue Schneider Voit

Seventh Edition

Pearson New International Edition

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We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.
—*T. S. Eliot*

Far from city lights on a clear night, you can gaze upward at a sky filled with stars. Lie back and watch for a few hours, and you will observe the stars marching steadily across the sky. Confronted by the seemingly infinite heavens, you might wonder how Earth and the universe came to be. If you do, you will be sharing an experience common to humans around the world and in thousands of generations past.

Modern science offers answers to many of our fundamental questions about the universe and our place within it. We now know the basic content and scale of the universe. We know the age of Earth and the approximate age of the universe. And, although much remains to be discovered, we are rapidly learning how the simple ingredients of the early universe developed into the incredible diversity of life on Earth.

In this chapter, we will survey the scale, history, and motion of the universe. This "big picture" perspective on our universe will provide a base on which you'll be able to build a deeper understanding.

1 THE SCALE OF THE UNIVERSE

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

The historical path to this knowledge was long and complex. The ancient belief in an Earth-centered (or *geocentric*) universe changed only when people were confronted by strong evidence to the contrary, and the method of learning that we call *science* enabled us to acquire this evidence. To start, it's useful to have a general picture of the universe as we know it today.

What is our place in the universe?

Take a look at the remarkable photo that opens this chapter. This photo, taken by the Hubble Space Telescope, shows a piece of the sky so small that you could block your view of it with a grain of sand held at arm's length. Yet it encompasses an almost unimaginable expanse of both space and time: Nearly every object within it is a *galaxy* filled with billions of stars, and some of the smaller smudges are galaxies so far away that their light has taken billions of years to reach us. Let's begin our study of astronomy by exploring what a photo like this one tells us about our own place in the universe.

Our Cosmic Address The galaxies that we see in the Hubble Space Telescope photo are just one of several levels of structure in our universe. A good way to build context on these levels is to consider what we might call our "cosmic address," illustrated in **FIGURE 1**.

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

Our solar system belongs to the huge, disk-shaped collection of stars called the **Milky Way Galaxy**. A **galaxy** is a great island of stars in space, containing between a few hundred million and a trillion or more stars. The Milky Way is a relatively large galaxy, containing more than 100 billion stars. Our solar system is located a little over halfway from the galactic center to the edge of the galactic disk.

Billions of other galaxies are scattered throughout space. Some galaxies are fairly isolated, but many others are found in groups. Our Milky Way, for example, is one of the two largest among about 40 galaxies in the **Local Group.** Groups of galaxies with more than a few dozen members are often called **galaxy clusters.**

On a very large scale, galaxies and galaxy clusters appear to be arranged in giant chains and sheets with huge voids between them; the background of Figure 1 shows this large-scale structure. The regions in which galaxies and galaxy clusters are most tightly packed are called **superclusters,** which are essentially clusters of galaxy clusters. Our Local Group is located in the outskirts of the Local Supercluster.

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

THINK ABOUT IT

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

Astronomical Distance Measurements Notice that Figure 1 is labeled with an approximate size for each structure in kilometers. In astronomy, many of the distances are so large that kilometers are not the most convenient unit. Instead, we often use two other units:

- One **astronomical unit (AU)** is Earth's average distance from the Sun, which is about 150 million kilometers (93 million miles). We commonly describe distances within our solar system in astronomical units.
- One **light-year (ly)** is the distance that light can travel in 1 year, which is about 10 trillion kilometers (6 trillion miles). We generally use light-years to describe the distances of stars and galaxies.

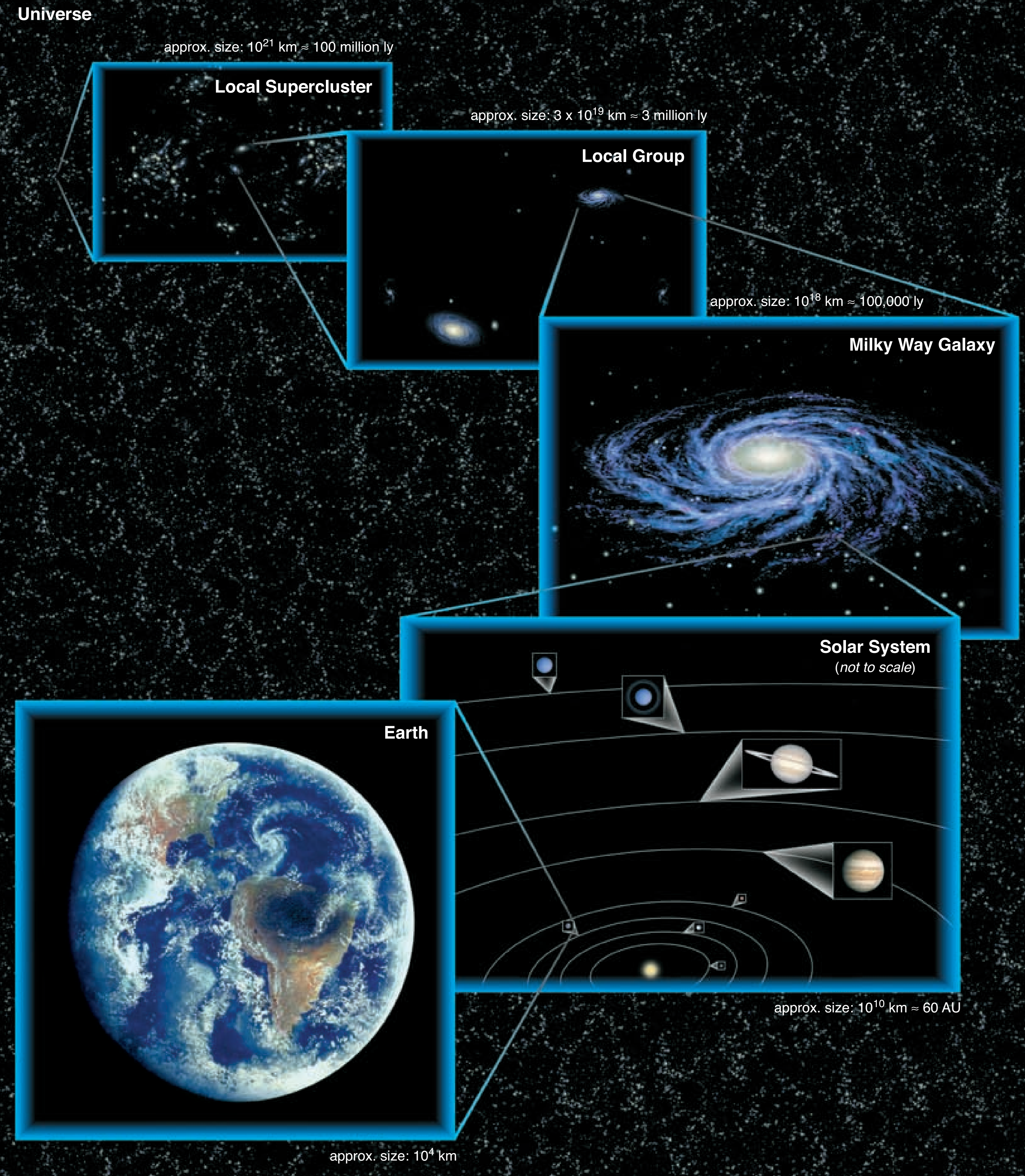


FIGURE 1 Our cosmic address. These diagrams show key levels of structure in our universe.

Be sure to note that a light-year is a unit of *distance*, not of time. Light travels at the speed of light, which is 300,000 kilometers per second. We therefore say that one *light-second* is about 300,000 kilometers, because that is the distance light travels in one second. Similarly, one light-minute is the distance that light travels in one minute, one light-hour is the distance that light travels in one hour, and so on. Mathematical Insight 1 shows that light travels about 10 trillion kilometers in one year, so that distance represents a light-year.

Looking Back in Time The speed of light is extremely fast by earthly standards. It is so fast that if you could make light go in circles, it could circle Earth nearly eight times in a single second. Nevertheless, even light takes time to travel the vast distances in space. Light takes a little more than 1 second to reach Earth from the Moon, and about 8 minutes to reach Earth from the Sun. Stars are so far away that their light takes years to reach us, which is why we measure their distances in light-years.

Consider Sirius, the brightest star in the night sky, which is located about 8 light-years away. Because it takes light 8 years to travel this distance, we see Sirius not as it is today, but rather as it was 8 years ago. The effect is more dramatic at greater distances. The Orion Nebula (FIGURE 2) is a giant cloud in which stars and planets are forming. It is located about 1500 light-years from Earth, which means we see it as it looked about 1500 years ago—about the time of the fall of the Roman Empire. If any major events have occurred in the Orion Nebula since that time, we cannot yet know about them because the light from these events has not yet reached us.

The general idea that light takes time to travel through space leads to a remarkable fact:

> *The farther away we look in distance, the further back we look in time.*

The Andromeda Galaxy (FIGURE 3) is about 2.5 million light-years away, which means we see it as it looked about 2.5 million years ago. We see more distant galaxies as they were even further in the past. Some of the galaxies in the Hubble Space Telescope photo that opens the chapter are billions of light-years away, meaning we see them as they were billions of years ago.

SEE IT FOR YOURSELF

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

Basic Astronomical Definitions

ASTRONOMICAL OBJECTS

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

planet A moderately large object that orbits a star and shines primarily by reflecting light from its star. According to a definition adopted in 2006, an object can be considered a planet only if it (1) orbits a star, (2) is large enough for its own gravity to make it round, and (3) has cleared most other objects from its orbital path. An object that meets the first two criteria but has not cleared its orbital path, like Pluto, is designated a **dwarf planet.**

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

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

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

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

COLLECTIONS OF ASTRONOMICAL OBJECTS

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

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

galaxy A great island of stars in space, containing from a few hundred million to a trillion or more stars, all held together by gravity and orbiting a common center.

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

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

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

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

ASTRONOMICAL DISTANCE UNITS

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

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

TERMS RELATING TO MOTION

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

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

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

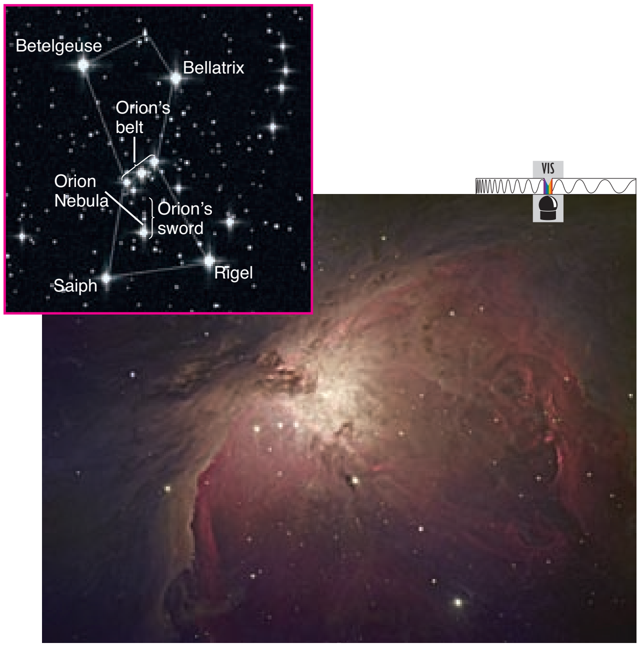


FIGURE 2 The Orion Nebula, located about 1500 light-years away. The inset shows its location in the constellation Orion.

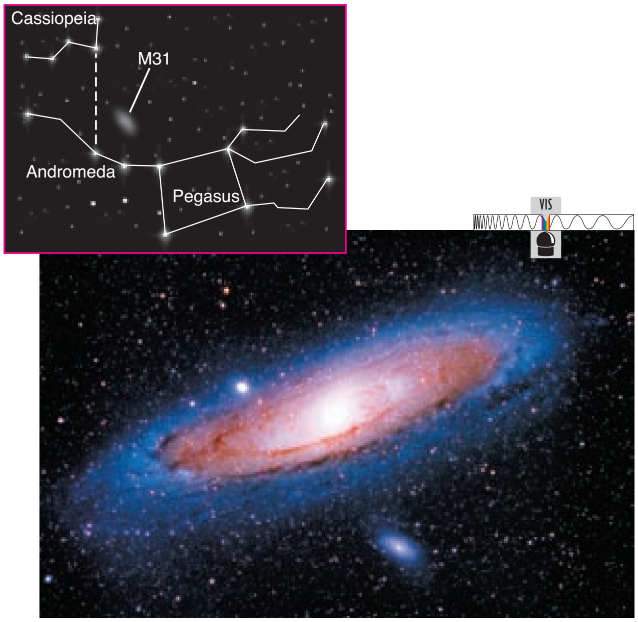


FIGURE 3 The Andromeda Galaxy (M31). When we look at this galaxy, we see light that has been traveling through space for 2.5 million years.

It's also amazing to realize that any "snapshot" of a distant galaxy is a picture of both space and time. For example, because the Andromeda Galaxy is about 100,000 light-years in diameter, the light we currently see from the far side of the galaxy must have left on its journey to us some 100,000 years before the light we see from the near side. Figure 3 therefore shows different parts of the galaxy spread over a time period of 100,000 years. When we study the universe, it is impossible to separate space and time.

The Observable Universe As we'll discuss in Section 2, astronomers estimate that the universe is about 14 billion years old. This fact, combined with the fact that looking deep into space means looking far back in time, places a limit on the portion of the universe that we can see, even in principle.

FIGURE 4 shows the idea. If we look at a galaxy that is 7 billion light-years away, we see it as it looked 7 billion years ago*—which means we see it as it was when the universe was half its current age. If we look at a galaxy that is 12 billion light-years away (like the most distant ones in the Hubble Space Telescope photo), we see it as it was 12 billion years ago, when the universe was only 2 billion years old. And if we tried to look beyond 14 billion light-years, we'd be looking to a time more than 14 billion years ago—which is before the universe existed and therefore means that there is nothing to see. This distance of 14 billion light-years therefore marks the boundary (or *horizon*) of our **observable universe**—the portion of the entire universe that we can potentially observe. Note that this fact does not put any limit on the size of the

*Distances to faraway galaxies must be defined carefully in an expanding universe; distances like those given here are based on the time it has taken a galaxy's light to reach us (called the *lookback time*).

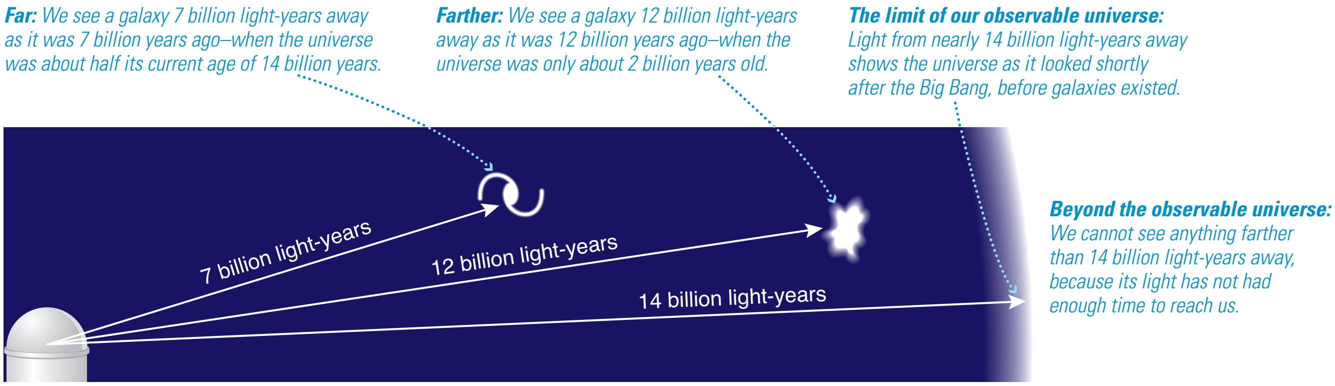


FIGURE 4 **interactive figure** The farther away we look in space, the further back we look in time. The age of the universe therefore puts a limit on the size of the *observable* universe—the portion of the entire universe that we can observe, at least in principle.

COMMON MISCONCEPTIONS

The Meaning of a Light-Year

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

entire universe, which may be far larger than our observable universe. We simply have no hope of seeing or studying anything beyond the bounds of our observable universe.

MA® Scale of the Universe Tutorial, Lessons 1–3

How big is the universe?

Figure 1 put numbers on the sizes of different structures in the universe, but these numbers have little meaning for most people—after all, they are literally astronomical. Therefore, to help you develop a greater appreciation of our modern view of the universe, we'll discuss a few ways of putting these numbers into perspective.

The Scale of the Solar System One of the best ways to develop perspective on cosmic sizes and distances is to imagine our solar system shrunk down to a scale that would allow you to walk through it. The Voyage scale model solar system in Washington, D.C., makes such a walk possible (**FIGURE 5**). The Voyage model shows the Sun and the planets, and the distances between them, at *one ten-billionth* of their actual sizes and distances.

FIGURE 6a shows the Sun and planets at their correct sizes (but not distances) on the Voyage scale. The model Sun is about the size of a large grapefruit, Jupiter is about the size of a marble, and Earth is about the size of the ball point in a pen. You can immediately see some key facts about our solar system. For example, the Sun is far larger than any of the planets; in mass, the Sun outweighs all the planets combined by a factor of nearly 1000. The planets also vary considerably in size: The storm on Jupiter known as the Great Red Spot (visible near Jupiter's lower left in the painting) could swallow up the entire Earth.

The scale of the solar system is even more remarkable when you combine the sizes shown in Figure 6a with the distances illustrated by the map of the Voyage model in **FIGURE 6b**. For example, the ball-point-size Earth is located about 15 meters (16.5 yards) from the grapefruit-size Sun, which means you can picture Earth's orbit as a circle of radius 15 meters around a grapefruit.

MATHEMATICAL INSIGHT 1

How Far Is a Light-Year? An Introduction to Astronomical Problem Solving

MA® Math Review Video: Problem Solving Part 1

We can develop greater insight into astronomical ideas by applying mathematics. The key to using mathematics is to approach problems in a clear and organized way. One simple approach uses the following three steps:

Step 1 Understand the problem: Ask yourself what the solution will look like (for example, what units will it have? will it be big or small?) and what information you need to solve the problem. Draw a diagram or think of a simpler analogous problem to help you decide how to solve it.

Step 2 Solve the problem: Carry out the necessary calculations.

Step 3 Explain your result: Be sure that your answer makes sense, and consider what you've learned by solving the problem.

You can remember this process as "Understand, Solve, and Explain," or USE for short. You may not always need to write out the three steps explicitly, but they may help if you are stuck.

EXAMPLE: How far is a light-year?

SOLUTION: Let's use the three-step process.

Step 1 Understand the problem: The question asks how *far*, so we are looking for a *distance*. In this case, the definition of a light-year tells us that we are looking for the *distance that light can travel in 1 year*. We know that light travels at the speed of light, so we are looking for an equation that gives us distance from speed. If you don't remember this equation, just think of a simpler but analogous problem, such as "If you drive at 50 kilometers per hour, how far will you travel in 2 hours?" You'll realize that you simply multiply the speed by the time: distance = speed × time. In this case, the speed is the speed of light, or 300,000 km/s, and the time is 1 year.

Step 2 Solve the problem: From Step 1, our equation is that 1 light-year is the speed of light times one year. To make the units consistent, we convert 1 year to seconds by remembering that there are 60 seconds in 1 minute, 60 minutes in 1 hour, 24 hours in 1 day, and 365 days in 1 year. We now carry out the calculations:

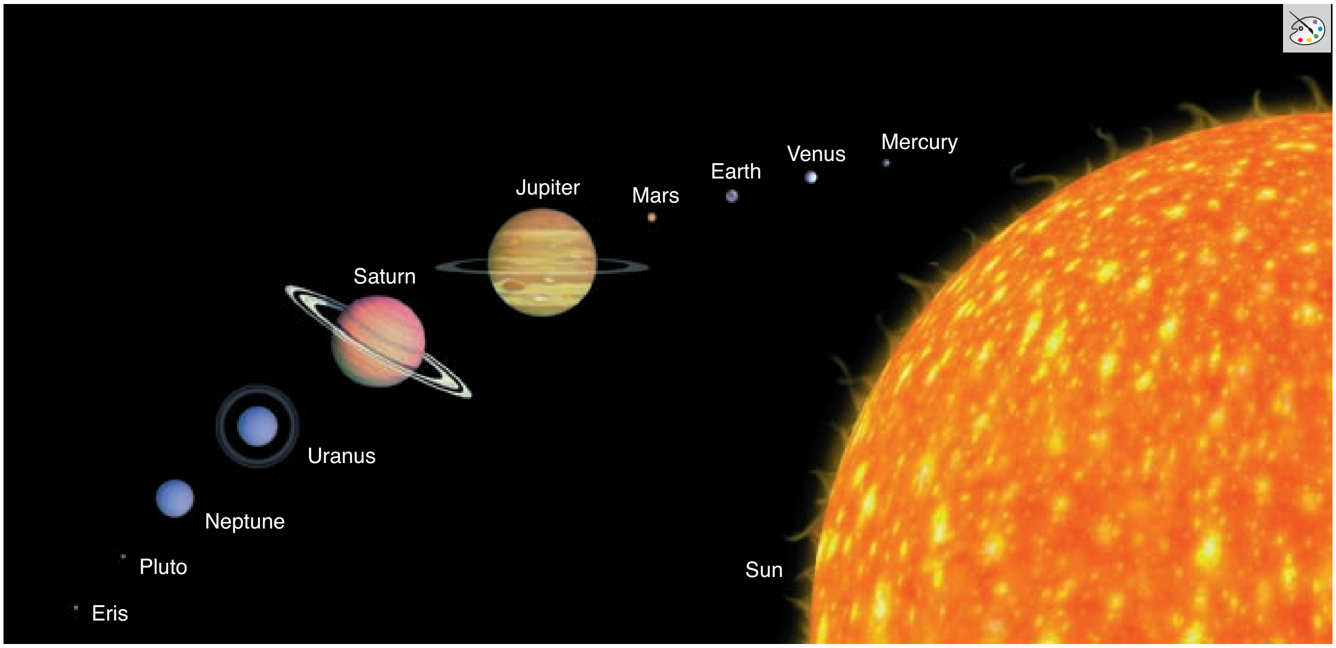
$$\begin{aligned}1\text{ light-year} &= (\text{speed of light}) \times (1\text{ yr}) \\ &= \left(300{,}000\,\frac{\text{km}}{\cancel{\text{s}}}\right) \times \left(1\,\cancel{\text{yr}} \times \frac{365\,\cancel{\text{days}}}{1\,\cancel{\text{yr}}} \right. \\ &\qquad \left. \times \frac{24\,\cancel{\text{hr}}}{1\,\cancel{\text{day}}} \times \frac{60\,\cancel{\text{min}}}{1\,\cancel{\text{hr}}} \times \frac{60\,\cancel{\text{s}}}{1\,\cancel{\text{min}}}\right) \\ &= 9{,}460{,}000{,}000{,}000\text{ km (9.46 trillion km)}\end{aligned}$$

Step 3 Explain your result: In sentence form, our answer is "One light-year is about 9.46 trillion kilometers." This answer makes sense: It has the expected units of distance (kilometers) and it is a long way, which we expect for the distance that light can travel in a year. We say "about" in the answer because we know it is not exact. For example, a year is not exactly 365 days long. In fact, for most purposes, we can approximate the answer further as "One light-year is about 10 trillion kilometers."

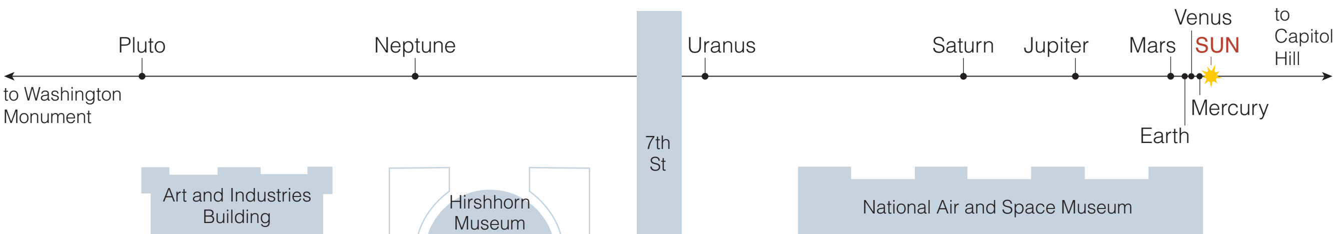
FIGURE 5 This photo shows the pedestals housing the Sun (the gold sphere on the nearest pedestal) and the inner planets in the Voyage scale model solar system (Washington, D.C.). The model planets are encased in the sidewalk-facing disks visible at about eye level on the planet pedestals. The building at the left is the National Air and Space Museum.

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

Seeing our solar system to scale also helps put space exploration into perspective. The Moon, the only other world on which humans have ever stepped (**FIGURE 7**), lies only about 4 centimeters ($1\frac{1}{2}$ inches) from Earth in the Voyage model. On this scale, the palm of your hand can cover the entire region of the universe in which humans have so far traveled. The trip to Mars is more than 150 times as far as the trip to the Moon, even when Mars is on the same side of its orbit as Earth. And while you can walk from the Sun to Pluto in a few minutes on the Voyage scale, the *New Horizons* spacecraft that is making the real journey will have been in space nearly a decade when it flies past Pluto in July 2015.



a The scaled sizes (but not distances) of the Sun, planets, and two largest known dwarf planets.



b Locations of the Sun and planets in the Voyage model, Washington, D.C.; the distance from the Sun to Pluto is about 600 meters (1/3 mile). Planets are lined up in the model, but in reality each planet orbits the Sun independently and a perfect alignment never occurs.

FIGURE 6 **interactive figure** The Voyage scale model represents the solar system at *one ten-billionth* of its actual size. Pluto is included in the Voyage model, which was built before the International Astronomical Union reclassified Pluto as a dwarf planet.

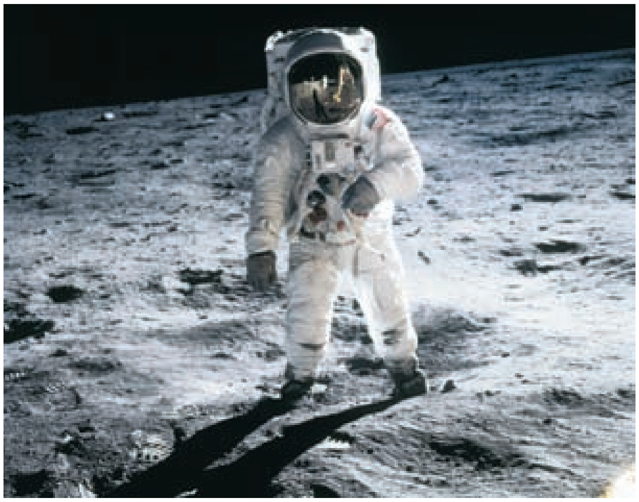


FIGURE 7 This famous photograph from the first Moon landing (*Apollo 11* in July 1969) shows astronaut Buzz Aldrin, with Neil Armstrong reflected in his visor. Armstrong was the first to step onto the Moon's surface, saying, "That's one small step for a man, one giant leap for mankind."

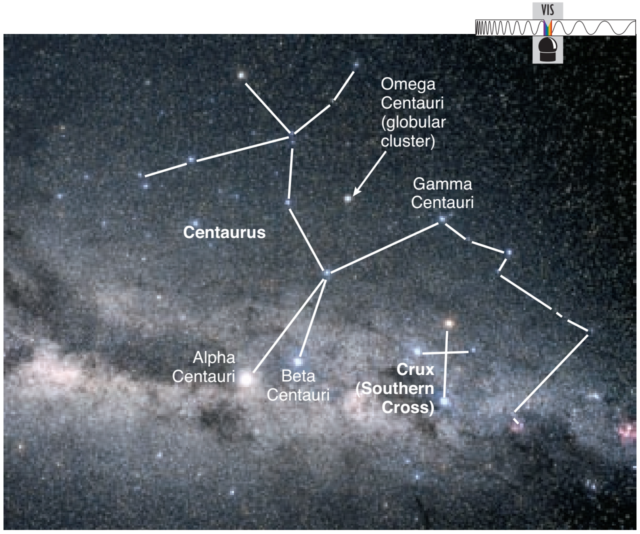


FIGURE 8 This photograph and diagram show the constellation Centaurus, which is visible from tropical and southern latitudes. Alpha Centauri's real distance of 4.4 light-years is 4400 kilometers on the 1-to-10-billion Voyage scale.

Distances to the Stars If you visit the Voyage model in Washington, D.C., you can walk the roughly 600-meter distance from the Sun to Pluto in just a few minutes. How much farther would you have to walk to reach the next star on this scale?

Amazingly, you would need to walk to California. If this answer seems hard to believe, you can check it for yourself. A light-year is about 10 trillion kilometers, which becomes 1000 kilometers on the 1-to-10-billion scale (because 10 trillion ÷ 10 billion = 1000). The nearest star system to our own, a three-star system called Alpha Centauri (**FIGURE 8**), is about 4.4 light-years away. That distance is about 4400 kilometers (2700 miles) on the 1-to-10-billion scale, or roughly equivalent to the distance across the United States.

The tremendous distances to the stars give us some perspective on the technological challenge of astronomy. For example, because the largest star of the Alpha Centauri system is roughly the same size and brightness as our Sun, viewing it in the night sky is somewhat like being in Washington, D.C., and seeing a very bright grapefruit in San Francisco (neglecting the problems introduced by the curvature of Earth). It may seem

SPECIAL TOPIC

How Many Planets Are There in Our Solar System?

Until recently, children were taught that our solar system had nine planets. However, in 2006 astronomers voted to demote Pluto to a *dwarf planet*, leaving our solar system with only eight official planets (**FIGURE 1**). Why the change?

FIGURE 1 Notes left at the Voyage scale model solar system Pluto plaque upon Pluto's demotion to dwarf planet.

When Pluto was discovered in 1930, it was assumed to be similar to other planets. But we now know that Pluto is much smaller than any of the first eight planets and that it shares the outer solar system with thousands of other icy objects. Still, as long as Pluto was the largest known of these objects, most astronomers were content to leave the planetary status quo. Change was forced by the 2005 discovery of an object called Eris. Because Eris is slightly larger than Pluto, astronomers could no longer avoid the question of what objects should count as planets.

Official decisions on astronomical names and definitions rest with the International Astronomical Union (IAU), an organization made up of professional astronomers from around the world. The question of Pluto's status was voted upon during the IAU's 2006 meeting. The result was the new definition of "planet" that you see in the Basic Astronomical Definitions box, and the addition of the "dwarf planet" category to accommodate objects like Pluto and Eris.

Not all astronomers are happy with the new definitions, but for now they seem likely to hold. Of course, some people are likely to keep thinking of Pluto as a planet regardless of what professional astronomers say, much as many people still talk of Europe and Asia as separate continents even though both belong to the same land mass (Eurasia). So if you're a Pluto fan, don't despair: It's good to know the official classifications, but it's better to understand the science behind them.

remarkable that we can see the star at all, but the blackness of the night sky allows the naked eye to see it as a faint dot of light. It looks much brighter through powerful telescopes, but we still cannot see features of the star's surface.

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

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

The Size of the Milky Way Galaxy The vast separation between our solar system and Alpha Centauri is typical of the separations among star systems in our region of the Milky Way Galaxy. We therefore cannot use the 1-to-10-billion scale for thinking about distances beyond the nearest stars, because more distant stars would not fit on Earth with this scale. To visualize the galaxy, let's reduce our scale by another factor of 1 billion (making it a scale of 1 to 10^{19}).

On this new scale, each light-year becomes 1 millimeter, and the 100,000-light-year diameter of the Milky Way Galaxy becomes 100 meters, or about the length of a football field. Visualize a football field with a scale model of our galaxy centered over midfield. Our entire solar system is a microscopic dot located around the

COMMON MISCONCEPTIONS

Confusing Very Different Things

Most people are familiar with the terms *solar system* and *galaxy*, but few realize how incredibly different they are. Our solar system is a single star system, while our galaxy is a collection of more than 100 billion star systems—so many that it would take thousands of years just to count them. Moreover, if you look at the sizes in Figure 1, you'll see that our galaxy is about 100 million times larger in diameter than our solar system. So be careful; numerically speaking, mixing up *solar system* and *galaxy* is a gigantic mistake!

MATHEMATICAL INSIGHT 2

The Scale of Space and Time

MA Math Review Video: Scientific Notation, Parts 1 to 3

Making a scale model usually requires nothing more than division. For example, in a 1-to-20 architectural scale model, a building that is actually 6 meters tall will be only $6 \div 20 = 0.3$ meter tall. The idea is the same for astronomical scaling, except that we usually divide by such large numbers that it's easier to work in *scientific notation*—that is, with the aid of powers of 10.

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

SOLUTION:

Step 1 Understand: We are looking for the scaled *size* of the Sun, so we simply need to divide its actual radius by 10 billion, or 10^{10}. The Sun's radius is 695,000 km, or 6.95×10^5 km in scientific notation.

Step 2 Solve: We carry out the division:

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

Notice that we used the rule that dividing powers of 10 means subtracting their exponents.

Step 3 Explain: We have found an answer, but because most of us don't have a good sense of what 10^{-5} kilometer looks like, the answer will be more meaningful if we convert it to units that will be easier to interpret. In this case, because there are 1000 (10^3) meters in a kilometer and 100 (10^2) centimeters in a meter, we convert to centimeters:

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

We've found that on the 1-to-10-billion scale the Sun's radius is about 7 centimeters, which is a diameter of about 14 centimeters—about the size of a large grapefruit.

EXAMPLE 2: What scale allows the 100,000-light-year diameter of the Milky Way Galaxy to fit on a 100-meter-long football field?

SOLUTION:

Step 1 Understand: We want to know *how many times larger* the actual diameter of the galaxy is than 100 meters, so we'll divide the actual diameter by 100 meters. To carry out the division, we'll need both numbers in the same units. We can put the galaxy's diameter in meters by using the fact that a light-year is about 10^{13} kilometers (see Mathematical Insight 1) and a kilometer is 10^3 meters; because we are working with powers of 10, we'll write the galaxy's 100,000-light-year diameter as 10^5 ly.

Step 2 Solve: We now convert the units and carry out the division:

$$\frac{\text{galaxy diameter}}{\text{football field diameter}} = \frac{10^5\ \cancel{\text{ly}} \times \frac{10^{13}\ \cancel{\text{km}}}{1\ \cancel{\text{ly}}} \times \frac{10^3\ \cancel{\text{m}}}{1\ \cancel{\text{km}}}}{10^2\ \cancel{\text{m}}} = 10^{(5+13+3-2)} = 10^{19}$$

Note that the answer has no units, because it simply tells us how many times larger one thing is than the other.

Step 3 Explain: We've found that we need a scale of 1 to 10^{19} to make the galaxy fit on a football field.

20-yard line. The 4.4-light-year separation between our solar system and Alpha Centauri becomes just 4.4 millimeters on this scale—smaller than the width of your little finger. If you stood at the position of our solar system in this model, millions of star systems would lie within reach of your arms.

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

THINK ABOUT IT

Contemplate the fact that it would take more than 3000 years just to count out loud the stars in our galaxy, and that each star is a potential sun for a system of planets. How does this perspective affect your thoughts about the possibilities for finding life—or intelligent life—beyond Earth? Explain.

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

Think for a moment about the total number of stars in all these galaxies. If we assume 100 billion stars per galaxy, the total number of stars in the observable universe is roughly 100 billion × 100 billion, or 10,000,000,000,000,000,000,000 (10^{22}). How big is this number? Visit a beach. Run your hands through the fine-grained sand. Imagine counting each tiny grain of sand as it slips through your fingers. Then imagine counting every grain of sand on the beach and continuing to count *every* grain of dry sand on *every* beach on Earth (see Mathematical Insight 3). If you could actually complete this task, you would find that the number of grains of sand is comparable to the number of stars in the observable universe (**FIGURE 9**).

THINK ABOUT IT

Overall, how does visualizing Earth to scale affect your perspective on our planet and on human existence? Explain.

MATHEMATICAL INSIGHT 3

Order of Magnitude Estimation

In astronomy, numbers are often so large that an estimate can be useful even if it's good only to about the nearest power of 10. For example, when we multiplied 100 billion stars per galaxy by 100 billion galaxies to estimate that there are about 10^{22} stars in the observable universe, we knew that the "ballpark" nature of these numbers means the actual number of stars could easily be anywhere from about 10^{21} to 10^{23}. Estimates good to about the nearest power of 10 are called **order of magnitude estimates**.

EXAMPLE: Verify the claim that the number of grains of (dry) sand on all the beaches on Earth is comparable to the number of stars in the observable universe.

SOLUTION:

Step 1 Understand: To verify the claim, we need to estimate the number of grains of sand and see if it is close to our estimate of 10^{22} stars. We can estimate the total number of sand grains by dividing the *total volume* of sand on Earth's beaches by the *average volume* of an individual sand grain. Volume is equal to length times width times depth, so the total volume is the total length of sandy beach on Earth multiplied by the typical width and depth of dry sand. That is,

$$\text{total sand grains} = \frac{\text{total volume of beach sand}}{\text{average volume of 1 sand grain}} = \frac{\text{beach length} \times \text{beach width} \times \text{beach depth}}{\text{average volume of 1 sand grain}}$$

We now need numbers to put into the equation. We can estimate the average volume of an individual sand grain by measuring out a small volume of sand, counting the number of grains in this volume, and then dividing the volume by the number of grains. If you do this, you'll find that a reasonable order of magnitude estimate is one-tenth of a cubic millimeter, or 10^{-10} m^3, per sand grain. We can estimate beach width and depth from experience or photos of beaches. Typical widths are about 20 to 50 meters and typical sand depth is about 2 to 5 meters, so we can make the numbers easy by assuming that the product of beach width times depth is about 100 square meters, or 10^2 m^2. The total length of sandy beach on Earth is more difficult to estimate, but you can look online and find that it is less than about 1 million kilometers, or 10^9 m.

Step 2 Solve: We already have our equation and all the numbers we need, so we just put them in; note that we group beach width and depth together, since we estimated them together in Step 1:

$$\text{total sand grains} = \frac{\text{beach length} \times (\text{beach width} \times \text{beach depth})}{\text{average volume of 1 sand grain}} = \frac{10^9\ \cancel{\text{m}} \times 10^2\ \cancel{\text{m}^2}}{10^{-10}\ \cancel{\text{m}^3}} = 10^{[9+2-(-10)]} = 10^{21}$$

Step 3 Explain: Our order of magnitude estimate for the total number of grains of dry sand on all the beaches on Earth is 10^{21}, which is within a factor of 10 of the estimated 10^{22} stars in the observable universe. Because both numbers could easily be off by a factor of 10 or more, we cannot say with certainty that one is larger than the other, but the numbers are clearly comparable.

FIGURE 9 The number of stars in the observable universe is comparable to the number of grains of dry sand on all the beaches on Earth.

2 THE HISTORY OF THE UNIVERSE

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

Before we begin, you may wonder how we can claim to know anything about what the universe was like in the distant past. We'll devote much of the rest of this text to understanding how science enables us to do this, but you already know part of the answer: Because looking farther into space means looking further back in time, we can actually *see* parts of the universe as they were long ago, simply by looking far enough away. In other words, our telescopes act somewhat like time machines, enabling us to observe the history of the universe. At great distances, we see the universe as it was long ago, when it was much younger than it is today.

How did we come to be?

FIGURE 10 summarizes the history of the universe according to modern science. Let's start at the upper left of the figure, and discuss the key events and what they mean.

The Big Bang, Expansion, and the Age of the Universe Telescopic observations of distant galaxies show that the entire universe is *expanding,* meaning that average distances between galaxies are increasing with time. This fact implies that galaxies must have been closer together in the past, and if we go back far enough, we must reach the point at which the expansion began. We call this beginning the **Big Bang,** and scientists use the observed rate of expansion to calculate that it occurred about 14 billion years ago. The three cubes in the upper left portion of Figure 10 represent the expansion of a small piece of the universe through time.

The universe as a whole has continued to expand ever since the Big Bang, but on smaller size scales the force of gravity has drawn matter together. Structures such as galaxies and galaxy clusters occupy regions where gravity has won out against the overall expansion. That is, while the universe as a whole continues to expand, individual galaxies and galaxy clusters (and objects within them such as stars and planets) do *not* expand. This idea is also illustrated by the three cubes in Figure 10. Notice that as the cube as a whole grew larger, the matter within it clumped into galaxies and galaxy clusters. Most galaxies, including our own Milky Way, formed within a few billion years after the Big Bang.

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

In its final death throes, a star blows much of its content back out into space. The most massive stars die in titanic explosions called *supernovae*. The returned matter mixes with other matter floating between the stars in the galaxy, eventually becoming part of new clouds of gas and dust from which new generations of stars can be born. Galaxies therefore function as cosmic recycling plants, recycling material expelled from dying stars into new generations of stars and planets. This cycle is illustrated in the lower right of Figure 10. Our own solar system is a product of many generations of such recycling.

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

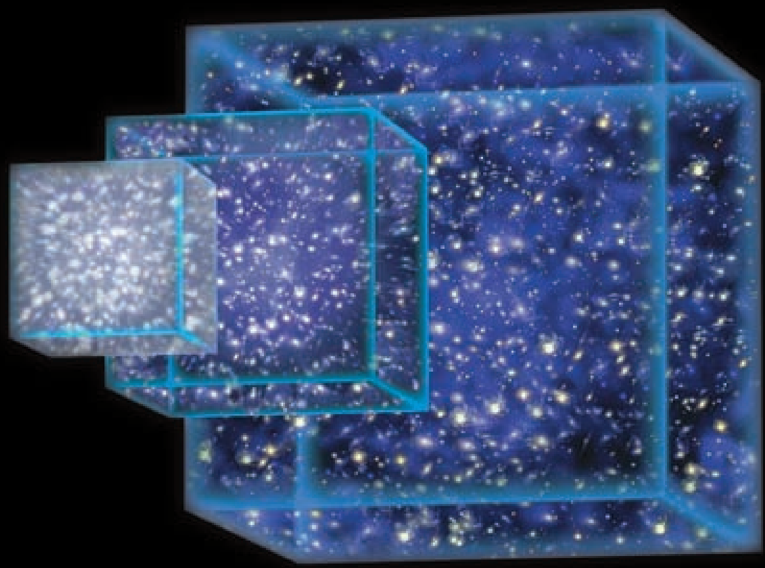
By the time our solar system formed, about $4\frac{1}{2}$ billion years ago, earlier generations of stars had already converted about 2% of our galaxy's original hydrogen and helium into heavier elements. Therefore, the cloud that gave birth to our solar system was made of about 98% hydrogen and helium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

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

COSMIC CONTEXT FIGURE 10 Our Cosmic Origins

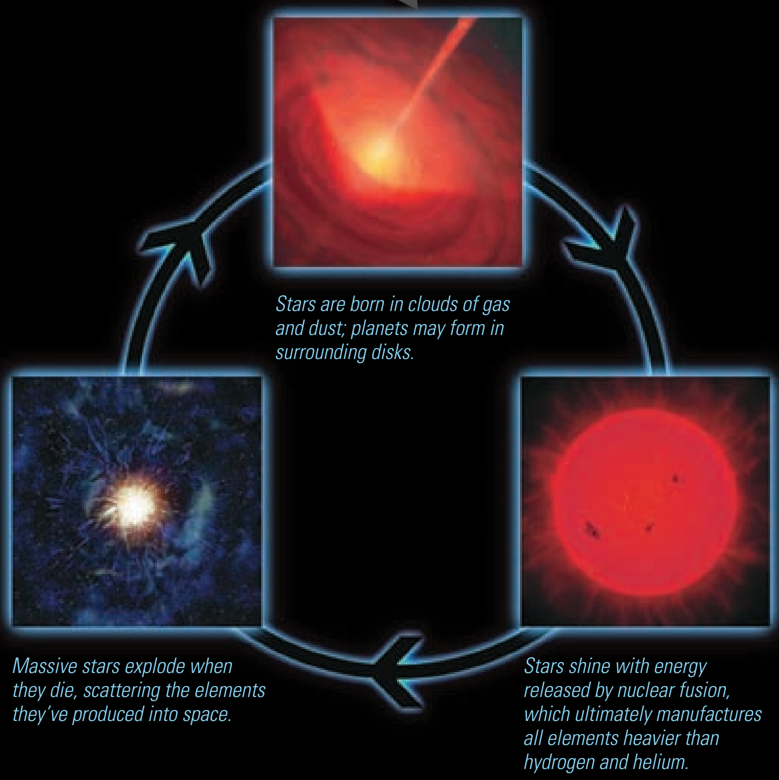
Throughout this book we will see that human life is intimately connected with the development of the universe as a whole. This illustration presents an overview of our cosmic origins, showing some of the crucial steps that made our existence possible.

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



(4) **Earth and Life:** By the time our solar system was born, $4\frac{1}{2}$ billion years ago, about 2% of the original hydrogen and helium had been converted into heavier elements. We are therefore "star stuff," because we and our planet are made from elements manufactured in stars that lived and died long ago.

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



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

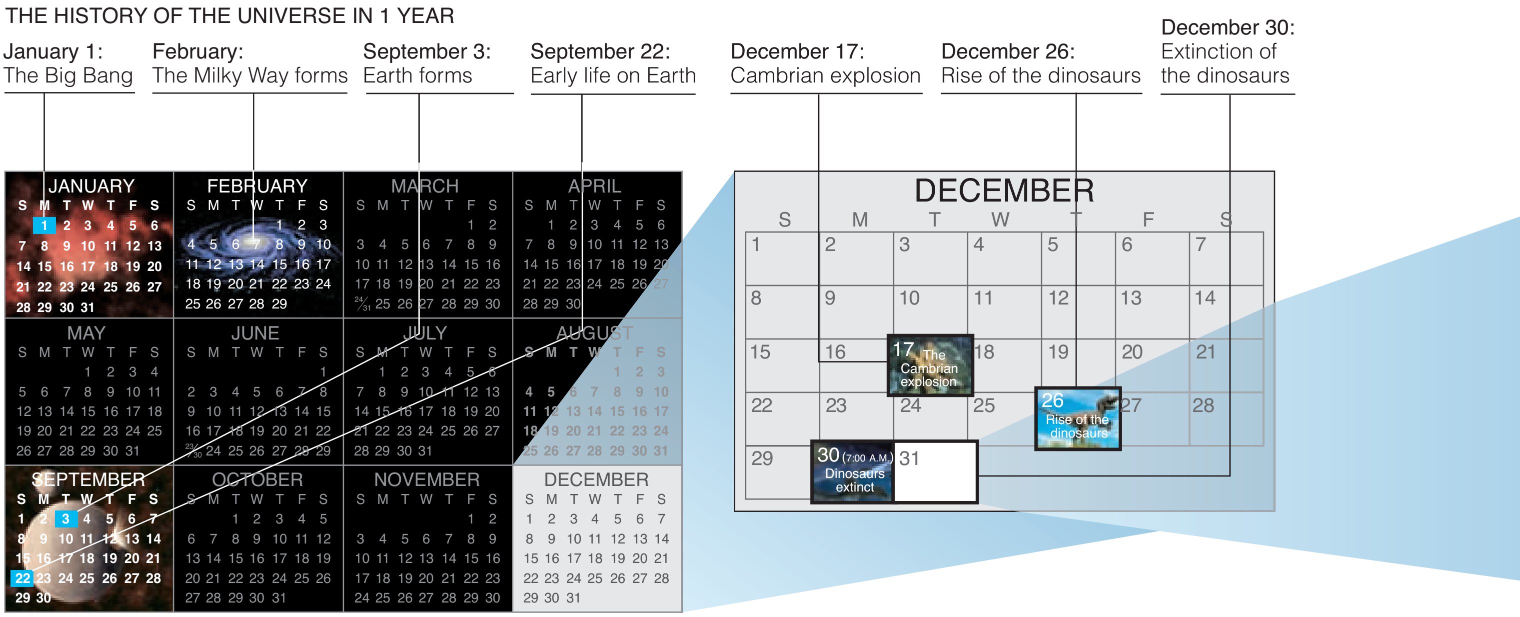


FIGURE 11 The cosmic calendar compresses the 14-billion-year history of the universe into 1 year, so each month represents a little more than 1 billion years. This cosmic calendar is adapted from a version created by Carl Sagan.

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

We can put the 14-billion-year age of the universe into perspective by imagining this time compressed into a single year, so each month represents a little more than 1 billion years. On this *cosmic calendar*, the Big Bang occurred at the first instant of January 1 and the present is the stroke of midnight on December 31 (**FIGURE 11**).

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

Our solar system and our planet did not form until early September on this scale ($4\frac{1}{2}$ billion years ago in real time). By late September, life on Earth was flourishing. However, for most of Earth's history, living organisms remained relatively primitive and microscopic. On the scale of the cosmic calendar, recognizable animals became prominent only in mid-December. Early dinosaurs appeared on the day after Christmas. Then, in a cosmic instant, the dinosaurs disappeared forever—probably because of the impact of an asteroid or a comet. In real time the death of the dinosaurs occurred some 65 million years ago, but on the cosmic calendar it was only yesterday. With the dinosaurs gone, small furry mammals inherited Earth. Some 60 million years later, or around 9 p.m. on December 31 of the cosmic calendar, early hominids (human ancestors) began to walk upright.

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

THINK ABOUT IT

How does an understanding of the scale of time affect your view of human civilization? Explain.

3 SPACESHIP EARTH

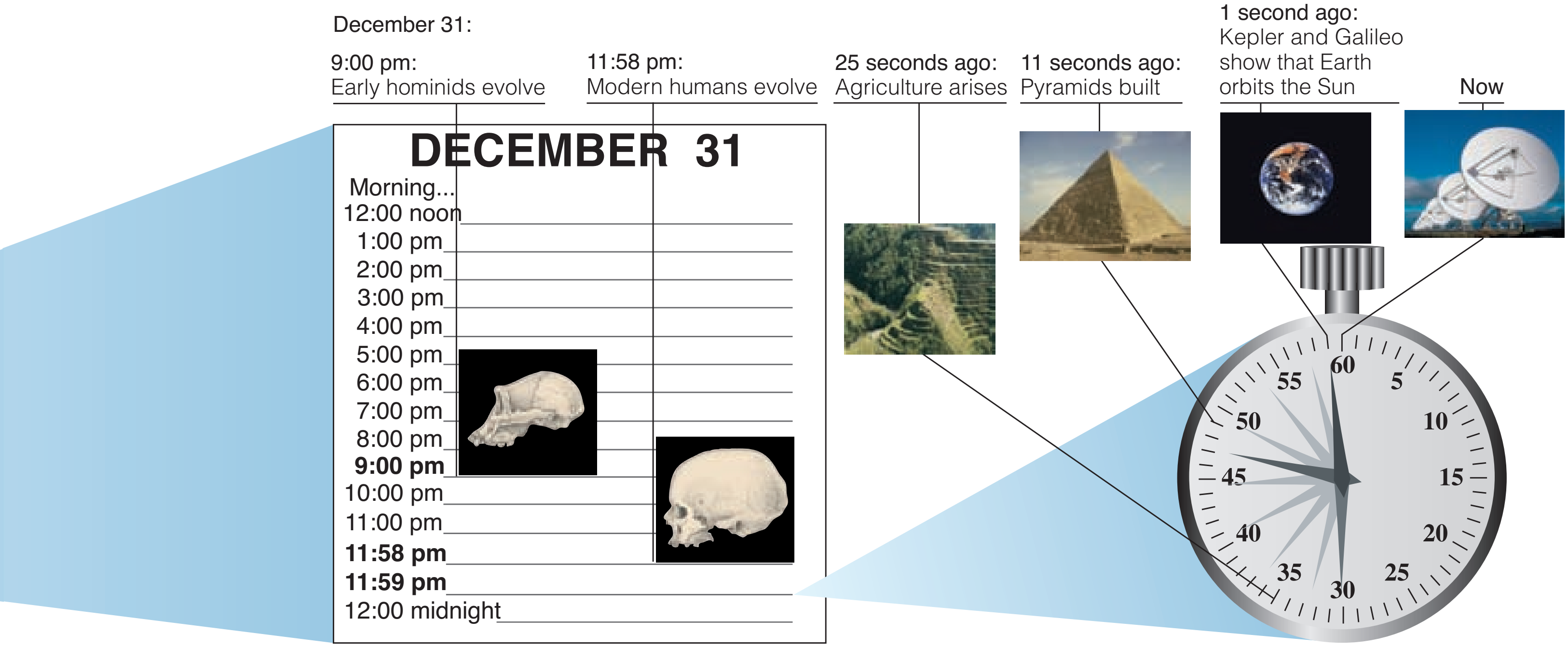
Wherever you are as you read this book, you probably have the feeling that you're "just sitting here." Nothing could be further from the truth. As we'll discuss in this section, all of us are moving through space in so many ways that noted inventor and philosopher R. Buckminster Fuller (1895–1983) described us as travelers on *spaceship Earth.*

How is Earth moving through space?

As you "sit" on spaceship Earth, you are in fact being spun in circles as Earth rotates, you are racing around the Sun in Earth's orbit, you are circling the galactic center with our Sun, and you are careening through the cosmos in the Milky Way Galaxy. Let's explore each of these motions in a little more detail.

Rotation and Orbit The most basic motions of Earth are its daily **rotation** (spin) and its yearly **orbit** (or *revolution*) around the Sun.

Earth rotates once each day around its axis, which is the imaginary line connecting the North Pole to the South Pole. Earth rotates from west to east—counterclockwise as



viewed from above the North Pole—which is why the Sun and stars appear to rise in the east and set in the west each day. Although the physical effects of rotation are so subtle that our ancestors assumed the heavens revolved around us, the rotation speed is substantial (**FIGURE 12**): Unless you live very near the North or South Pole, you are whirling around Earth's axis at a speed of more than 1000 kilometers per hour (600 miles per hour)—faster than most airplanes travel.

At the same time as it is rotating, Earth also orbits the Sun, completing one orbit each year (**FIGURE 13**). Earth's orbital distance varies slightly over the course of each year, but as we discussed earlier, the average distance is one astronomical unit (AU), which is about 150 million kilometers. Again, even though we don't feel this motion, the speed is impressive: We are racing around the Sun at a speed in excess of 100,000 kilometers per hour (60,000 miles per hour), which is faster than any spacecraft yet launched.

As you study Figure 13, notice that Earth's orbital path defines a flat plane that we call the **ecliptic plane**. Earth's axis is tilted by $23\frac{1}{2}°$ from a line *perpendicular* to the ecliptic plane. This **axis tilt** happens to be oriented so that the axis points almost directly at a star called *Polaris,* or the *North Star*. Keep in mind that the idea of axis tilt makes sense only in relation to the ecliptic plane. That is, the idea of "tilt" by itself has no meaning in space, where there is no absolute up or down. In space, "up" and "down" mean only "away from the center of Earth" (or another planet) and "toward the center of Earth," respectively.

THINK ABOUT IT

If there is no up or down in space, why do you think that most globes and maps have the North Pole on top? Would it be equally correct to have the South Pole on top or to turn a globe sideways? Explain.

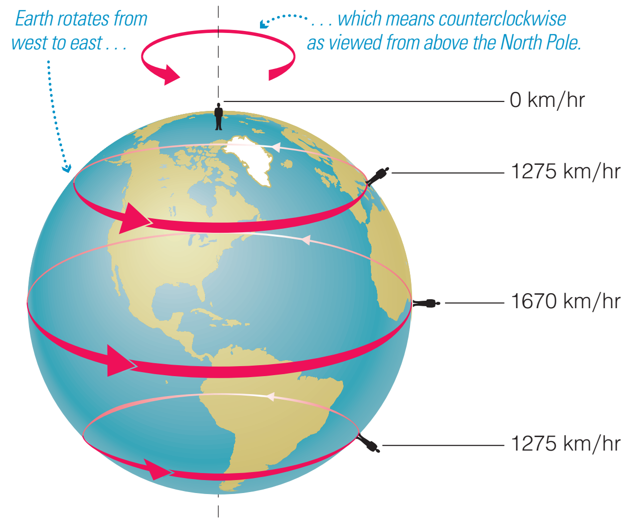


FIGURE 12 As Earth rotates, your speed around Earth's axis depends on your location: The closer you are to the equator, the faster you travel with rotation.

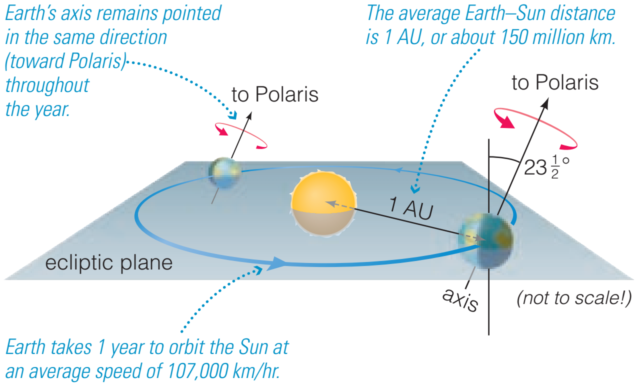


FIGURE 13 Earth orbits the Sun at a surprisingly high speed. Notice that Earth both rotates and orbits counterclockwise as viewed from above the North Pole.

Notice also that Earth orbits the Sun in the same direction that it rotates on its axis: counterclockwise as viewed from above the North Pole. This is not a coincidence but a consequence of the way our planet was born. Strong evidence indicates that Earth and the other planets were born in a spinning disk of gas that surrounded our Sun when it was young, and Earth rotates and orbits in the same direction that the disk was spinning.

Motion Within the Local Solar Neighborhood

Rotation and orbit are only a small part of the travels of spaceship Earth. Our entire solar system is on a great journey within the Milky Way Galaxy. There are two major components to this motion, both shown in **FIGURE 14**. Let's begin with our motion relative to other stars in our *local solar neighborhood,* by which we mean the region of the Sun and nearby stars.

To get a sense of the size of our local solar neighborhood relative to the galaxy, imagine drawing a tiny dot on the painting of the galaxy. Because the galaxy contains at least 100 billion stars, even a dot that is 10,000 times smaller than the whole painting will cover a region representing more than 10 million stars (because 100 billion ÷ 10,000 = 10 million). We usually think of our local solar neighborhood as a region containing just a few thousand to a few million of the nearest stars.

The arrows in the box in Figure 14 indicate that stars in our local solar neighborhood move essentially at random relative to one another. The speeds are quite fast: On average, our Sun is moving relative to nearby stars at a speed of about 70,000 kilometers per hour (40,000 miles per hour), almost three times as fast as the Space Station orbits Earth.

Given these high speeds, you might wonder why we don't see stars racing around our sky. The answer lies in their vast distances from us. You've probably noticed that a distant airplane appears to move through your sky more slowly than one flying close overhead. Stars are so far away that even at speeds of 70,000 kilometers per hour, their motions would be noticeable to the naked eye only if we watched them for thousands of years. That is why the patterns in the constellations seem to remain fixed. Nevertheless, in 10,000 years the constellations will be noticeably different from those we see today.

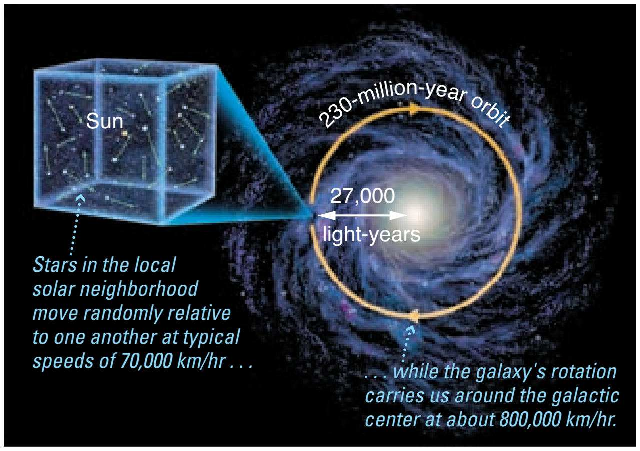


FIGURE 14 This painting illustrates the motion of the Sun both within the local solar neighborhood and around the center of the galaxy.

In 500,000 years they will be unrecognizable. If you could watch a time-lapse movie made over millions of years, you *would* see stars racing across our sky.

THINK ABOUT IT

Despite the chaos of motion in the local solar neighborhood over millions and billions of years, collisions between star systems are extremely rare. Explain why. (*Hint*: Consider the sizes of star systems, such as the solar system, relative to the distances between them.)

Galactic Rotation If you look closely at leaves floating in a stream, their motions relative to one another might appear random, just like the motions of stars in the local solar neighborhood. As you widen your view, you see that all the leaves are being carried in the same general direction by the downstream current. In the same way, as we widen our view beyond the local solar neighborhood, the seemingly random motions of its stars give way to a simpler and even faster motion: rotation of the Milky Way Galaxy. Our solar system, located about 27,000 light-years from the galactic center, completes one orbit of the galaxy in about 230 million years. Even if you could watch from outside our galaxy, this motion would be unnoticeable to your naked eye. However, if you calculate the speed of our solar system as we orbit the center of the galaxy, you will find that it is close to 800,000 kilometers (500,000 miles) per hour.

Careful study of the galaxy's rotation reveals one of the greatest mysteries in science. Stars at different distances from the galactic center orbit at different speeds, and we can learn how mass is distributed in the galaxy by measuring these speeds. Such studies indicate that the stars in the disk of the galaxy represent only the "tip of the iceberg" compared to the mass of the entire galaxy (**FIGURE 15**). Most of the mass of the galaxy seems to be located outside the visible disk (occupying the galactic *halo* that surrounds and encompasses the disk), but the matter that makes up this mass is completely invisible to our telescopes. We therefore know very little about the nature of this matter, which we refer to as *dark matter* (because of the lack of light from it). Studies of other galaxies suggest that they also are made mostly of dark matter, which means this mysterious matter must significantly outweigh the ordinary matter that makes up planets and stars. We know even less about the mysterious *dark energy* that seems to make up much of the total energy content of the universe.

How do galaxies move within the universe?

The billions of galaxies in the universe also move relative to one another. Within the Local Group (see Figure 1), some of the galaxies move toward us, some move away from us, and at least two small galaxies (known as the Large and Small Magellanic Clouds) apparently orbit our Milky Way Galaxy. Again, the speeds are enormous by earthly standards. For example, the Milky Way is moving toward the Andromeda Galaxy at about 300,000 kilometers per hour (180,000 miles per hour). Despite this high speed, we needn't worry about a collision anytime soon. Even if the Milky Way and Andromeda

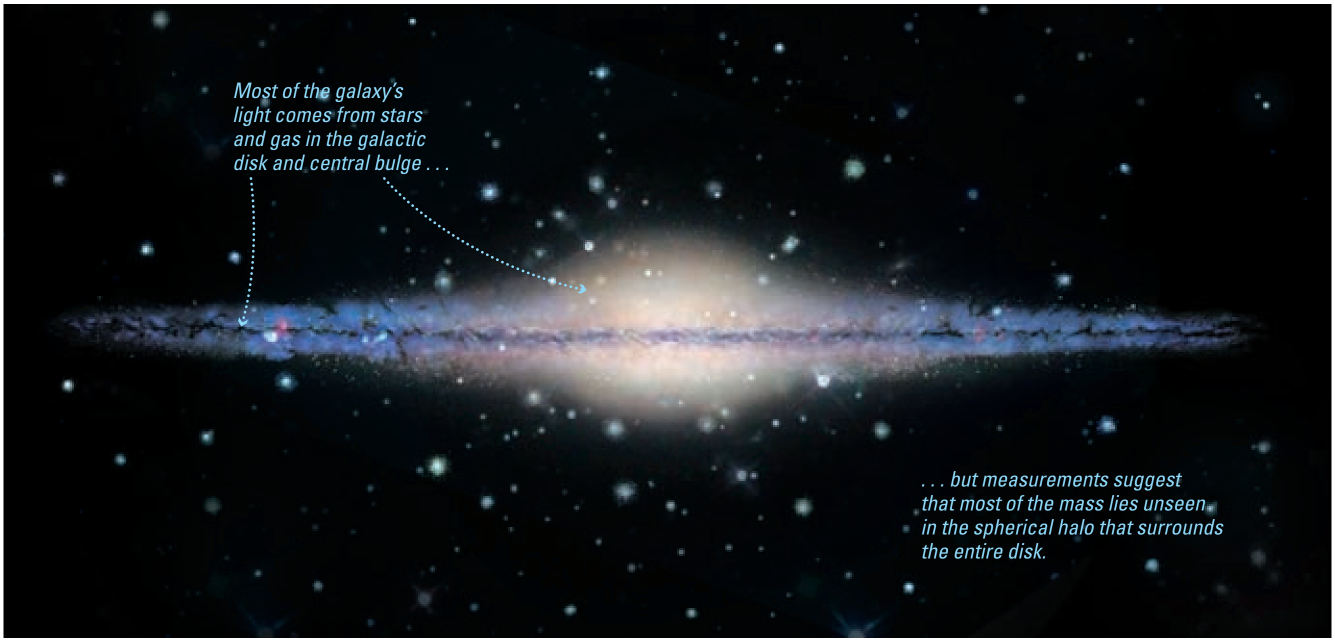


FIGURE 15 This painting shows an edge-on view of the Milky Way Galaxy. Study of galactic rotation shows that although most visible stars lie in the central bulge or thin disk, most of the mass lies in the halo that surrounds and encompasses the disk. Because this mass emits no light that we have detected, we call it *dark matter*.

MATHEMATICAL INSIGHT 4

Speeds of Rotation and Orbit

MA Math Review Video: Problem Solving, Part 3

Building upon prior Mathematical Insights, we will now see how simple formulas—such as the formula for the circumference of a circle—expand the range of astronomical problems we can solve.

EXAMPLE 1: How fast is a person on Earth's equator moving with Earth's rotation?

SOLUTION:

Step 1 Understand: The question *how fast* tells us we are looking for a *speed*. If you remember that highway speeds are posted in miles (or kilometers) per hour, you'll realize that speed is a distance (such as miles) divided by a time (such as hours). In this case, the distance is Earth's equatorial circumference, because that is how far a person at the equator travels with each rotation (see Figure 12); we'll therefore use the formula for the circumference of a circle, $C = 2 \times \pi \times \text{radius}$. The time is 24 hours, because that is how long each rotation takes.

Step 2 Solve: Earth's equatorial radius is 6378 km, so its circumference is $2 \times \pi \times 6378\text{ km} = 40{,}074\text{ km}$. We divide this distance by the time of 24 hours:

$$\text{rotation speed at equator} = \frac{\text{equatorial circumference}}{\text{length of day}} = \frac{40{,}074\text{ km}}{24\text{ hr}} = 1670\,\frac{\text{km}}{\text{hr}}$$

Step 3 Explain: A person at the equator is moving with Earth's rotation at a speed of about 1670 kilometers per hour, which is a little over 1000 miles per hour, or about twice the flying speed of a commercial jet.

EXAMPLE 2: How fast is Earth orbiting the Sun?

SOLUTION:

Step 1 Understand: We are again asked *how fast* and therefore need to divide a distance by a time. In this case, the distance is the circumference of Earth's orbit, and the time is the 1 year that Earth takes to complete each orbit.

Step 2 Solve: Earth's average distance from the Sun is 1 AU, or about 150 million (1.5×10^8) km, so the orbit circumference is about $2 \times \pi \times 1.5 \times 10^8\text{ km} \approx 9.40 \times 10^8\text{ km}$. The orbital speed is this distance divided by the time of 1 year, which we convert to hours so that we end up with units of km/hr:

$$\text{orbital speed} = \frac{\text{orbital circumference}}{1\text{ yr}} = \frac{9.40 \times 10^8\text{ km}}{1\,\cancel{\text{yr}} \times \frac{365\,\cancel{\text{day}}}{\cancel{\text{yr}}} \times \frac{24\text{ hr}}{\cancel{\text{day}}}} \approx 107{,}000\,\frac{\text{km}}{\text{hr}}$$

Step 3 Explain: Earth orbits the Sun at an average speed of about 107,000 km/hr (66,000 mi/hr). Most "speeding bullets" travel between about 500 and 1000 km/hr, so Earth's orbital speed is more than 100 times as fast as a speeding bullet.

Galaxies are approaching each other head-on, it will be billions of years before any collision begins.

When we look outside the Local Group, however, we find two astonishing facts recognized in the 1920s by Edwin Hubble, for whom the Hubble Space Telescope was named:

1. Virtually every galaxy outside the Local Group is moving *away* from us.
2. The more distant the galaxy, the faster it appears to be racing away.

These facts might make it sound as if we suffered from a cosmic case of chicken pox, but there is a much more natural explanation: *The entire universe is expanding*. You can understand the basic idea by thinking about a raisin cake baking in an oven.

The Raisin Cake Analogy Imagine that you make a raisin cake in which the distance between adjacent raisins is 1 centimeter. You place the cake into the oven, where it expands as it bakes. After 1 hour, you remove the cake, which has expanded so that the distance between adjacent raisins has increased to 3 centimeters (**FIGURE 16**). The expansion of the cake seems fairly obvious. But what would you see if you lived *in* the cake, as we live in the universe?

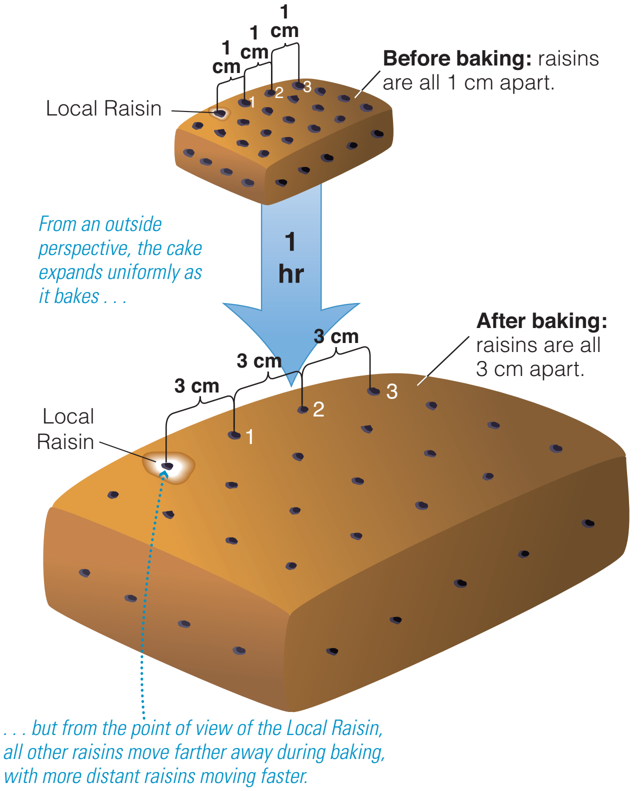
Pick any raisin (it doesn't matter which one) and call it the Local Raisin. Figure 16 shows one possible choice, with three nearby raisins also labeled. The accompanying table summarizes what you would see if you lived within the Local Raisin. Notice, for example, that Raisin 1 starts out at a distance of 1 centimeter before baking and ends up at a distance of 3 centimeters after baking, which means it moves a distance of 2 centimeters away from the Local Raisin during the hour of baking. Hence, its speed as seen from the Local Raisin is 2 centimeters per hour. Raisin 2 moves from a distance of 2 centimeters before baking to a distance of 6 centimeters after baking, which means it moves a distance of 4 centimeters away from the Local Raisin during the hour. Hence, its speed is 4 centimeters per hour, or twice the speed of Raisin 1. Generalizing, the fact that the cake is expanding means that all the raisins are moving away from the Local Raisin, with more distant raisins moving away faster.

THINK ABOUT IT

Suppose a raisin started out 10 centimeters from the Local Raisin. How far away would it be after one hour, and how fast would it be moving away from the Local Raisin?

Hubble's discovery that galaxies are moving in much the same way as the raisins in the cake, with most moving away from us and more distant ones moving away faster, implies that the universe is expanding much like the raisin cake. If you now imagine the Local Raisin as representing our Local Group of galaxies and the other raisins as representing more distant galaxies or clusters of galaxies, you have a basic picture of the expansion of the universe. Like the expanding dough between the raisins in the cake, *space* itself is growing between galaxies. More distant galaxies move away from us faster because they are carried along with this expansion like the raisins in the expanding cake. Many billions of light-years away, we see galaxies moving away from us at speeds approaching the speed of light.

The Real Universe There's at least one important distinction between the raisin cake and the universe: A cake has a center and edges, but we do not think the same is true



Distances and Speeds as Seen from the Local Raisin

Raisin Number	Distance Before Baking	Distance After Baking (1 hour later)	Speed
1	1 cm	3 cm	2 cm/hr
2	2 cm	6 cm	4 cm/hr
3	3 cm	9 cm	6 cm/hr
⋮	⋮	⋮	⋮

FIGURE 16 **interactive figure** An expanding raisin cake offers an analogy to the expanding universe. Someone living in one of the raisins inside the cake could figure out that the cake is expanding by noticing that all other raisins are moving away, with more distant raisins moving away faster. In the same way, we know that we live in an expanding universe because all galaxies outside our Local Group are moving away from us, with more distant ones moving faster.

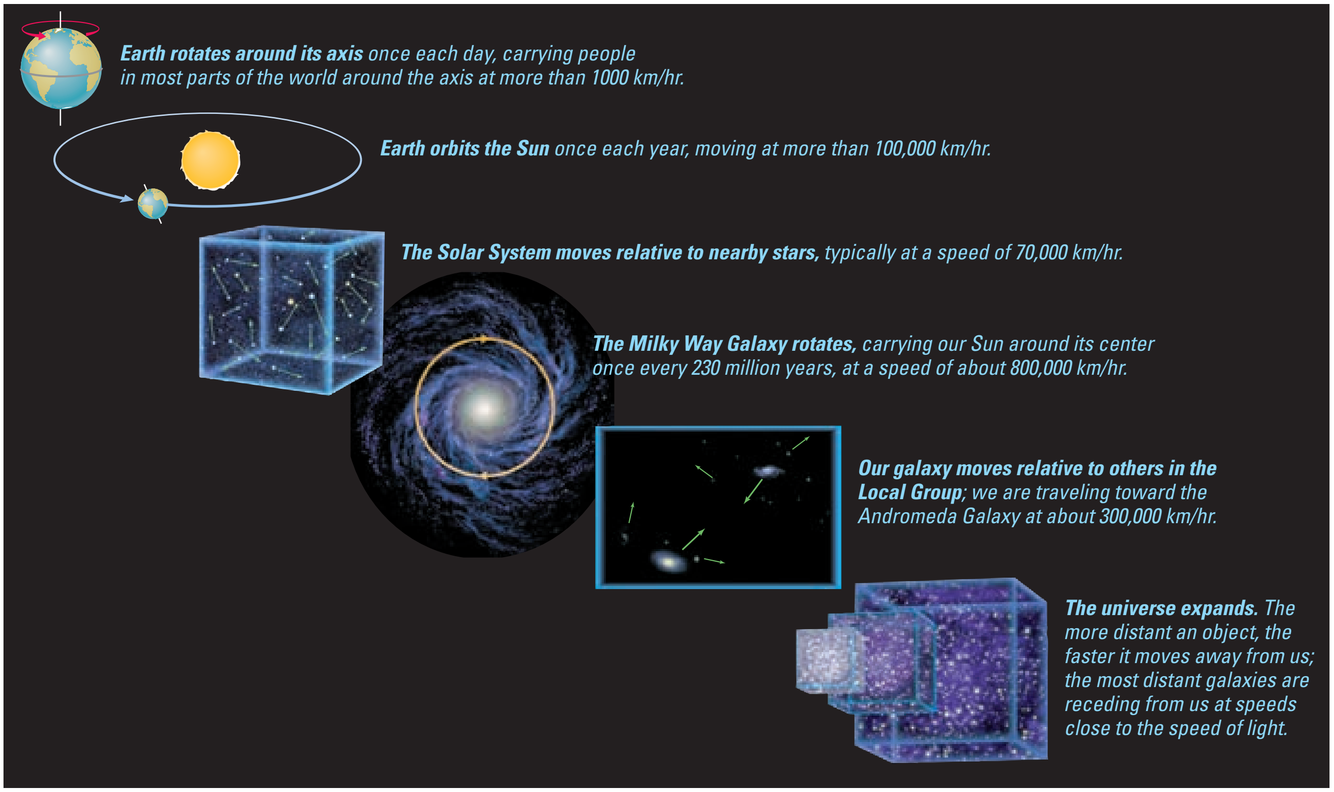


FIGURE 17 This figure summarizes the basic motions of Earth in the universe, along with their associated speeds.

of the entire universe. Anyone living in any galaxy in an expanding universe sees just what we see—other galaxies moving away, with more distant ones moving away faster. Because the view from each point in the universe is about the same, no place can claim to be more "central" than any other place.

It's also important to realize that, unlike the case with a raisin cake, we can't actually *see* galaxies moving apart with time—the distances are too vast for any motion to be noticeable on the time scale of a human life. Instead, we measure the speeds of galaxies by spreading their light into spectra and observing what we call *Doppler shifts*. This illustrates how modern astronomy depends both on careful observations and on using current understanding of the laws of nature to explain what we see.

Motion Summary FIGURE 17 summarizes the motions we have discussed. As we have seen, we are never truly sitting still. We spin around Earth's axis at more than 1000 kilometers per hour, while our planet orbits the Sun at more than 100,000 kilometers per hour. Our solar system moves among the stars of the local solar neighborhood at typical speeds of 70,000 kilometers per hour, while also orbiting the center of the Milky Way Galaxy at a speed of about 800,000 kilometers per hour. Our galaxy moves among the other galaxies of the Local Group, while all other galaxies move away from us at speeds that grow greater with distance in our expanding universe. Spaceship Earth is carrying us on a remarkable journey.

4 THE HUMAN ADVENTURE OF ASTRONOMY

In relatively few words, we've laid out a fairly complete overview of modern scientific ideas about the universe. But our goal in this text is not simply for you to be able to recite these ideas. Rather, it is to help you understand the evidence that supports them and the extraordinary story of how they developed.

How has the study of astronomy affected human history?

Astronomy is a human adventure in the sense that it affects everyone—even those who have never looked at the sky—because the history of astronomy has been so deeply intertwined with the development of civilization. Revolutions in astronomy have gone hand in hand with the revolutions in science and technology that have shaped modern life.

Witness the repercussions of the *Copernican revolution*, which showed us that Earth is not the center of the universe but rather just one planet orbiting the Sun. This revolution began when Copernicus published his idea of a Sun-centered solar system in 1543. Three later figures—Tycho Brahe, Johannes Kepler, and Galileo—provided the key evidence that eventually led to wide acceptance of the Copernican idea. The revolution culminated with Isaac Newton's uncovering of the laws of motion and gravity. Newton's work, in turn, became the foundation of physics that helped fuel the industrial revolution.

More recently, the development of space travel and the computer revolution have helped fuel tremendous progress in astronomy. We've sent probes to all the planets in our solar system, and many of our most powerful observatories, including the Hubble Space Telescope, reside in space. On the ground, computer design and control have led to tremendous growth in the size and power of telescopes.

Many of these efforts, and the achievements they spawned, led to profound social change. The most famous example is the fate of Galileo, whom the Vatican put under house arrest in 1633 for his claims that Earth orbits the Sun. Although the Church soon recognized that Galileo was right, he was formally vindicated only in 1992 with a statement by Pope John Paul II. In the meantime, his case spurred great debate in religious circles and profoundly influenced both theological and scientific thinking.

As you learn about astronomical discovery, try to keep in mind the context of the human adventure. You will then be learning not just about a science, but also about one of the great forces that has shaped our modern world.

These forces will continue to play a role in our future. What will it mean to us when we learn the nature of dark matter and dark energy? How will our view of Earth change when we learn whether life is common or rare in the universe? Only time may answer these questions, but this text will give you the foundation you need to understand how we changed from a primitive people looking at patterns in the night sky to a civilization capable of asking deep questions about our existence.

The Big Picture

Putting This Chapter into Context

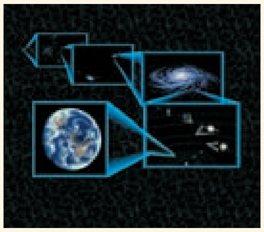
In this chapter, we developed a broad overview of our place in the universe. As we consider the universe in more depth, remember the following "big picture" ideas:

- Earth is not the center of the universe but instead is a planet orbiting a rather ordinary star in the Milky Way Galaxy. The Milky Way Galaxy, in turn, is one of billions of galaxies in our observable universe.
- Cosmic distances are literally astronomical, but we can put them in perspective with the aid of scale models and other scaling techniques. When you think about these enormous scales, don't forget that every star is a sun and every planet is a unique world.
- We are "star stuff." The atoms from which we are made began as hydrogen and helium in the Big Bang and were later fused into heavier elements by massive stars. Stellar deaths released these atoms into space, where our galaxy recycled them into new stars and planets. Our solar system formed from such recycled matter some $4\frac{1}{2}$ billion years ago.
- We are latecomers on the scale of cosmic time. The universe was already more than half its current age when our solar system formed, and it took billions of years more before humans arrived on the scene.
- All of us are being carried through the cosmos on spaceship Earth. Although we cannot feel this motion in our everyday lives, the associated speeds are surprisingly high. Learning about the motions of spaceship Earth gives us a new perspective on the cosmos and helps us understand its nature and history.

SUMMARY OF KEY CONCEPTS

1 THE SCALE OF THE UNIVERSE

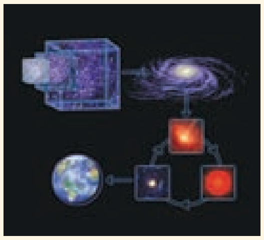
- **What is our place in the universe?** Earth is a planet orbiting the Sun. Our Sun is one of more than 100 billion stars in the **Milky Way Galaxy**. Our galaxy is one of about 40 galaxies in the **Local Group**. The Local Group is one small part of the **Local Supercluster**, which is one small part of the **universe**.



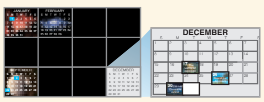
- **How big is the universe?** If we imagine our Sun as a large grapefruit, Earth is a ball point that orbits 15 meters away; the nearest stars are thousands of kilometers away on the same scale. Our galaxy contains more than 100 billion stars—so many that it would take thousands of years just to count them out loud. The observable universe contains roughly 100 billion galaxies, and the total number of stars is comparable to the number of grains of dry sand on all the beaches on Earth.

2 THE HISTORY OF THE UNIVERSE

- **How did we come to be?** The universe began in the **Big Bang** and has been expanding ever since, except in localized regions where gravity has caused matter to collapse into galaxies and stars. The Big Bang essentially produced only two chemical elements: hydrogen and helium. The rest have been produced by stars and recycled within galaxies from one generation of stars to the next, which is why we are "star stuff."

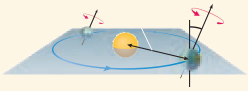


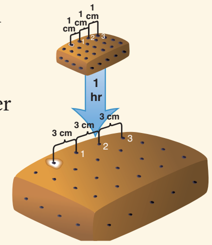
- **How do our lifetimes compare to the age of the universe?** On a cosmic calendar that compresses the history of the universe into 1 year, human civilization is just a few seconds old, and a human lifetime lasts only a fraction of a second.



3 SPACESHIP EARTH

- **How is Earth moving through space?** Earth **rotates** on its axis once each day and **orbits** the Sun once each year. At the same time, we move with our Sun in random directions relative to other stars in our local solar neighborhood, while the galaxy's rotation carries us around the center of the galaxy every 230 million years.





- **How do galaxies move within the universe?** Galaxies move essentially at random within the Local Group, but all galaxies beyond the Local Group are moving away from us. More distant galaxies are moving faster, which tells us that we live in an expanding universe.

4 THE HUMAN ADVENTURE OF ASTRONOMY

- **How has the study of astronomy affected human history?** Throughout history, astronomy has developed hand in hand with social and technological development. Astronomy thereby touches all of us and is a human adventure that all can enjoy.

VISUAL SKILLS CHECK

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. For additional practice, try the Visual Quiz at MasteringAstronomy®.

Useful Data:

Earth-Sun distance = 150,000,000 km

Diameter of Sun = 1,400,000 km

Earth-Moon distance = 384,000 km

Diameter of Earth = 12,800 km

The figure above shows the sizes of Earth and the Moon to scale; the scale used is 1 cm = 4000 km. Using what you've learned about astronomical scale in this chapter, answer the following questions. Hint: *If you are unsure of the answers, you can calculate them using the data given above.*

1. If you wanted to show the *distance* between Earth and the Moon on the same scale, about how far apart would you need to place the two photos?
   a. 10 centimeters (about the width of your hand)
   b. 1 meter (about the length of your arm)
   c. 100 meters (about the length of a football field)
   d. 1 kilometer (a little more than a half mile)
2. Suppose you wanted to show the Sun on the same scale. About how big would it need to be?
   a. 2.5 centimeters in diameter (the size of a golf ball)
   b. 25 centimeters in diameter (the size of a basketball)
   c. 2.5 meters in diameter (about 8 feet across)
   d. 2.5 kilometers in diameter (the size of a small town)
3. About how far away from Earth would the Sun be located on this scale?
   a. 3.75 meters (about 12 feet)
   b. 37.5 meters (about the height of a 12-story building)
   c. 375 meters (about the length of four football fields)
   d. 37.5 kilometers (the size of a large city)
4. Could you use the same scale to represent the distances to nearby stars? Why or why not?

EXERCISES AND PROBLEMS

MasteringAstronomy®

For instructor-assigned homework go to MasteringAstronomy®.

REVIEW QUESTIONS

Short-Answer Questions Based on the Reading

1. Briefly describe the major levels of structure (such as planet, star, galaxy) in the universe.
2. Define *astronomical unit* and *light-year*.
3. Explain the statement *The farther away we look in distance, the further back we look in time.*
4. What do we mean by the *observable universe*? Is it the same thing as the entire universe?
5. Using techniques described in the chapter, put the following into perspective: the size of our solar system; the distance to nearby stars; the size and number of stars in the Milky Way Galaxy; the number of stars in the observable universe.
6. What do we mean when we say that the universe is *expanding*, and how does expansion lead to the idea of the *Big Bang* and our current estimate of the age of the universe?
7. In what sense are we "star stuff"?

8. Use the cosmic calendar to describe how the human race fits into the scale of time.
9. Briefly explain Earth's daily rotation and annual orbit, defining the terms *ecliptic plane* and *axis tilt*.
10. Briefly describe our solar system's location and motion within the Milky Way Galaxy.
11. Where does *dark matter* seem to reside in our galaxy? What makes dark matter and *dark energy* so mysterious?
12. What key observations lead us to conclude that the universe is expanding? Use the raisin cake model to explain how these observations imply expansion.

TEST YOUR UNDERSTANDING

Does It Make Sense?

Decide whether the statement makes sense (or is clearly true) or does not make sense (or is clearly false). Explain clearly; not all of these have definitive answers, so your explanation is more important than your chosen answer.

Example: I walked east from our base camp at the North Pole.

Solution: The statement does not make sense because east has no meaning at the North Pole—all directions are south from the North Pole.

13. Our solar system is bigger than some galaxies.
14. The universe is billions of light-years in age.
15. It will take me light-years to complete this homework assignment!
16. Someday we may build spaceships capable of traveling a light-year in only a decade.
17. Astronomers recently discovered a moon that does not orbit a planet.
18. NASA plans soon to launch a spaceship that will photograph our Milky Way Galaxy from beyond its halo.
19. The observable universe is the same size today as it was a few billion years ago.
20. Photographs of distant galaxies show them as they were when they were much younger than they are today.
21. At a nearby park, I built a scale model of our solar system in which I used a basketball to represent Earth.
22. Because nearly all galaxies are moving away from us, we must be located at the center of the universe.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

23. Which of the following correctly lists our "cosmic address" from small to large? (a) Earth, solar system, Milky Way Galaxy, Local Group, Local Supercluster, universe (b) Earth, solar system, Local Group, Local Supercluster, Milky Way Galaxy, universe (c) Earth, Milky Way Galaxy, solar system, Local Group, Local Supercluster, universe.
24. An astronomical unit is (a) any planet's average distance from the Sun. (b) Earth's average distance from the Sun. (c) any large astronomical distance.
25. The star Betelgeuse is about 600 light-years away. If it explodes tonight, (a) we'll know because it will be brighter than the full Moon in the sky. (b) we'll know because debris from the explosion will rain down on us from space. (c) we won't know about it until about 600 years from now.
26. If we represent the solar system on a scale that allows us to walk from the Sun to Pluto in a few minutes, then (a) the planets are the size of basketballs and the nearest stars are a few miles away. (b) the planets are marble-size or smaller and the nearest stars are thousands of miles away. (c) the planets are microscopic and the stars are light-years away.
27. The total number of stars in the observable universe is roughly equivalent to (a) the number of grains of sand on all the beaches on Earth. (b) the number of grains of sand on Miami Beach. (c) infinity.
28. When we say the universe is *expanding*, we mean that (a) everything in the universe is growing in size. (b) the average distance between galaxies is growing with time. (c) the universe is getting older.
29. If stars existed but galaxies did not, (a) we would probably still exist anyway. (b) we would not exist because life on Earth depends on the light of galaxies. (c) we would not exist because we are made of material that was recycled in galaxies.
30. Could we see a galaxy that is 50 billion light-years away? (a) Yes, if we had a big enough telescope. (b) No, because it would be beyond the bounds of our observable universe. (c) No, because a galaxy could not possibly be that far away.
31. The age of our solar system is about (a) one-third of the age of the universe. (b) three-fourths of the age of the universe. (c) two billion years less than the age of the universe.
32. The fact that nearly all galaxies are moving away from us, with more distant ones moving faster, helped us to conclude that (a) the universe is expanding. (b) galaxies repel each other like magnets. (c) our galaxy lies near the center of the universe.

PROCESS OF SCIENCE

Examining How Science Works

33. *Earth as a Planet.* For most of human history, scholars assumed Earth was the center of the universe. Today, we know that our Sun is just one star in a vast universe. How did science make it possible for us to learn these facts about Earth?
34. *Thinking About Scale.* One key to success in science is finding simple ways to evaluate new ideas, and making a simple scale model is often helpful. Suppose someone tells you that the reason it is warmer during the day than at night is that the day side of Earth is closer to the Sun than the night side. Evaluate this idea by thinking about the size of Earth and its distance from the Sun in a scale model of the solar system.
35. *Looking for Evidence.* In this chapter, we have discussed the scientific story of the universe but have not yet discussed most of the evidence that backs it up. Choose one idea presented in this chapter—such as the idea that there are billions of galaxies in the universe, or that the universe was born in the Big Bang, or that the galaxy contains more dark matter than ordinary matter—and briefly discuss the type of evidence you would want to see before accepting the idea.

GROUP WORK EXERCISE

36. *Counting the Milky Way's Stars.* In this exercise, you will first make an estimate of the number of stars in the Milky Way and then apply some scientific thinking to your estimation method. Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Proposer* (proposes explanations to the group), *Skeptic* (points out weaknesses in proposed explanations), and *Moderator* (leads group discussion and makes sure everyone contributes).
a. Estimate the number of stars in the Milky Way as follows. First, find out how many stars there are within 12 light-years of the Sun. Assuming that the Milky Way's disk is 100,000 light-years across and 1000 light-years thick, its volume is about 1 billion times the volume of the region of your star count. You should therefore multiply your count by 1 billion to get an estimate of the total number of stars in the Milky Way. **b.** Your estimate from part a is based on the number of stars near the Sun. Compare it to the value given in this chapter and determine whether your estimate

is an underestimate or an overestimate of the total number of stars in the Milky Way. Write down a list of possible reasons why your technique gave you an under/overestimate.

INVESTIGATE FURTHER

In-Depth Questions to Increase Your Understanding

Short-Answer/Essay Questions

37. *Alien Technology.* Some people believe that Earth is regularly visited by aliens who travel here from other star systems. For this to be true, how much more advanced than our own technology would the alien space travel technology have to be? Write one to two paragraphs to give a sense of the technological difference. (*Hint:* Use the scale model from this chapter to contrast the distance the aliens would have to travel easily with the distances we currently are capable of traveling.)
38. *Raisin Cake Universe.* Suppose that all the raisins in a cake are 1 centimeter apart before baking and 4 centimeters apart after baking.
a. Draw diagrams to represent the cake before and after baking. **b.** Identify one raisin as the Local Raisin on your diagrams. Construct a table showing the distances and speeds of other raisins as seen from the Local Raisin. **c.** Briefly explain how your expanding cake is similar to the expansion of the universe.
39. *Scaling the Local Group of Galaxies.* Both the Milky Way Galaxy and the Andromeda Galaxy (M31) have a diameter of about 100,000 light-years. The distance between the two galaxies is about 2.5 million light-years.
a. Using a scale on which 1 centimeter represents 100,000 light-years, draw a sketch showing both galaxies and the distance between them to scale. **b.** How does the separation between galaxies compare to the separation between stars? Based on your answer, discuss the likelihood of galactic collisions in comparison to the likelihood of stellar collisions.
40. *The Cosmic Perspective.* Write a short essay describing how the ideas presented in this chapter affect your perspectives on your own life and on human civilization.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

41. *Distances by Light.* Just as a light-year is the distance that light can travel in 1 year, we define a light-second as the distance that light can travel in 1 second, a light-minute as the distance that light can travel in 1 minute, and so on. Calculate the distance in both kilometers and miles represented by each of the following:
a. 1 light-second. **b.** 1 light-minute. **c.** 1 light-hour. **d.** 1 light-day.
42. *Spacecraft Communication.* We use radio waves, which travel at the speed of light, to communicate with robotic spacecraft. How long does it take a message to travel from Earth to a spacecraft at
a. Mars at its closest to Earth (about 56 million km)? **b.** Mars at its farthest from Earth (about 400 million km)? **c.** Pluto at its average distance from Earth (about 5.9 billion km)?
43. *Saturn vs. the Milky Way.* Photos of Saturn and photos of galaxies can look so similar that children often think the photos show similar objects. In reality, a galaxy is far larger than any planet. About how many times larger is the diameter of the Milky Way Galaxy than the diameter of Saturn's rings? (Data: Saturn's rings are about 270,000 km in diameter; the Milky Way is 100,000 light-years in diameter.)
44. *Galaxy Scale.* Consider the 1-to-10^{19} scale on which the disk of the Milky Way Galaxy fits on a football field. On this scale, how far is it from the Sun to Alpha Centauri (real distance: 4.4 light-years)? How big is the Sun itself on this scale? Compare the Sun's size on this scale to the actual size of a typical atom (about 10^{-10} m in diameter).
45. *Universal Scale.* Suppose we wanted to make a scale model of the Local Group of galaxies, in which the Milky Way Galaxy was the size of a marble (about 1 cm in diameter).
a. How far from the Milky Way Galaxy would the Andromeda Galaxy be on this scale? **b.** How far would the Sun be from Alpha Centauri on this scale? **c.** How far would it be from the Milky Way Galaxy to the most distant galaxies in the observable universe on this scale?
46. *Driving Trips.* Imagine that you could drive your car at a constant speed of 100 km/hr (62 mi/hr), even across oceans and in space. (In reality, the law of gravity would make driving through space at a constant speed all but impossible.) How long would it take to drive
a. around Earth's equator? **b.** from the Sun to Earth? **c.** from the Sun to Pluto? **d.** to Alpha Centauri?
47. *Faster Trip.* Suppose you wanted to reach Alpha Centauri in 100 years.
a. How fast would you have to go, in km/hr? **b.** How many times faster is the speed you found in part a than the speeds of our fastest current spacecraft (around 50,000 km/hr)?
48. *Galactic Rotation Speed.* We are located about 27,000 light-years from the galactic center and we orbit the center about once every 230 million years. How fast are we traveling around the galaxy, in km/hr?
49. *Earth Rotation Speed.* Mathematical Insight 3 shows how to find Earth's equatorial rotation speed. To find the rotation speed at any other latitude, you need the following fact: The radial distance from Earth's axis at any latitude is equal to the equatorial radius times the *cosine* of the latitude. Use this fact to find the rotation speed at the following latitudes. (*Hint:* When using the cosine (cos) function, be sure your calculator is set to recognize angles in degree mode, not in radian or gradient mode.)
a. 30°N **b.** 60°N **c.** your latitude.

Discussion Questions

50. *Eliot Quote.* Think carefully about the chapter-opening quotation from T. S. Eliot. What do you think he means? Explain clearly.
51. *Infant Species.* In the last few tenths of a second before midnight on December 31 of the cosmic calendar, we have developed an incredible civilization and learned a great deal about the universe, but we also have developed technology with which we could destroy ourselves. The midnight bell is striking, and the choice for the future is ours. How far into the next cosmic year do you think our civilization will survive? Defend your opinion.
52. *A Human Adventure.* Astronomical discoveries clearly are important to science, but are they also important to our personal lives? Defend your opinion.

Web Projects

53. *Astronomy on the Web.* The Web contains a vast amount of astronomical information. Spend at least an hour exploring astronomy on the Web. Write two or three paragraphs summarizing what you learned from your research. What was your favorite astronomical website, and why?
54. *NASA Missions.* Visit the NASA website to learn about upcoming astronomy missions. Write a one-page summary of the mission you believe is most likely to give us new astronomical information before the end of your astronomy course.
55. *The Hubble Ultra Deep Field.* The photo that opens this chapter is called the Hubble Ultra Deep Field. Find this photo on the Hubble Space Telescope website. Learn how it was taken, what it shows, and what we've learned from it. Write a short summary of your findings.

ANSWERS TO VISUAL SKILLS CHECK QUESTIONS

1. B
2. C
3. C
4. No; the nearest stars would not fit on Earth on this scale.

PHOTO CREDITS

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DISCOVERING THE UNIVERSE FOR YOURSELF

DISCOVERING THE UNIVERSE FOR YOURSELF

LEARNING GOALS

1 PATTERNS IN THE NIGHT SKY

- What does the universe look like from Earth?
- Why do stars rise and set?
- Why do the constellations we see depend on latitude and time of year?

2 THE REASON FOR SEASONS

- What causes the seasons?
- How does the orientation of Earth's axis change with time?

3 THE MOON, OUR CONSTANT COMPANION

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

4 THE ANCIENT MYSTERY OF THE PLANETS

- Why was planetary motion so hard to explain?
- Why did the ancient Greeks reject the real explanation for planetary motion?

We had the sky, up there, all speckled with stars, and we used to lay on our backs and look up at them, and discuss about whether they was made, or only just happened.

—*Mark Twain, Huckleberry Finn*

This is an exciting time in the history of astronomy. A new generation of telescopes is scanning the depths of the universe. Increasingly sophisticated space probes are collecting new data about the planets and other objects in our solar system. Rapid advances in computing technology are allowing scientists to analyze the vast amount of new data and to model the processes that occur in planets, stars, galaxies, and the universe.

One goal of this book is to help *you* share in the ongoing adventure of astronomical discovery. One of the best ways to become a part of this adventure is to do what other humans have done for thousands of generations: Go outside, observe the sky around you, and contemplate the awe-inspiring universe of which you are a part. In this chapter, we'll discuss a few key ideas that will help you understand what you see in the sky.

FIGURE 1 This photo shows the Milky Way over Haleakala crater on the island of Maui, Hawaii. The bright spot just below (and slightly left of) the center of the band is the planet Jupiter.

1 PATTERNS IN THE NIGHT SKY

Today we take for granted that we live on a small planet orbiting an ordinary star in one of many galaxies in the universe. But this fact is not obvious from a casual glance at the night sky, and we've learned about our place in the cosmos only through a long history of careful observations. In this section, we'll discuss major features of the night sky and how we understand them in light of our current knowledge of the universe.

What does the universe look like from Earth?

Shortly after sunset, as daylight fades to darkness, the sky appears to slowly fill with stars. On clear, moonless nights far from city lights, more than 2000 stars may be visible to your naked eye, along with the whitish band of light that we call the Milky Way (**FIGURE 1**). As you look at the stars, your mind may group them into patterns that look like familiar shapes or objects. If you observe the sky night after night or year after year, you will recognize the same patterns of stars. These patterns have not changed noticeably in the past few thousand years.

Constellations People of nearly every culture gave names to patterns they saw in the sky. We usually refer to such patterns as constellations, but to astronomers the term has a more precise meaning: A **constellation** is a *region* of the sky with well-defined borders; the familiar patterns of stars merely help us locate the constellations. Just as every spot of land in the continental United States is part of some state, every point in the sky belongs to some constellation. **FIGURE 2** shows the borders of the constellation Orion and several of its neighbors.

The names and borders of the 88 official constellations were chosen in 1928 by members of the International Astronomical Union (IAU). Most of the IAU members lived in Europe or the United States, so they chose names familiar in the western world. That is why the official names for constellations visible in the Northern Hemisphere can be traced back to civilizations of the ancient Middle East,

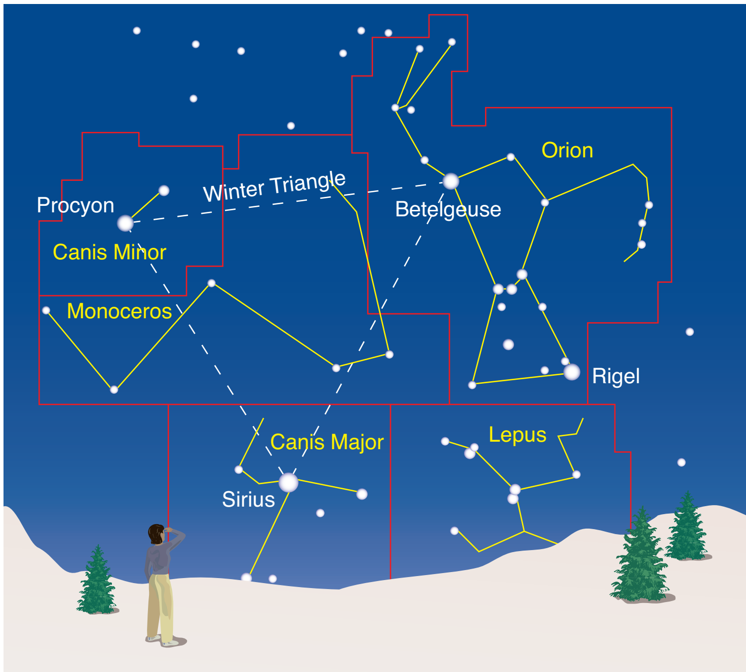


FIGURE 2 Red lines mark official borders of several constellations near Orion. Yellow lines connect recognizable patterns of stars within constellations. Sirius, Procyon, and Betelgeuse form a pattern that spans several constellations and is called the *Winter Triangle*. This view shows how it appears on winter evenings from the Northern Hemisphere.

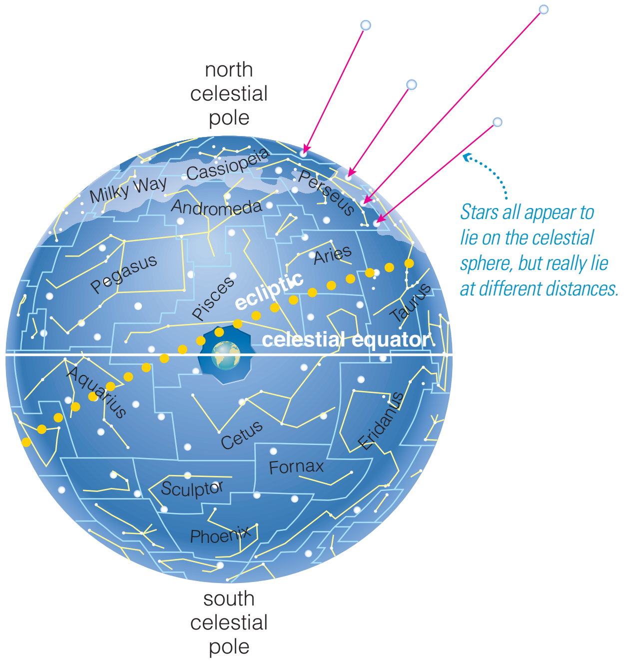


FIGURE 3 The stars and constellations appear to lie on a celestial sphere that surrounds Earth. This is an illusion created by our lack of depth perception in space, but it is useful for mapping the sky.

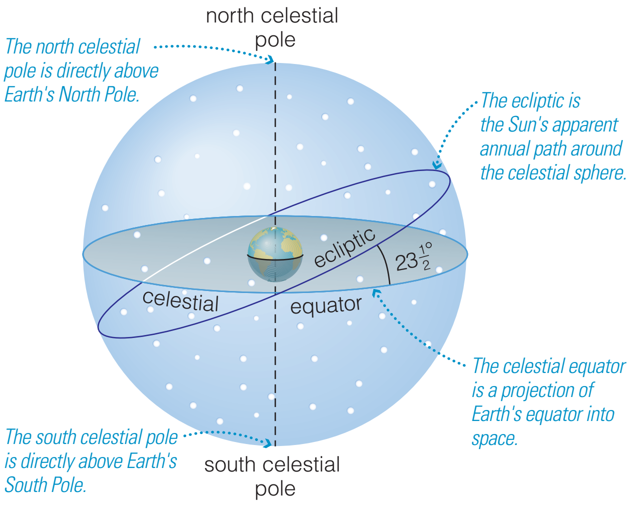


FIGURE 4 This schematic diagram shows key features of the celestial sphere.

while Southern Hemisphere constellations carry names that originated with 17th-century European explorers.

Recognizing the patterns of just 20 or so constellations is enough to make the sky seem as familiar as your own neighborhood. The best way to learn the constellations is to go out and view them, guided by a few visits to a planetarium, star charts, or sky-viewing apps for smart phones and tablets.

The Celestial Sphere The stars in a particular constellation appear to lie close to one another but may be quite far apart in reality, because they may lie at very different distances from Earth. This illusion occurs because we lack depth perception when we look into space, a consequence of the fact that the stars are so far away. The ancient Greeks mistook this illusion for reality, imagining the stars and constellations to lie on a great **celestial sphere** that surrounds Earth (**FIGURE 3**).

We now know that Earth seems to be in the center of the celestial sphere only because it is where we are located as we look into space. Nevertheless, the celestial sphere is a useful illusion, because it allows us to map the sky as seen from Earth. For reference, we identify four special points and circles on the celestial sphere (**FIGURE 4**).

- The **north celestial pole** is the point directly over Earth's North Pole.
- The **south celestial pole** is the point directly over Earth's South Pole.
- The **celestial equator,** which is a projection of Earth's equator into space, makes a complete circle around the celestial sphere.
- The **ecliptic** is the path the Sun follows as it appears to circle around the celestial sphere once each year. It crosses the celestial equator at a $23\frac{1}{2}°$ angle, because that is the tilt of Earth's axis.

The Milky Way The band of light that we call the Milky Way circles all the way around the celestial sphere, passing through more than a dozen constellations. The widest and brightest parts of the Milky Way are most easily seen from the Southern Hemisphere, which probably explains why the Aborigines of Australia gave names to patterns within the Milky Way in the same way other cultures named patterns of stars.

Our Milky Way Galaxy gets its name from this band of light, and the two "Milky Ways" are closely related: *The Milky Way in the night sky traces our galaxy's disk of stars—the galactic plane—as it appears from our location within the Milky Way Galaxy.* **FIGURE 5** shows the idea. Our galaxy is shaped like a thin pancake with a bulge in the middle. We view the universe from our location a little more than halfway out from the center of this "pancake." In all directions that we look within the pancake, we see the countless stars and vast interstellar clouds that make up the Milky Way in the night sky; that is why the band of light makes a full circle around our sky. The Milky Way appears somewhat wider in the direction of the constellation Sagittarius, because that is the direction in which we are looking toward the galaxy's central bulge. We have a clear view to the distant universe only when we look *away* from the galactic plane, along directions that have relatively few stars and clouds to block our view.

The dark lanes that run down the center of the Milky Way contain the densest clouds, obscuring our view of stars behind them. In fact, these clouds generally prevent us from seeing more than a few thousand light-years into our galaxy's disk. As a result, much of our own galaxy remained hidden from view until just a few decades ago, when new technologies allowed us to peer through the clouds by observing forms of light that are invisible to our eyes (such as radio waves and X rays).

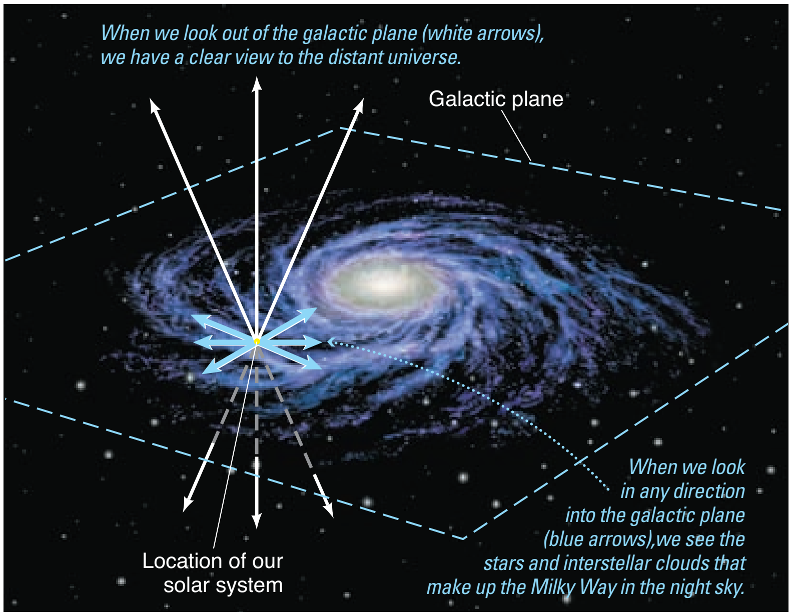


FIGURE 5 This painting shows how our galaxy's structure affects our view from Earth.

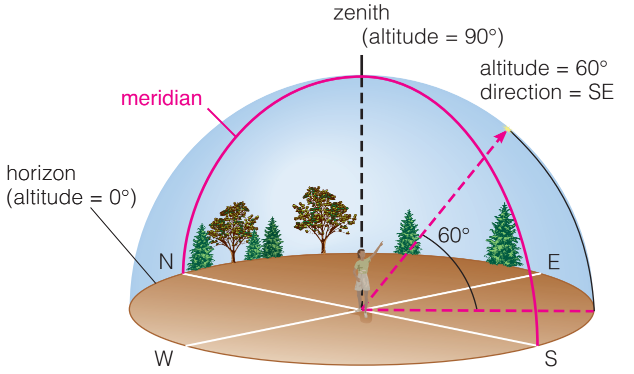


FIGURE 6 From any place on Earth, the local sky looks like a dome (hemisphere). This diagram shows key reference points in the local sky. It also shows how we can describe any position in the local sky by its altitude and direction.

THINK ABOUT IT

Consider a distant galaxy located in the same direction from Earth as the center of our own galaxy (but much farther away). Could we see it with our eyes? Explain.

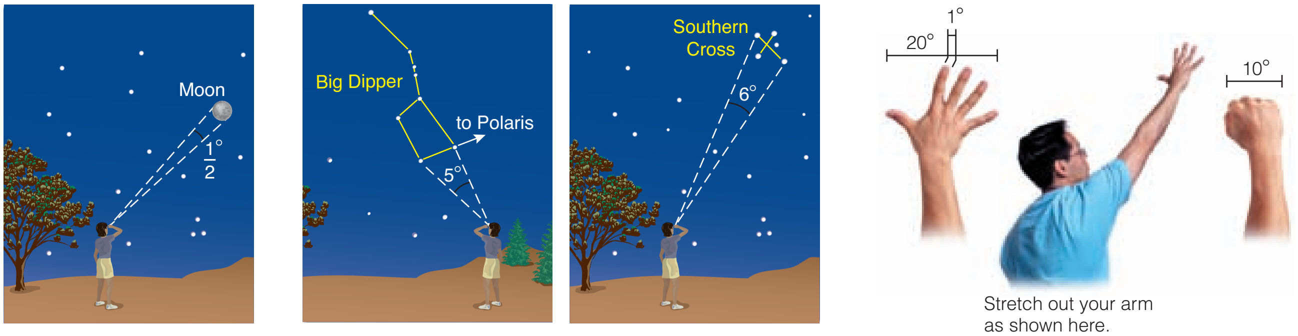
The Local Sky The celestial sphere provides a useful way of thinking about the appearance of the universe from Earth. But it is not what we actually see when we go outside. Instead, your **local sky**—the sky as seen from wherever you happen to be standing—appears to take the shape of a hemisphere or dome, which explains why people of many ancient cultures imagined that we lived on a flat Earth under a great dome encompassing the world. The dome shape arises from the fact that we see only half of the celestial sphere at any particular moment from any particular location, while the ground blocks the other half from view.

FIGURE 6 shows key reference features of the local sky. The boundary between Earth and sky defines the **horizon.** The point directly overhead is the **zenith.** The **meridian** is an imaginary half circle stretching from the horizon due south, through the zenith, to the horizon due north.

We can pinpoint the position of any object in the local sky by stating its **direction** along the horizon (sometimes stated as *azimuth*, which is degrees clockwise from due north) and its **altitude** above the horizon. For example, Figure 6 shows a person pointing to a star located in the direction of southeast at an altitude of 60°. Note that the zenith has altitude 90° but no direction, because it is straight overhead.

Angular Sizes and Distances Our lack of depth perception on the celestial sphere means we have no way to judge the true sizes or separations of the objects we see in the sky. However, we can describe the *angular* sizes or separations of objects without knowing how far away they are.

The **angular size** of an object is the angle it appears to span in your field of view. For example, the angular sizes of the Sun and Moon are each about $\frac{1}{2}°$ (**FIGURE 7a**). Note that angular size does not by itself tell us an object's true size, because angular



a The angular sizes of the Sun and the Moon are about 1/2°.

b The angular distance between the "pointer stars" of the Big Dipper is about 5°, and the angular length of the Southern Cross is about 6°.

c You can estimate angular sizes or distances with your outstretched hand.

FIGURE 7 We measure *angular sizes* or *angular distances,* rather than actual sizes or distances, when we look at objects in the sky.

size also depends on distance. The Sun is about 400 times as large in diameter as the Moon, but it has the same angular size in our sky because it is also about 400 times as far away.

The **angular distance** between a pair of objects in the sky is the angle that appears to separate them. For example, the angular distance between the "pointer stars" at the end of the Big Dipper's bowl is about 5° and the angular length of the Southern Cross is about 6° (**FIGURE 7b**). You can use your outstretched hand to make rough estimates of angles in the sky (**FIGURE 7c**).

For more precise astronomical measurements, we subdivide each degree into 60 **arcminutes** and subdivide each arcminute into 60 **arcseconds** (**FIGURE 8**). We abbreviate arcminutes with the symbol ′ and arcseconds with the symbol ″. For example, we read 35°27′15″ as "35 degrees, 27 arcminutes, 15 arcseconds."

MATHEMATICAL INSIGHT 1

Angular Size, Physical Size, and Distance

An object's angular size depends on its physical (actual) size and distance. **FIGURE 1a** shows the basic idea: An object's physical size does not change as you move it farther from your eye, but its *angular size* gets smaller, making it appear smaller against the background.

FIGURE 1b shows a simple approximation that we can use to find a formula relating angular size to physical size and distance. As long as an object's angular size is relatively small (less than a few degrees), its physical size (diameter) is similar to that of a small piece of a circle going all the way around your eye with a radius equal to the object's distance from your eye. The object's angular size (in degrees) is therefore the *same fraction* of the full 360° circle as its physical size is of the circle's full circumference (given by the formula $2\pi \times$ *distance*). That is,

$$\frac{\text{angular size}}{360°} = \frac{\text{physical size}}{2\pi \times \text{distance}}$$

We solve for the angular size by multiplying both sides by 360°:

$$\text{angular size} = \text{physical size} \times \frac{360°}{2\pi \times \text{distance}}$$

This formula is often called the **small-angle formula**, because it is valid only when the angular size is small.

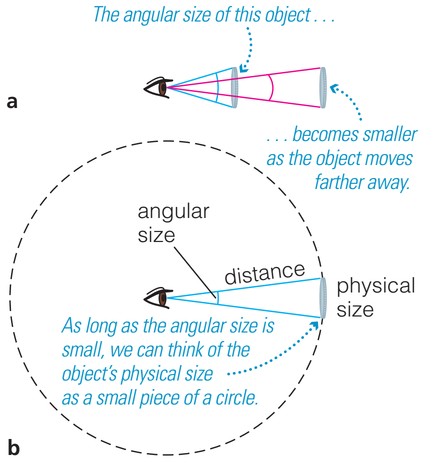


FIGURE 1 Angular size depends on physical size and distance.

EXAMPLE 1: The two headlights on a car are separated by 1.5 meters. What is their angular separation when the car is 500 meters away?

SOLUTION:

Step 1 Understand: We can use the small-angle formula by thinking of the "separation" between the two lights as a "size." That is, if we set the physical size to the actual separation of 1.5 meters, the small-angle formula will tell us the angular separation.

Step 2 Solve: We simply plug in the given values and solve:

$$\begin{aligned}\text{angular separation} &= \text{physical separation} \times \frac{360°}{2\pi \times \text{distance}} \\ &= 1.5\ \cancel{\text{m}} \times \frac{360°}{2\pi \times 500\ \cancel{\text{m}}} \approx 0.17°\end{aligned}$$

Step 3 Explain: We have found that the angular separation of the two headlights is 0.17°. This small angle will be easier to interpret if we convert it to arcminutes. There are 60 arcminutes in 1°, so 0.17° is equivalent to $0.17 \times 60 = 10.2$ arcminutes. In other words, the angular separation of the headlights is about 10 arcminutes, or about a third of the 30 arcminute (0.5°) angular diameter of the Moon.

EXAMPLE 2: Estimate the Moon's actual diameter from its angular diameter of about 0.5° and its distance of about 380,000 km.

SOLUTION:

Step 1 Understand: We are seeking to find a physical size (diameter) from an angular size and distance. We therefore need to solve the small-angle formula for the *physical size*, which we do by switching its left and right sides and multiplying both sides by ($2\pi \times$ *distance*)/360°:

$$\text{physical size} = \text{angular size} \times \frac{2\pi \times \text{distance}}{360°}$$

Step 2 Solve: We now plug in the given values of the Moon's angular size and distance:

$$\text{physical size} = 0.5° \times \frac{2\pi \times 380{,}000\ \text{km}}{360°} \approx 3300\ \text{km}$$

Step 3 Explain: We have used the Moon's approximate angular size and distance to find that its diameter is about 3300 kilometers. We could find a more exact value (3476 km) by using more precise values for the angular diameter and distance.

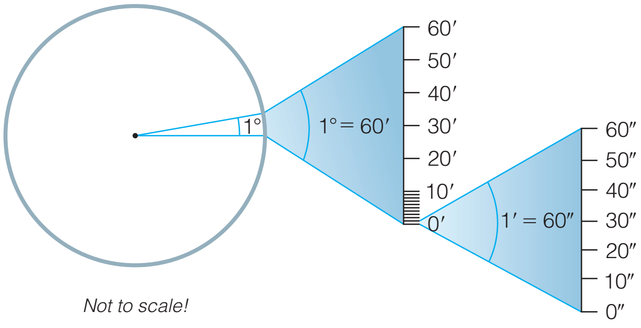


FIGURE 8 We subdivide each degree into 60 arcminutes and each arcminute into 60 arcseconds.

THINK ABOUT IT

Children often try to describe the sizes of objects in the sky (such as the Moon or an airplane) in inches or miles, or by holding their fingers apart and saying "it was THIS big." Can we really describe objects in the sky in this way? Why or why not?

Why do stars rise and set?

If you spend a few hours out under a starry sky, you'll notice that the universe seems to be circling around us, with stars moving gradually across the sky from east to west. Many ancient people took this appearance at face value, concluding that we lie at the center of a universe that rotates around us each day. Today we know that the ancients had it backward: It is Earth that rotates daily, not the rest of the universe.

We can picture the movement of the sky by imagining the celestial sphere rotating around Earth (**FIGURE 9**). From this perspective you can see how the universe seems to turn around us: Every object on the celestial sphere appears to make a simple daily circle around Earth. However, the motion can look a little more complex in the local sky, because the horizon cuts the celestial sphere in half. **FIGURE 10** shows the idea for a location in the United States. If you study the figure carefully,

COMMON MISCONCEPTIONS

The Moon Illusion

You've probably noticed that the full moon appears to be larger when it is near the horizon than when it is high in your sky. However, this apparent size change is an illusion: If you compare the Moon's angular size to that of a small object (such as a small button) held at arm's length, you'll see that it remains essentially the same throughout the night. The reason is that the Moon's angular size depends on its true size and distance, and while the latter varies over the course of the Moon's monthly orbit, it does not change enough to cause a noticeable effect on a single night. The Moon illusion clearly occurs within the human brain, though its precise cause is still hotly debated. Interestingly, you may be able to make the illusion go away by viewing the Moon upside down between your legs.

you'll notice the following key facts about the paths of various stars through the local sky:

- Stars near the north celestial pole are **circumpolar**, meaning that they remain perpetually above the horizon, circling (counterclockwise) around the north celestial pole each day.
- Stars near the south celestial pole never rise above the horizon at all.
- All other stars have daily circles that are partly above the horizon and partly below it, which means they appear to rise in the east and set in the west.

The time-exposure photograph that opens this chapter, taken at Arches National Park in Utah, shows a part of the daily paths of stars. Paths of circumpolar stars are visible within the arch; notice that the complete daily circles for these stars are above the horizon, although the photo shows only a portion of each circle. The north celestial pole lies at the center of these circles. The circles grow larger for stars farther

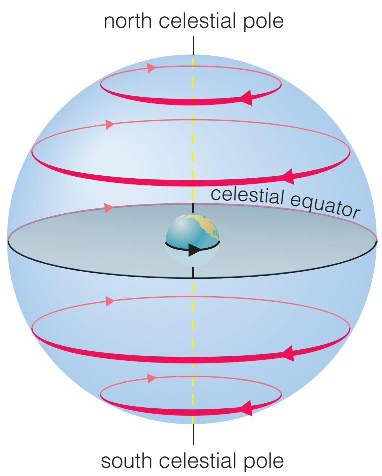


FIGURE 9 Earth rotates from west to east (black arrow), making the celestial sphere *appear* to rotate around us from east to west (red arrows).

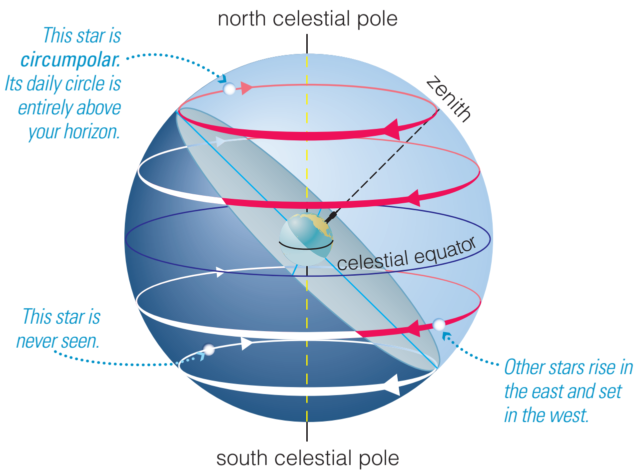
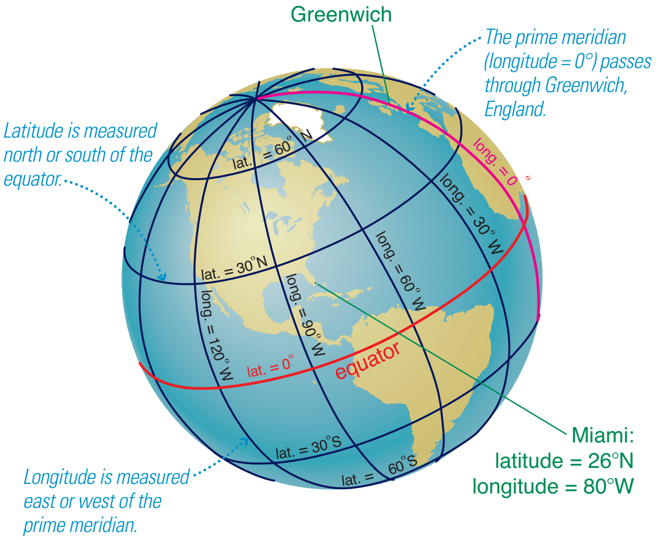


FIGURE 10 The local sky for a location in the United States (40°N). The horizon slices through the celestial sphere at an angle to the equator, causing the daily circles of stars to appear tilted in the local sky. Note: It may be easier to follow the star paths in the local sky if you rotate the page so that the zenith points up.



a We can locate any place on Earth's surface by its latitude and longitude.

b The entrance to the Old Royal Greenwich Observatory, near London. The line emerging from the door marks the prime meridian.

FIGURE 11 Definitions of latitude and longitude.

from the north celestial pole. If they are large enough, the circles cross the horizon, so that the stars rise in the east and set in the west. The same ideas apply in the Southern Hemisphere, except that circumpolar stars are those near the south celestial pole and they circle clockwise rather than counter-clockwise.

THINK ABOUT IT

Do distant galaxies also rise and set like the stars in our sky? Why or why not?

Why do the constellations we see depend on latitude and time of year?

If you stay in one place, the basic patterns of motion in the sky will stay the same from one night to the next. However, if you travel far north or south, you'll see a different set of constellations than you see at home. And even if you stay in one place, you'll see different constellations at different times of year. Let's explore why.

COMMON MISCONCEPTIONS

Stars in the Daytime

Stars may appear to vanish in the daytime and "come out" at night, but in reality the stars are always present. The reason you don't see stars in the daytime is that their dim light is overwhelmed by the bright daytime sky. You *can* see bright stars in the daytime with the aid of a telescope, or if you are fortunate enough to observe a total eclipse of the Sun. Astronauts can also see stars in the daytime. Above Earth's atmosphere, where there is no air to scatter sunlight, the Sun is a bright disk against a dark sky filled with stars. (However, the Sun is so bright that astronauts must block its light if they wish to see the stars.)

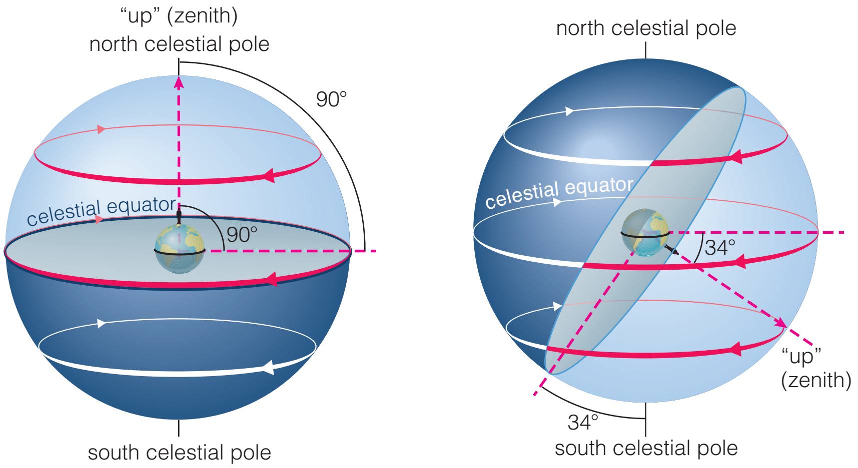
Variation with Latitude **Latitude** measures north-south position on Earth, and **longitude** measures east-west position (FIGURE 11). Latitude is defined to be 0° at the equator, increasing to 90°N at the North Pole and 90°S at the South Pole. By international treaty, longitude is defined to be 0° along the **prime meridian**, which passes through Greenwich, England. Stating a latitude and a longitude pinpoints a location on Earth. For example, Miami lies at about 26°N latitude and 80°W longitude.

Latitude affects the constellations we see because it affects the locations of the horizon and zenith relative to the celestial sphere. FIGURE 12 shows how this works for the latitudes of the North Pole (90°N) and Sydney, Australia (34°S). Note that although the sky varies with latitude, it does *not* vary with longitude. For example, Charleston (South Carolina) and San Diego (California) are at about the same latitude, so people in both cities see the same set of constellations at night.

You can learn more about how the sky varies with latitude by studying diagrams like those in Figures 10 and 12. For example, at the North Pole, you can see only objects that lie on the northern half of the celestial sphere, and they are all circumpolar. That is why the Sun remains above the horizon for 6 months at the North Pole: The Sun lies north of the celestial equator for half of each year (see Figure 3), so during these 6 months it circles the sky at the North Pole just like a circumpolar star.

The diagrams also show a fact that is very important to navigation:

> **The altitude of the celestial pole in your sky is equal to your latitude.**



a The local sky at the North Pole (latitude 90°N).

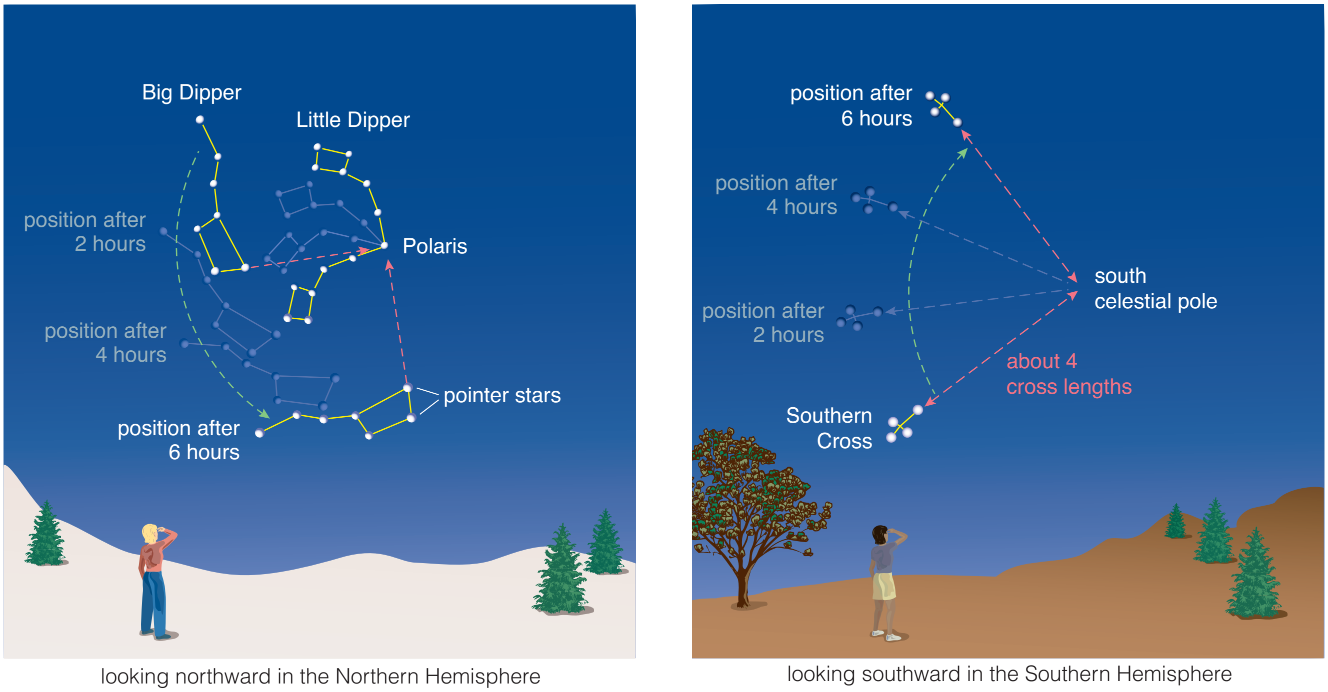
b The local sky at latitude 34°S.

FIGURE 12 The sky varies with latitude. Notice that the altitude of the celestial pole that is visible in your sky is always equal to your latitude.

For example, if you see the north celestial pole at an altitude of 40° above your north horizon, your latitude is 40°N. Similarly, if you see the south celestial pole at an altitude of 34° above your south horizon, your latitude is 34°S. You can therefore determine your latitude simply by finding the celestial pole in your sky (**FIGURE 13**). Finding the north celestial pole is fairly easy, because it lies very close to the star Polaris, also known as the North Star (Figure 13a). In the Southern Hemisphere, you can find the south celestial pole with the aid of the Southern Cross (Figure 13b).

SEE IT FOR YOURSELF

What is *your* latitude? Use Figure 13 to find the celestial pole in your sky, and estimate its altitude with your hand as shown in Figure 7c. Is its altitude what you expect?



a The pointer stars of the Big Dipper point to the North Star, Polaris, which lies within 1° of the north celestial pole. The sky appears to turn *counterclockwise* around the north celestial pole.

b The Southern Cross points to the south celestial pole, which is not marked by any bright star. The sky appears to turn *clockwise* around the south celestial pole.

FIGURE 13 interactive figure You can determine your latitude by measuring the altitude of the celestial pole in your sky.

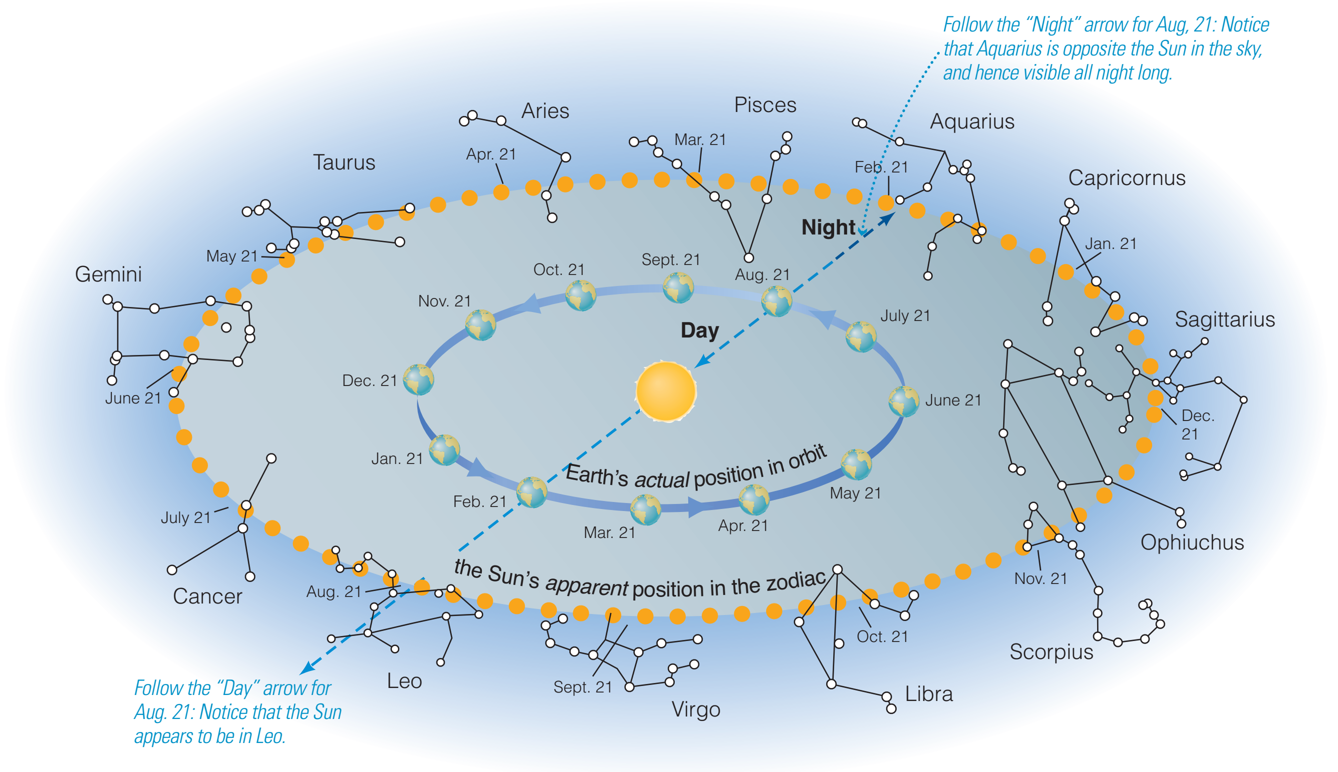


FIGURE 14 interactive figure The Sun appears to move steadily eastward along the ecliptic as Earth orbits the Sun, so we see the Sun against the background of different zodiac constellations at different times of year. For example, on August 21 the Sun appears to be in Leo, because it is between us and the much more distant stars that make up Leo.

Variation with Time of Year The night sky changes throughout the year because of Earth's changing position in its orbit around the Sun. **FIGURE 14** shows how this works. As Earth orbits, the Sun *appears* to move steadily eastward along the ecliptic, with the stars of different constellations in the background at different times of year. The constellations along the ecliptic make up what we call the **zodiac**; tradition places 12 constellations along the zodiac, but the official borders include a thirteenth constellation, Ophiuchus.

The Sun's apparent location along the ecliptic determines which constellations we see at night. For example, Figure 14 shows that the Sun appears to be in Leo in late August. We therefore cannot see Leo at this time (because it is in our daytime sky), but we can see Aquarius all night long because of its location opposite Leo on the celestial sphere. Six months later, in February, we see Leo at night while Aquarius is above the horizon only in the daytime.

COMMON MISCONCEPTIONS

What Makes the North Star Special?

Most people are aware that the North Star, Polaris, is a special star. Contrary to a relatively common belief, however, it is *not* the brightest star in the sky. More than 50 other stars are just as bright or brighter. Polaris is special not because of its brightness, but because it is so close to the north celestial pole and therefore very useful in navigation.

SEE IT FOR YOURSELF

Based on Figure 14 and today's date, in what constellation does the Sun currently appear? What constellation of the zodiac will be on your meridian at midnight? What constellation of the zodiac will you see in the west shortly after sunset? Go outside at night to confirm your answers to the last two questions.

MA Seasons Tutorial, Lessons 1–3

2 THE REASON FOR SEASONS

We have seen how Earth's rotation makes the sky appear to circle us daily and how the night sky changes as Earth orbits the Sun each year. The combination of Earth's rotation and orbit also leads to the progression of the seasons.

What causes the seasons?

You know that we have seasonal changes, such as longer and warmer days in summer and shorter and cooler days in winter. But why do the seasons occur? The answer is that the tilt of Earth's axis causes sunlight to fall differently on Earth at different times of year.

FIGURE 15 illustrates the key ideas. Step 1 illustrates the tilt of Earth's axis, which remains pointed in the same direction in space (toward Polaris) throughout the year. As a result, the

COMMON MISCONCEPTIONS

The Cause of Seasons

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

orientation of the axis *relative to the Sun* changes over the course of each orbit: The Northern Hemisphere is tipped toward the Sun in June and away from the Sun in December, while the reverse is true for the Southern Hemisphere. That is why the two hemispheres experience opposite seasons. The rest of the figure shows how the changing angle of sunlight on the two hemispheres leads directly to seasons.

Step 2 shows Earth in June, when axis tilt causes sunlight to strike the Northern Hemisphere at a steeper angle and the Southern Hemisphere at a shallower angle. The steeper sunlight angle makes it summer in the Northern Hemisphere for two reasons. First, as shown in the zoom-out, the steeper angle means more concentrated sunlight, which tends to make it warmer. Second, if you visualize what happens as Earth rotates each day, you'll see that the steeper angle also means the Sun follows a longer and higher path through the sky, giving the Northern Hemisphere more hours of daylight during which it is warmed by the Sun. The opposite is true for the Southern Hemisphere at this time: The shallower sunlight angle makes it winter there because sunlight is less concentrated and the Sun follows a shorter, lower path through the sky.

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

Notice that the seasons on Earth are caused only by the axis tilt and *not* by any change in Earth's distance from the Sun. Although Earth's orbital distance varies over the course of each year, the variation is fairly small: Earth is only about 3% farther from the Sun at its farthest point than at its nearest. The difference in the strength of sunlight due to this small change in distance is easily overwhelmed by the effects caused by the axis tilt. If Earth did not have an axis tilt, we would not have seasons.

THINK ABOUT IT

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

Solstices and Equinoxes To help us mark the changing seasons, we define four special moments in the year, each of which corresponds to one of the four special positions in Earth's orbit shown in Figure 15.

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

The exact dates and times of the solstices and equinoxes vary from year to year, but stay within a couple of days of the dates given above. In fact, our modern calendar includes leap years in a pattern specifically designed to keep the solstices and equinoxes around the same dates.

We can mark the dates of the equinoxes and solstices by observing changes in the Sun's path through our sky (**FIGURE 16**). The equinoxes occur on the only two days of the year on which the Sun rises precisely due east and sets precisely due west. The June solstice occurs on the day on which the Sun follows its longest and highest path through the Northern Hemisphere sky (and its shortest and lowest path through the Southern Hemisphere sky). It is therefore the day on which the Sun rises and sets farther to the north than on any other day of the year, and on which the noon Sun reaches its highest point in the Northern Hemisphere sky. The opposite is true on the day of the December solstice, when the Sun rises and sets farthest to the south and the noon Sun is lower in the Northern Hemisphere sky than on any other day of the year. **FIGURE 17** shows how the Sun's position in the sky varies over the course of the year.

First Days of Seasons We usually say that each equinox and solstice marks the first day of a season. For example, the day of the summer solstice is usually called the "first day of summer." Notice, however, that the summer (June) solstice occurs when the Northern Hemisphere has its *maximum* tilt toward the Sun. You might then wonder why we consider the solstice to be the beginning rather than the midpoint of summer.

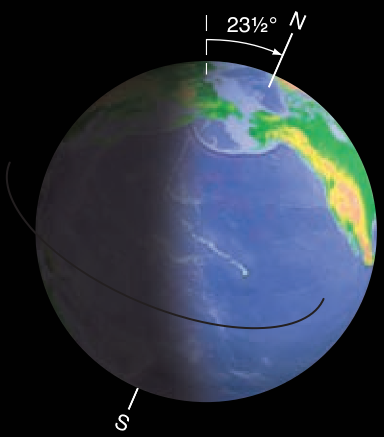
The choice is somewhat arbitrary, but it makes sense in at least two ways. First, it was much easier for ancient people to identify the days on which the Sun reached extreme positions in the sky—such as when it reached its highest point on the summer solstice—than other days in between.

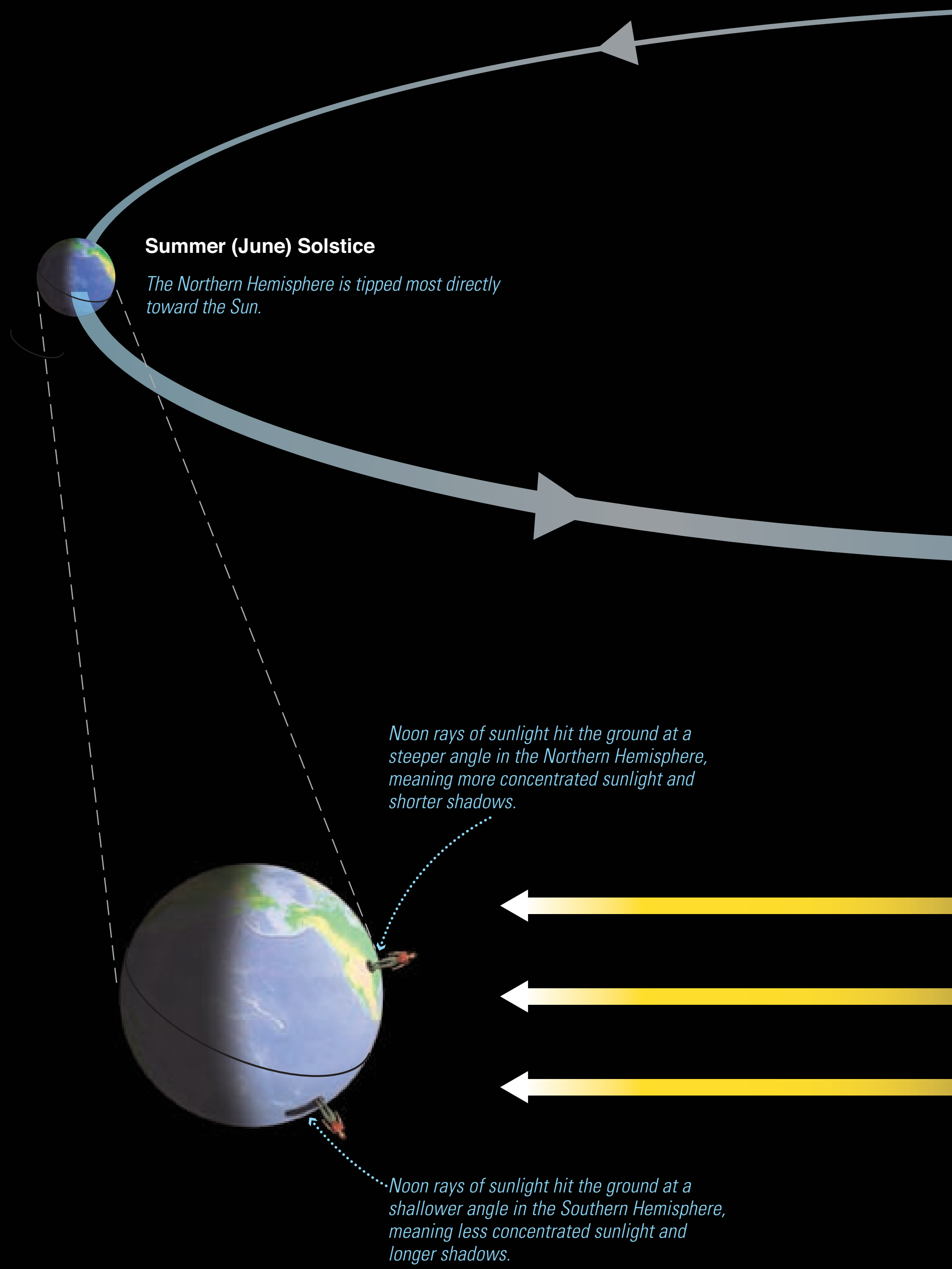
COSMIC CONTEXT FIGURE 15 interactive figure The Seasons

Earth's seasons are caused by the tilt of its rotation axis, which is why the seasons are opposite in the two hemispheres. The seasons do *not* depend on Earth's distance from the Sun, which varies only slightly throughout the year.

1. **Axis Tilt:** Earth's axis points in the same direction throughout the year, which causes changes in Earth's orientation *relative to the Sun*.

2. **Northern Summer/Southern Winter:** In June, sunlight falls more directly on the Northern Hemisphere, which makes it summer there because solar energy is more concentrated and the Sun follows a longer and higher path through the sky. The Southern Hemisphere receives less direct sunlight, making it winter.



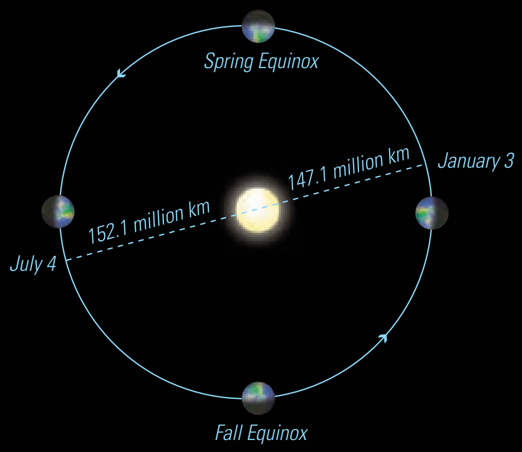


Interpreting the Diagram

To interpret the seasons diagram properly, keep in mind:

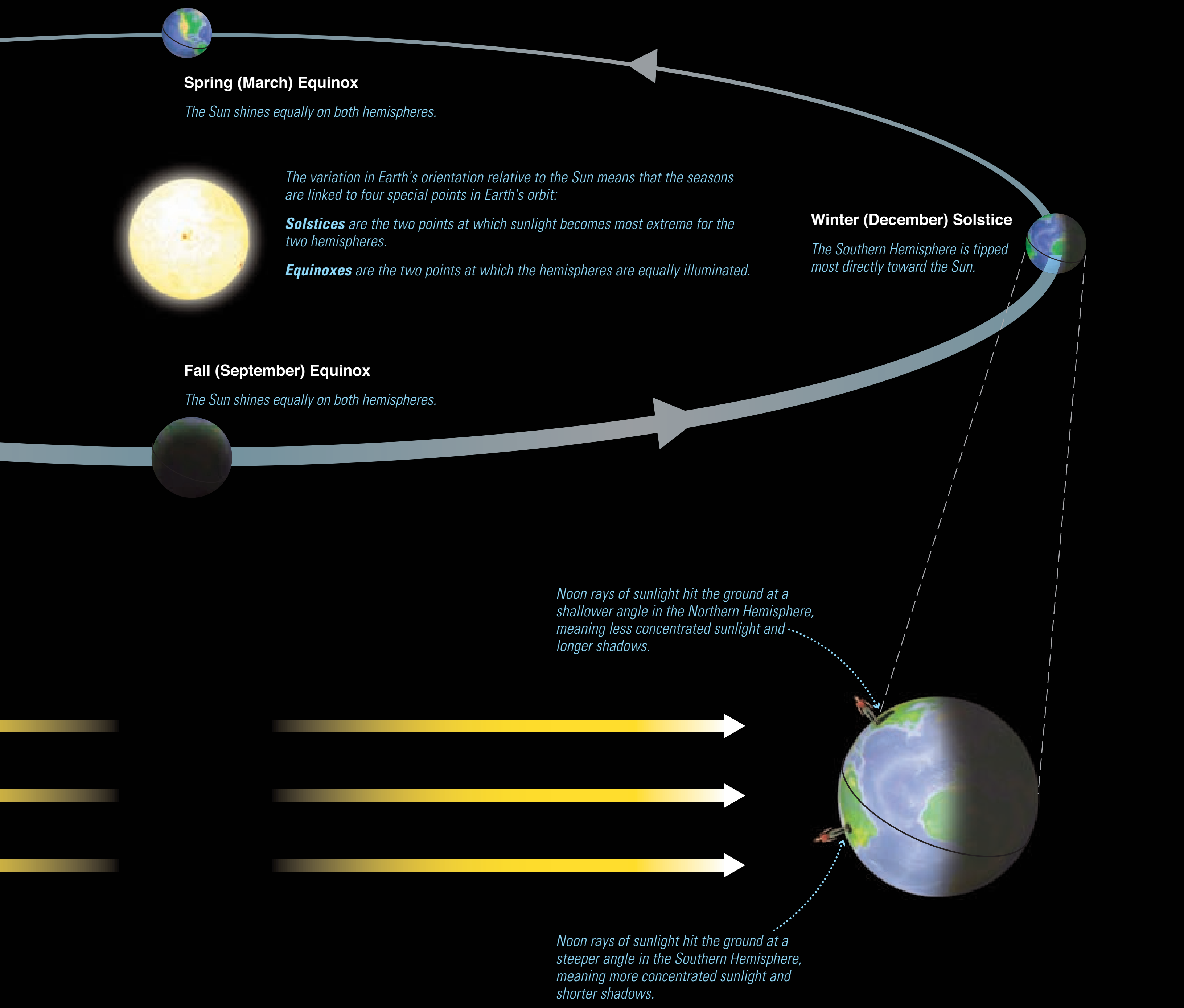
1. Earth's size relative to its orbit would be microscopic on this scale, meaning that both hemispheres are at essentially the same distance from the Sun.

2. The diagram is a side view of Earth's orbit. A top-down view (below) shows that Earth orbits in a nearly perfect circle and comes closest to the Sun in January.



3 **Spring/Fall:** Spring and fall begin when sunlight falls equally on both hemispheres, which happens twice a year: In March, when spring begins in the Northern Hemisphere and fall in the Southern Hemisphere; and in September, when fall begins in the Northern Hemisphere and spring in the Southern Hemisphere.

4 **Northern Winter/Southern Summer:** In December, sunlight falls less directly on the Northern Hemisphere, which makes it winter because solar energy is less concentrated and the Sun follows a shorter and lower path through the sky. The Southern Hemisphere receives more direct sunlight, making it summer.



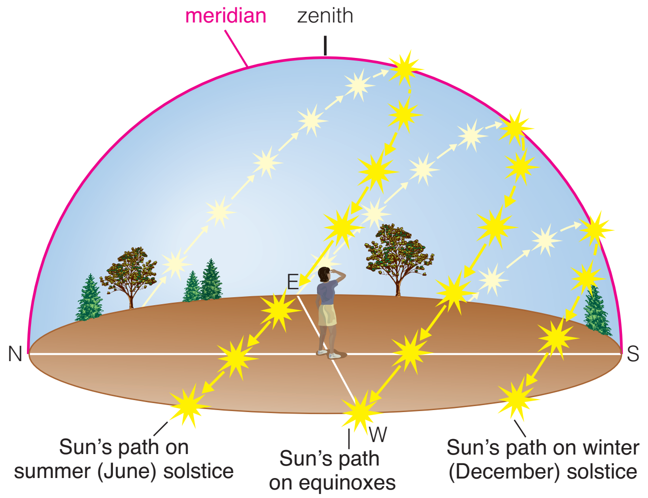


FIGURE 16 **interactive figure** This diagram shows the Sun's path on the solstices and equinoxes for a Northern Hemisphere sky (latitude 40°N). The precise paths are different for other latitudes; for example, at latitude 40°S, the paths look similar except tilted to the north rather than to the south. Notice that the Sun rises exactly due east and sets exactly due west only on the equinoxes.

FIGURE 17 This composite photograph shows images of the Sun taken at the same time of morning (technically, at the same "mean solar time") and from the same spot (over a large sundial in Carefree, Arizona) at 7- to 11-day intervals over the course of a year; the photo looks eastward, so north is to the left and south is to the right. Because this location is in the Northern Hemisphere, the Sun images that are high and to the north represent times near the summer solstice and the images that are low and to the south represent times near the winter solstice. The "figure 8" shape (called an *analemma*) arises from a combination of Earth's axis tilt and Earth's varying speed as it orbits the Sun.

Second, we usually think of the seasons in terms of weather, and the solstices and equinoxes correspond well with the beginnings of seasonal weather patterns. For example, although the Sun's path through the Northern Hemisphere sky is longest and highest around the time of the summer solstice, the warmest days tend to come 1 to 2 months later. To understand why, think about what happens when you heat a pot of cold soup. Even though you may have the stove turned on high from the start, it takes a while for the soup to warm up. In the same way, it takes some time for sunlight to heat the ground and oceans from the cold of winter to the warmth of summer. "Midsummer" in terms of weather therefore comes in late July and early August, which makes the summer solstice a pretty good choice for the "first day of summer." For similar reasons, the winter solstice is a good choice for the first day of winter, and the spring and fall equinoxes are good choices for the first days of those seasons.

Seasons Around the World Notice that the names of the solstices and equinoxes reflect the northern seasons, and therefore sound backward to people who live in the Southern Hemisphere. For example, Southern Hemisphere winter begins when Earth is at the orbital point usually called the *summer* solstice. This apparent injustice to people in the Southern Hemisphere arose because the solstices and equinoxes were named long ago by people living in the Northern Hemisphere. A similar injustice is inflicted on people living in equatorial regions. If you study Figure 15 carefully, you'll see that Earth's equator gets its most direct sunlight on the two equinoxes and its least direct sunlight on the solstices. People living near the equator therefore don't experience four seasons in the same way as people living at mid-latitudes. Instead, equatorial regions generally have rainy and dry seasons, with the rainy seasons coming when the Sun is higher in the sky.

In addition, seasonal variations around the times of the solstices are more extreme at high latitudes. For example, Vermont has much longer summer days and much longer winter nights than Florida. At the Arctic Circle (latitude $66\frac{1}{2}°$), the Sun remains above the horizon all day long on the summer solstice (**FIGURE 18**), and never rises on the winter solstice. The most extreme cases occur at the North and South Poles, where the Sun remains above the horizon for 6 months in summer and below the horizon for 6 months in winter.*

COMMON MISCONCEPTIONS

High Noon

When is the Sun directly overhead in your sky? Many people answer "at noon." It's true that the Sun reaches its *highest* point each day when it crosses the meridian, giving us the term "high noon" (though the meridian crossing is rarely at precisely 12:00). However, unless you live in the Tropics (between latitudes 23.5°S and 23.5°N), the Sun is *never* directly overhead. In fact, any time you can see the Sun as you walk around, you can be sure it is not at your zenith. Unless you are lying down, seeing an object at the zenith requires tilting your head back into a very uncomfortable position.

Why Orbital Distance Doesn't Affect Our Seasons

We've seen that the seasons are caused by Earth's axis tilt, not by Earth's slightly varying distance from the Sun. Still, we might expect the varying orbital distance to play at least some role. For example, the Northern Hemisphere has winter when

*These statements are true for the Sun's *real* position, but the bending of light by Earth's atmosphere makes the Sun *appear* to be about 0.6° higher than it really is when it is near the horizon.

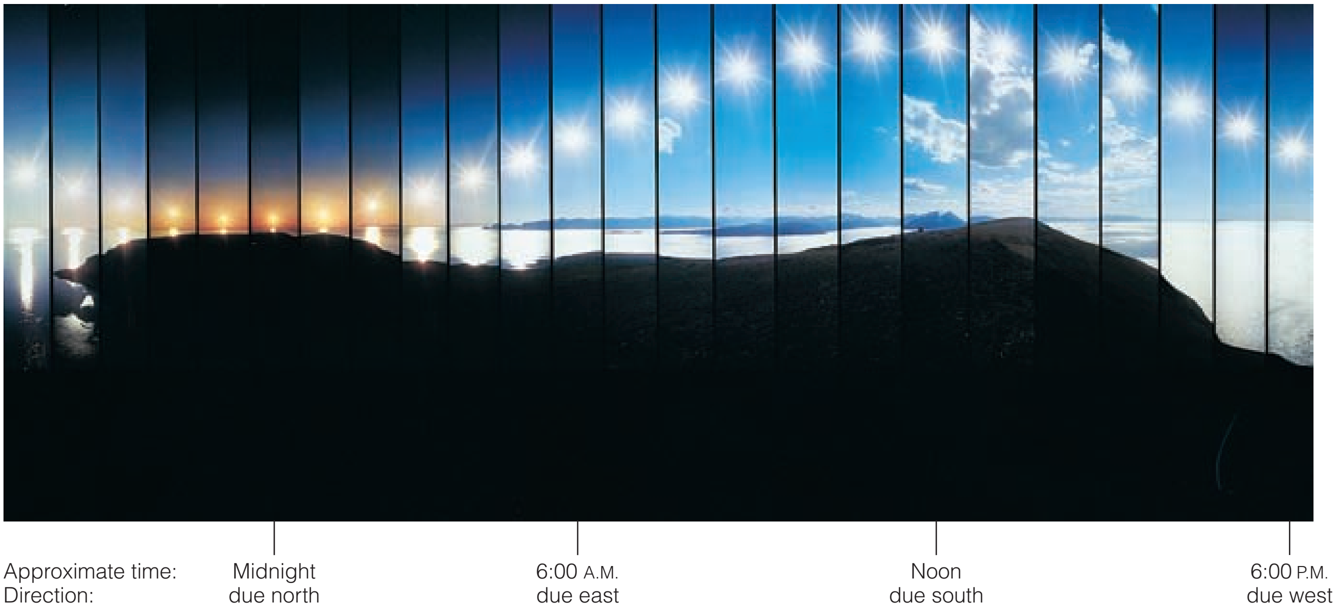


FIGURE 18 This sequence of photos shows the progression of the Sun around the horizon on the summer solstice at the Arctic Circle. Notice that the Sun skims the northern horizon at midnight, then gradually rises higher, reaching its highest point when it is due South at noon.

Earth is closer to the Sun and summer when Earth is farther away (see the lower left diagram in Figure 15), so we might expect the Northern Hemisphere to have more moderate seasons than the Southern Hemisphere. In fact, weather records show that the opposite is true: Northern Hemisphere seasons are slightly more extreme than those of the Southern Hemisphere.

The main reason for this surprising fact becomes clear when you look at a map of Earth (**FIGURE 19**). Most of Earth's land lies in the Northern Hemisphere, with far more ocean in the Southern Hemisphere. As you'll notice at any beach, lake, or pool, water takes longer to heat or cool than soil or rock (largely because sunlight heats bodies of water to a depth of many meters while heating only the very top layer of land). The water temperature therefore remains fairly steady both day and night, while the ground can heat up and cool down dramatically. The Southern Hemisphere's larger amount of ocean moderates its climate. The Northern Hemisphere, with more land and less ocean, heats up and cools down more easily, which is why it has the more extreme seasons.

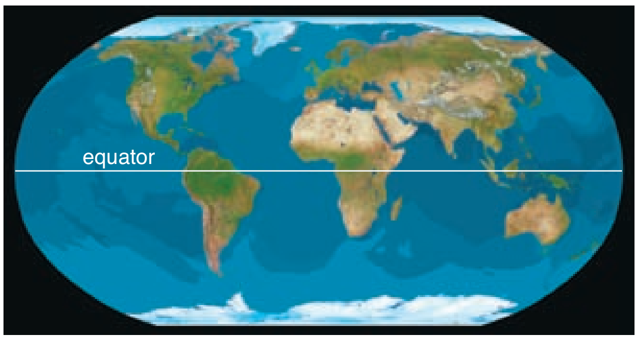


FIGURE 19 Most land lies in the Northern Hemisphere while most ocean lies in the Southern Hemisphere. The climate-moderating effects of water make Southern Hemisphere seasons less extreme than Northern Hemisphere seasons.

Although distance from the Sun plays no role in Earth's seasons, the same is not true for planets that have much greater distance variations. For example, Mars has about the same axis tilt as Earth and therefore has similar seasonal patterns. However, because Mars is more than 20% closer to the Sun during its Southern Hemisphere summer than during its Northern Hemisphere summer, its Southern Hemisphere experiences much more extreme seasonal changes.

How does the orientation of Earth's axis change with time?

We have now discussed both daily and seasonal changes in the sky, but there are other changes that occur over longer periods of time. One of the most important of these slow changes is **precession,** a gradual wobble that alters the orientation of Earth's axis in space.

Precession occurs with many rotating objects. You can see it easily by spinning a top (**FIGURE 20a**). As the top spins rapidly, you'll notice that its axis also sweeps out a circle at a slower rate. We say that the top's axis *precesses.* Earth's axis precesses in much the same way, but far more slowly (**FIGURE 20b**). Each cycle of Earth's precession takes about 26,000 years, gradually changing where the axis points in space. Today, the axis points toward Polaris, making it our North Star. Some 13,000 years from now, Vega will be the bright star closest to true north. At most other times, the axis does not point near any bright star.

Notice that precession does not change the *amount* of the axis tilt (which stays close to $23\frac{1}{2}°$) and therefore does not affect the pattern of the seasons. However, because the solstices and equinoxes correspond to points in Earth's orbit that depend on the direction the axis points in space, their positions in the orbit gradually shift with the cycle of precession. As a result, the constellations associated with the solstices and equinoxes

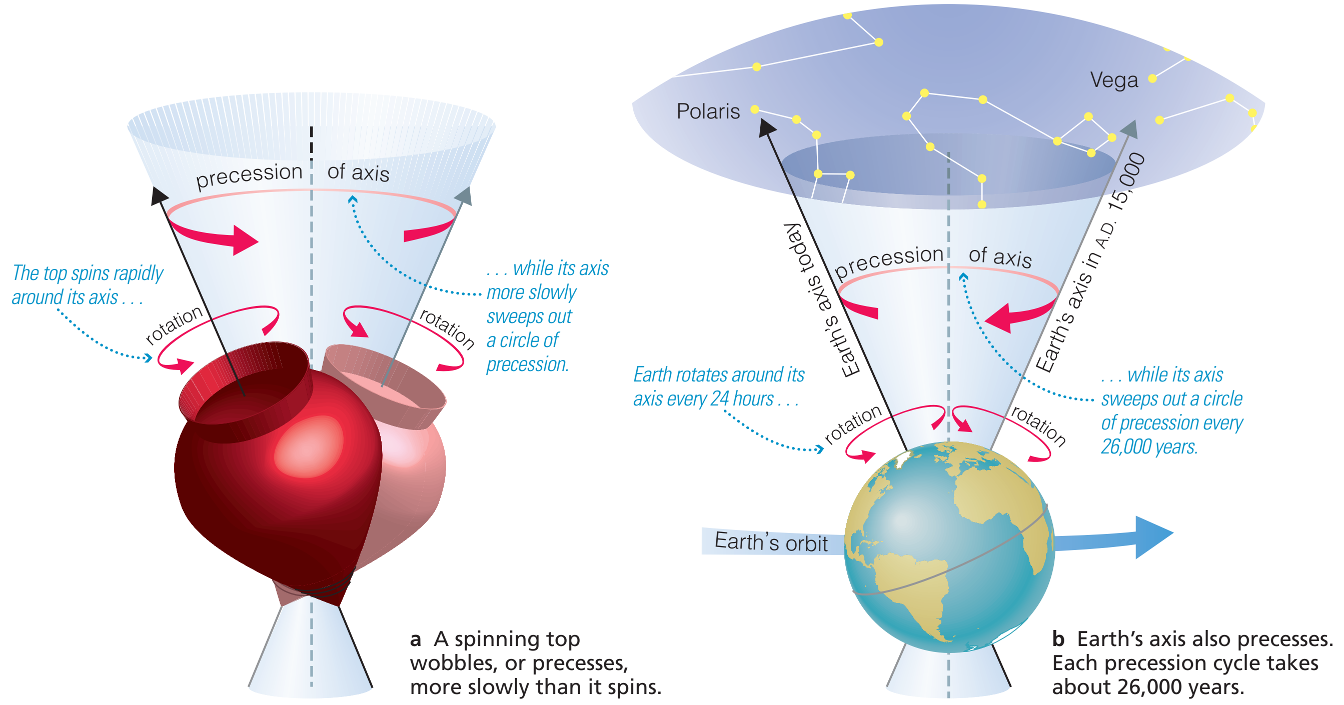


FIGURE 20 interactive figure Precession affects the orientation of a spinning object's axis but not the amount of its tilt.

change over time. For example, a couple thousand years ago the Sun appeared in the constellation Cancer on the day of the summer solstice, but now it appears in Gemini on that day. This explains something you can see on any world map: The latitude at which the Sun is directly overhead on the summer solstice ($23\frac{1}{2}$°N) is called the *Tropic of Cancer,* telling us that it got its name back when the Sun used to appear in Cancer on the summer solstice.

THINK ABOUT IT

What constellation will the Sun be in on the summer solstice about 2000 years from now? (*Hint:* Figure 14 shows the names and order of the zodiac constellations.)

Precession is caused by gravity's effect on a tilted, rotating object that is *not* a perfect sphere. You have probably seen how gravity affects a top. If you try to balance a nonspinning top on its point, it will fall over almost immediately. This happens because a top that is not spherical will inevitably lean a little to one side. No matter how slight this lean, gravity will quickly tip the nonspinning top over. However, if you spin the top rapidly, it does not fall over so easily. The spinning top stays upright because rotating objects tend to keep spinning around the same rotation axis (a consequence of the *law of conservation of angular momentum*). This tendency prevents gravity from immediately pulling the spinning top over, since falling over would mean a change in the spin axis from near-vertical to horizontal. Instead, gravity succeeds only in making the axis trace circles of precession. As friction slows the top's spin, the circles of precession get wider and wider, and ultimately the top falls over. If there were no friction to slow its spin, the top would spin and precess forever.

The spinning (rotating) Earth precesses because of gravitational tugs from the Sun and Moon. Earth is not quite a perfect sphere, because it bulges at its equator. Because the equator is tilted $23\frac{1}{2}$° to the ecliptic plane, the gravitational attractions of the Sun and Moon try to pull the equatorial bulge into the ecliptic plane, effectively trying to "straighten out" Earth's axis tilt. However, like the spinning top, Earth tends to keep rotating around the same axis. Gravity therefore does not succeed in changing Earth's axis tilt and instead only makes the axis precess. To gain a better understanding of precession and how it works, you might wish to experiment with a simple toy gyroscope. *Gyroscopes* are essentially

COMMON MISCONCEPTIONS

Sun Signs

You probably know your astrological "Sun sign." When astrology began a few thousand years ago, your Sun sign was supposed to represent the constellation in which the Sun appeared on your birth date. However, because of precession, this is no longer the case for most people. For example, if your birthday is March 21, your Sun sign is Aries even though the Sun now appears in Pisces on that date. The problem is that astrological Sun signs are based on the positions of the Sun among the stars as they were almost 2000 years ago. Because Earth's axis has moved about 1/13 of the way through its 26,000-year precession cycle since that time, the Sun signs are off by nearly a month from the actual positions of the Sun among the constellations today.

rotating wheels mounted in a way that allows them to move freely, which makes it easy to see how their spin rate affects their motion. (The fact that gyroscopes tend to keep the same rotation axis makes them very useful in aircraft and spacecraft navigation.)

MA Phases of the Moon Tutorial, Lessons 1–3

3 THE MOON, OUR CONSTANT COMPANION

Aside from the seasons and the daily circling of the sky, the most familiar pattern of change in the sky is that of the changing phases of the Moon. We will explore these changes in this section—along with the rarer changes that occur with eclipses—and see that they are consequences of the Moon's orbit around Earth.

Why do we see phases of the Moon?

As the Moon orbits Earth, it returns to the same position relative to the Sun in our sky (such as along the Earth-Sun line) about every $29\frac{1}{2}$ days. This time period marks the cycle of **lunar phases**, in which the Moon's appearance in our sky changes as its position relative to the Sun changes. This $29\frac{1}{2}$-day period is also the origin of the word *month* (think "moonth").

The Moon's Orbit to Scale FIGURE 21 shows the Moon's orbit on a 1-to-10-billion scale model of the solar system. On this scale, the Sun is about the size of a large grapefruit, which means the entire orbit of the Moon could fit inside it. When you then consider the fact that the Sun is located 15 meters away on this scale, you'll realize that for practical purposes the Sun's rays all hit Earth and the Moon from the same direction. This fact is helpful to understanding the Moon's phases, because it means we can think of sunlight coming from a single direction at both Earth and the Moon, an effect shown clearly in the inset photo. The figure also shows the elliptical shape of the Moon's orbit, which causes the Earth-Moon distance to vary between about 356,000 and 407,000 kilometers.

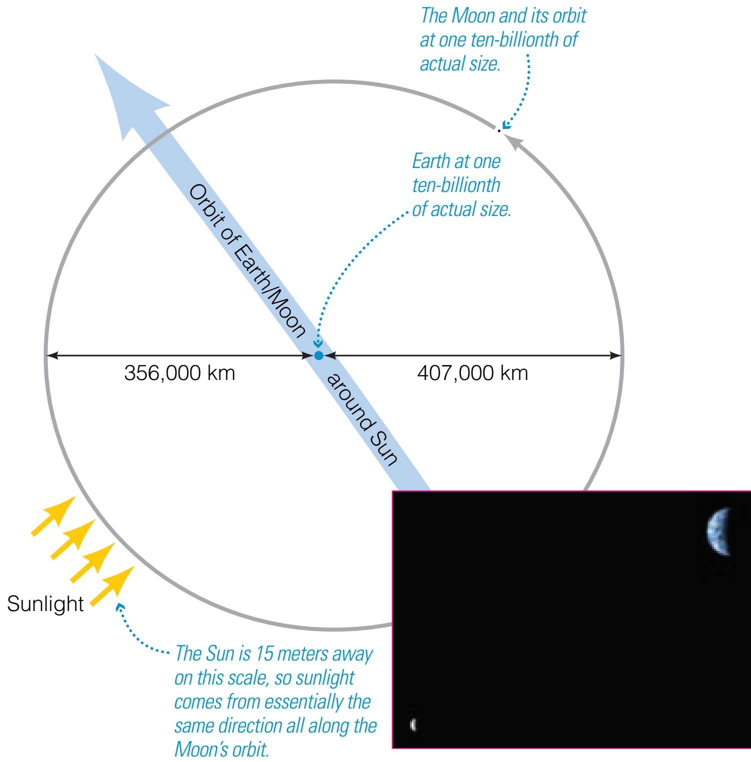


FIGURE 21 The Moon's orbit on a 1-to-10-billion scale; black labels indicate the Moon's actual distance at its nearest to and farthest from Earth. The orbit is so small compared to the distance to the Sun that sunlight strikes the entire orbit from the same direction. You can see this in the inset photo, which shows the Moon and Earth photographed from Mars by the Mars Reconnaissance Orbiter.

> **SEE IT FOR YOURSELF**
>
> Like the Sun, the Moon appears to move gradually eastward through the constellations of the zodiac. However, while the Sun takes a year for each circuit, the Moon takes only about a month, which means it moves at a rate of about 360° per month, or $\frac{1}{2}°$—its own angular size—each hour. If the Moon is visible tonight, go out and note its location relative to a few bright stars. Then go out again a couple hours later. Can you notice the Moon's change in position relative to the stars?

Understanding Phases The easiest way to understand the lunar phases is with the simple demonstration illustrated in FIGURE 22. Take a ball outside on a sunny day. (If it's dark or cloudy, you can use a flashlight instead of the Sun; put the flashlight on a table a few meters away and shine it toward you.) Hold the ball at arm's length to represent the Moon while your head represents Earth. Slowly spin counterclockwise so that the ball goes around you the way the Moon orbits Earth. (If you live in the Southern Hemisphere, spin clockwise because you view the sky "upside down" compared to the Northern Hemisphere.) As you turn, you'll see the ball go through phases just like the Moon's. If you think about what's happening, you'll realize that the phases of the ball result from just two basic facts:

1. Half the ball always faces the Sun (or flashlight) and therefore is bright, while the other half faces away from the Sun and therefore is dark.

2. As you look at the ball at different positions in its "orbit" around your head, you see different combinations of its bright and dark faces.

For example, when you hold the ball directly opposite the Sun, you see only the bright portion of the ball, which represents the "full" phase. When you hold the ball at its "first-quarter" position, half the face you see is dark and the other half is bright.

We see lunar phases for the same reason. Half the Moon is always illuminated by the Sun, but the amount of this illuminated half that we see from Earth depends on the Moon's position in its orbit. The photographs in Figure 22 show how the phases look.

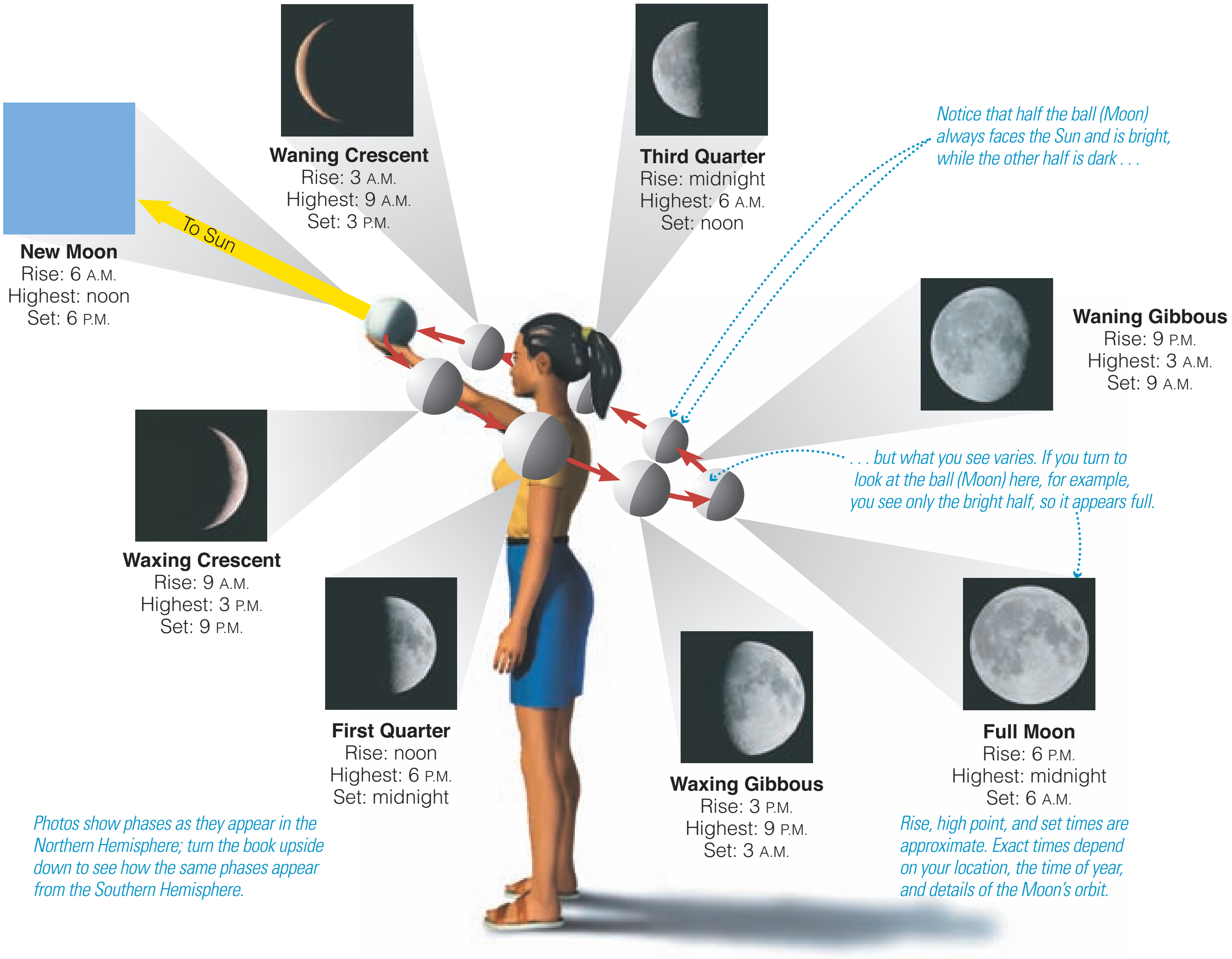


FIGURE 22 interactive figure A simple demonstration illustrates the phases of the Moon. The half of the ball (Moon) facing the Sun is always illuminated while the half facing away is always dark, but you see the ball go through phases as it orbits around your head (Earth). (The new moon photo shows blue sky, because a new moon is always close to the Sun in the sky and hence hidden from view by the bright light of the Sun.)

The Moon's phase is directly related to the time it rises, reaches its highest point in the sky, and sets. For example, the full moon must rise around sunset, because it occurs when the Moon is opposite the Sun in the sky. It therefore reaches its highest point in the sky at midnight and sets around sunrise. Similarly, a first-quarter moon must rise around noon, reach its highest point around 6 p.m., and set around midnight, because it occurs when the Moon is about 90° east of the Sun in our sky. Figure 22 lists the approximate rise, highest point, and set times for each phase.

THINK ABOUT IT

Suppose you go outside in the morning and notice that the visible face of the Moon is half light and half dark. Is this a first-quarter or third-quarter moon? How do you know?

Notice that the phases from new to full are said to be *waxing*, which means "increasing." Phases from full to new are *waning*, or "decreasing." Also notice that no phase is called a "half moon." Instead, we see half the Moon's face at first-quarter and third-quarter phases; these phases mark the times when the Moon is one quarter or three quarters of the way through its monthly cycle (which begins at new moon). The phases just before and after new moon are called *crescent*, while those just before and after full moon are called *gibbous* (pronounced with a hard *g* as in "gift"). A gibbous moon is

COMMON MISCONCEPTIONS

Shadows and the Moon

Many people guess that the Moon's phases are caused by Earth's shadow falling on its surface, but this is not the case. As we've seen, the Moon's phases are caused by the fact that we see different portions of its day and night sides at different times as it orbits around Earth. The only time Earth's shadow falls on the Moon is during the relatively rare event of a lunar eclipse.

essentially the opposite of a crescent moon—a crescent moon has a small sliver of light while a gibbous moon has a small sliver of dark. The term *gibbous* literally means "hump-backed," so you can see how the gibbous moon got its name.

The Moon's Synchronous Rotation Although we see many *phases* of the Moon, we do not see many *faces*. From Earth we always see (nearly*) the same face of the Moon. This happens because the Moon rotates on its axis in the same amount of time it takes to orbit Earth, a trait called **synchronous rotation**. A simple demonstration shows the idea. Place a ball on a table to represent Earth while you represent the Moon. Start by facing the ball. If you do not rotate as you walk around the ball, you'll be looking away from it by the time you are halfway around your orbit (**FIGURE 23a**). The only way you can face the ball at all times is by completing exactly one rotation while you complete one orbit (**FIGURE 23b**). Note that the Moon's synchronous rotation is *not* a coincidence; rather, it is a consequence of Earth's gravity affecting the Moon in much the same way the Moon's gravity causes tides on Earth.

The View from the Moon A good way to solidify your understanding of the lunar phases is to imagine that you live on the side of the Moon that faces Earth. For example, what would you see if you looked at Earth when people on Earth saw a new moon? By remembering that a new moon occurs when the Moon is between the Sun and Earth, you'll realize that from the Moon you'd be looking at Earth's daytime side and hence would see a *full earth*. Similarly, at full moon you would be facing the night side of Earth and would see a *new earth*. In general, you'd always see Earth in a phase opposite the phase of the Moon seen by people on Earth at the same time. Moreover, because the Moon always shows nearly the same face to Earth, Earth would appear to hang nearly stationary in your sky as it went through its cycle of phases.

*Because the Moon's orbital speed varies (in accord with Kepler's second law) while its rotation rate is steady, the visible face appears to wobble slightly back and forth as the Moon orbits Earth. This effect, called *libration*, allows us to see a total of about 59% of the Moon's surface over the course of a month, even though we see only 50% of the Moon at any single time.

COMMON MISCONCEPTIONS

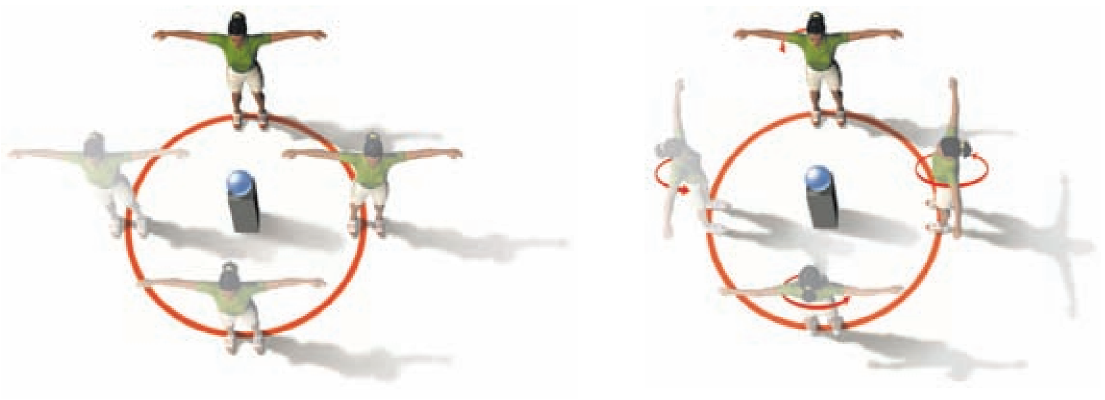
The "Dark Side" of the Moon

Some people refer to the far side of the Moon—meaning the side that we never see from Earth—as the *dark side*. But this is not correct, because the far side is not always dark. For example, during new moon the far side faces the Sun and hence is completely sunlit. In fact, because the Moon rotates with a period of approximately one month (the same time it takes to orbit Earth), points on both the near and the far side have two weeks of daylight alternating with two weeks of darkness. The only time the far side is completely dark is at full moon, when it faces away from both the Sun and Earth.

THINK ABOUT IT

About how long would each day and night last if you lived on the Moon? Explain.

Thinking about the view from the Moon clarifies another interesting feature of the lunar phases: The dark portion of the lunar face is not *totally* dark. Just as we can see at night by the light of the Moon, if you were in the dark area of the Moon during crescent phase your moonscape would be illuminated by a nearly full (gibbous) Earth. In fact, because Earth is much larger than the Moon, the illumination would be much greater than what the full moon provides on Earth. In other words, sunlight reflected by Earth faintly illuminates the "dark" portion of the Moon's face. We call this illumination the *ashen light*, or *earthshine*, and it enables us to see the outline of the full face of the Moon even when the Moon is not full.



a If you do not rotate while walking around the model, you will not always face it.

b You will face the model at all times only if you rotate exactly once during each orbit.

FIGURE 23 The fact that we always see the same face of the Moon means that the Moon must rotate once in the same amount of time it takes to orbit Earth once. You can see why by walking around a model of Earth while imagining that you are the Moon.

MA Eclipses Tutorial, Lessons 1–3

What causes eclipses?

Occasionally, the Moon's orbit around Earth causes events much more dramatic than lunar phases. The Moon and Earth both cast shadows in sunlight, and these shadows can create **eclipses** when the Sun, Earth, and Moon fall into a straight line. Eclipses come in two basic types:

- A **lunar eclipse** occurs when Earth lies directly between the Sun and Moon, so Earth's shadow falls on the Moon.
- A **solar eclipse** occurs when the Moon lies directly between the Sun and Earth, so the Moon's shadow falls on Earth.

Note that, because Earth is much larger than the Moon, Earth's shadow can cover the entire Moon during a lunar eclipse. Therefore, a lunar eclipse can be seen by anyone on the night side of Earth when it occurs. In contrast, the Moon's shadow can cover only a small portion of Earth at any one moment, so you must be living within the relatively small pathway through which the shadow moves to see a solar eclipse. That is why you see lunar eclipses more often than solar eclipses, even though both types occur about equally often.

Conditions for Eclipses Look once more at Figure 22. The figure makes it look as if the Sun, Earth, and Moon line up with every new and full moon. If this figure told the whole story of the Moon's orbit, we would have both a lunar and a solar eclipse every month—but we don't.

The missing piece of the story in Figure 22 is that the Moon's orbit is slightly inclined (by about 5°) to the ecliptic plane (the plane of Earth's orbit around the Sun). To visualize this inclination, imagine the ecliptic plane as the surface of a pond, as shown in FIGURE 24. Because of the inclination of its orbit, the Moon spends most of its time either above or below this surface. It crosses *through* this surface only twice during each orbit: once coming out and once going back in. The two points in each orbit at which the Moon crosses the surface are called the **nodes** of the Moon's orbit.

Notice that the nodes are aligned approximately the same way (diagonally on the page in Figure 24) throughout the year, which means they lie along a nearly straight line with

COMMON MISCONCEPTIONS

Moon in the Daytime and Stars on the Moon

Night is so closely associated with the Moon in traditions and stories that many people mistakenly believe that the Moon is visible only in the nighttime sky. In fact, the Moon is above the horizon as often in the daytime as at night, though it is easily visible only when its light is not drowned out by sunlight. For example, a first-quarter moon is easy to spot in the late afternoon as it rises through the eastern sky, and a third-quarter moon is visible in the morning as it heads toward the western horizon.

Another misconception appears in illustrations that show a star in the dark portion of the crescent moon. The star in the dark portion appears to be in front of the Moon, which is impossible because the Moon is much closer to us than is any star.

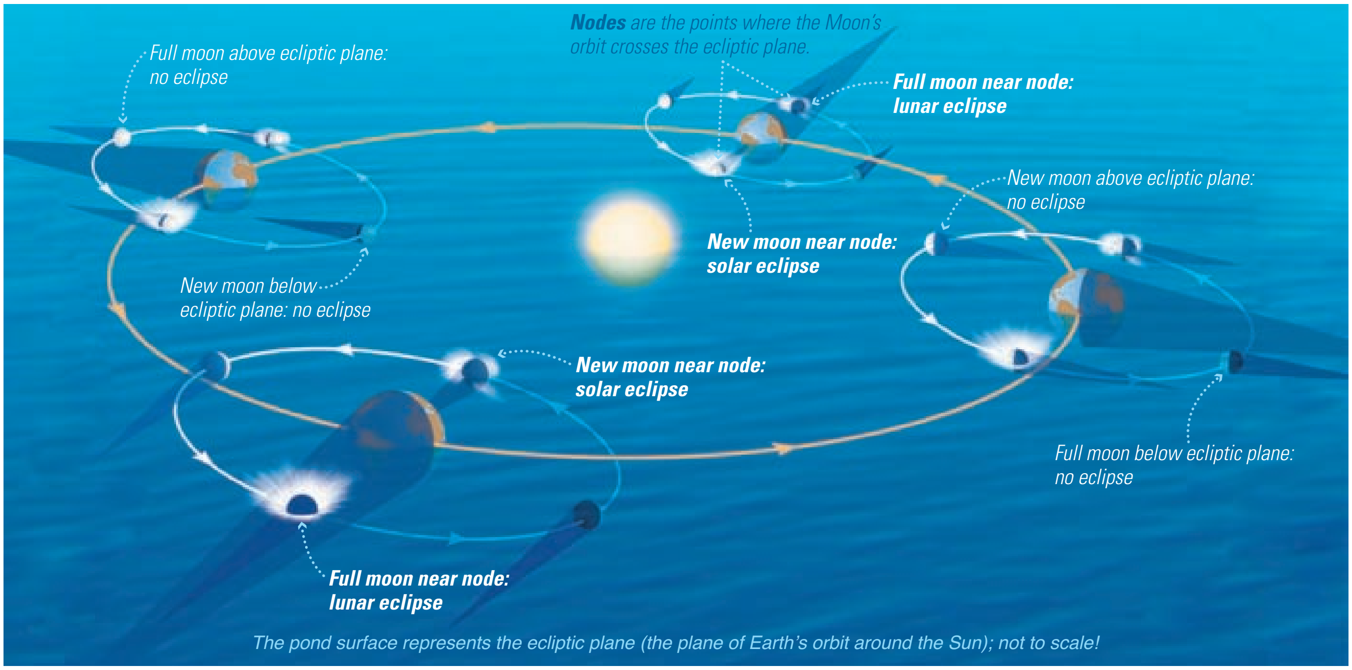


FIGURE 24 This illustration represents the ecliptic plane as the surface of a pond. The Moon's orbit is tilted by about 5° to the ecliptic plane, so the Moon spends half of each orbit above the plane (the pond surface) and half below it. Eclipses occur only when the Moon is at both a node (passing through the pond surface) and a phase of either new moon (for a solar eclipse) or full moon (for a lunar eclipse)—as is the case with the lower left and top right orbits shown.

the Sun and Earth about twice each year. We therefore find the following conditions for an eclipse to occur:

1. The phase of the Moon must be full (for a lunar eclipse) or new (for a solar eclipse).
2. The new or full moon must occur during one of the periods when the nodes of the Moon's orbit are aligned with the Sun and Earth.

Inner and Outer Shadows Figure 24 shows the Moon and Earth each casting only a simple "shadow cone" (extending away from the Sun) at each position shown. However, a closer look at the geometry shows that the shadow of the Moon or Earth actually consists of two distinct regions: a central **umbra,** where sunlight is completely blocked, and a surrounding **penumbra,** where sunlight is only partially blocked (**FIGURE 25**). The shadow cones in Figure 24 represent only the umbra, but both shadow regions are important to understanding eclipses.

Lunar Eclipses A lunar eclipse begins at the moment when the Moon's orbit first carries it into Earth's penumbra. After that, we will see one of three types of lunar eclipse (**FIGURE 26**). If the Sun, Earth, and Moon are nearly perfectly aligned, the

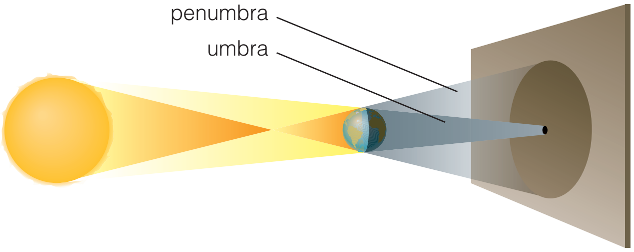


FIGURE 25 The shadow cast by an object in sunlight. Sunlight is fully blocked in the umbra and partially blocked in the penumbra.

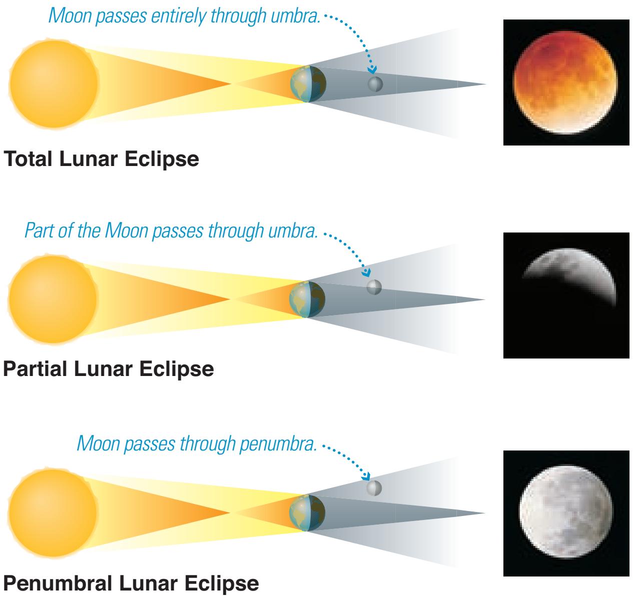


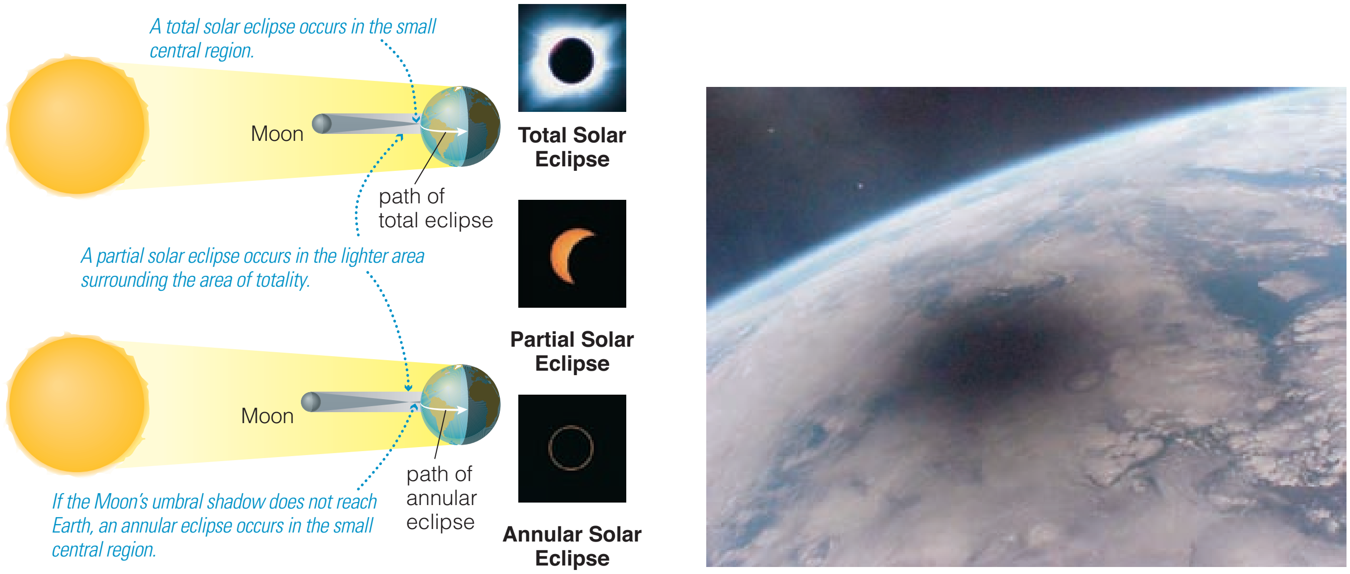
FIGURE 26 interactive figure The three types of lunar eclipse.

FIGURE 27 This multiple-exposure photograph shows the progression (left to right) of a total lunar eclipse observed from Tenerife, Canary Islands (Spain). Totality began (far right) just before the Moon set in the west. Notice Earth's curved shadow advancing across the Moon during the partial phases, and the redness of the full moon during totality.

Moon passes through Earth's umbra and we see a **total lunar eclipse.** If the alignment is somewhat less perfect, only part of the full moon passes through the umbra (with the rest in the penumbra) and we see a **partial lunar eclipse.** If the Moon passes through *only* Earth's penumbra, we see a **penumbral lunar eclipse.** Penumbral eclipses are the most common type of lunar eclipse, but they are the least visually impressive because the full moon darkens only slightly.

Total lunar eclipses are the most spectacular. The Moon becomes dark and eerily red during **totality**, when the Moon is entirely engulfed in the umbra. Totality usually lasts about an hour, with partial phases both before and after. The curvature of Earth's shadow during partial phases shows that Earth is round (**FIGURE 27**). To understand the redness during totality, consider the view of an observer on the eclipsed Moon, who would see Earth's night side surrounded by the reddish glow of all the sunrises and sunsets occurring on the Earth at that moment. It is this reddish light that illuminates the Moon during total eclipse.

Solar Eclipses We can also see three types of solar eclipse (**FIGURE 28**). If a solar eclipse occurs when the Moon is in a part of its orbit where it is relatively close to Earth (see Figure 21), the Moon's umbra can cover a small area of Earth's surface (up to about 270 kilometers in diameter). Within this area you will see a **total solar eclipse.** If the eclipse occurs when the Moon is in a part of its orbit that puts it farther from Earth, the umbra may not reach Earth's surface at all. In that case, you will see an **annular eclipse**—a ring of sunlight surrounding the Moon—in the small region of Earth directly behind the umbra. In either case, the region of totality or annularity will be surrounded by a much larger region (typically about 7000 kilometers in diameter) that falls within the Moon's penumbral shadow. Here you will see a **partial solar eclipse,** in which only part of the Sun is blocked from view. The combination of Earth's rotation and the Moon's orbital motion causes the Moon's shadows to race across the



a The three types of solar eclipse. The diagrams show the Moon's shadow falling on Earth; note the dark central umbra surrounded by the much lighter penumbra.

b This photo from Earth orbit shows the Moon's shadow (umbra) on Earth during a total solar elipse. Notice that only a small region of Earth experiences totality at any one time.

FIGURE 28 interactive figure During a solar eclipse, the Moon's small shadow moves rapidly across the face of Earth.

face of Earth at a typical speed of about 1700 kilometers per hour. As a result, the umbral shadow traces a narrow path across Earth, and totality never lasts more than a few minutes in any particular place.

A total solar eclipse is a spectacular sight. It begins when the disk of the Moon first appears to touch the Sun. Over the next couple of hours, the Moon appears to take a larger and larger "bite" out of the Sun. As totality approaches, the sky darkens and temperatures fall. Birds head back to their nests, and crickets begin their nighttime chirping. During the few minutes of totality, the Moon completely blocks the normally visible disk of the Sun, allowing the faint *corona* to be seen (**FIGURE 29**). The surrounding sky takes on a twilight glow, and planets and bright stars become visible in the daytime. As totality ends, the Sun slowly emerges from behind the Moon over the next couple of hours. However, because your eyes have adapted to the darkness, totality appears to end far more abruptly than it began.

FIGURE 29 This multiple-exposure photograph shows the progression of a total solar eclipse over La Paz, Mexico. Totality (central image) lasts only a few minutes, during which time we can see the faint corona around the outline of the Sun. The foreground church was photographed at a different time of day.

Predicting Eclipses Few phenomena have so inspired and humbled humans throughout the ages as eclipses. For many cultures, eclipses were mystical events associated with fate or the gods, and countless stories and legends surround them. One legend holds that the Greek philosopher Thales (c. 624–546 B.C.) successfully predicted the year (but presumably not the precise time) that a total eclipse of the Sun would be visible in the area where he lived, which is now part of Turkey. The eclipse occurred as two opposing armies (the Medes and the Lydians) were massing for battle, and it so frightened them that they put down their weapons, signed a treaty, and returned home. Because modern research shows that the only eclipse visible in that part of the world at about that time occurred on May 28, 585 B.C., we know the precise date on which the treaty was signed—the earliest historical event that can be dated precisely.

Much of the mystery of eclipses probably stems from the relative difficulty of predicting them. Look again at Figure 24. The two periods each year when the nodes of the Moon's orbit are nearly aligned with the Sun are called **eclipse seasons.** Each eclipse season lasts a few weeks. Some type of lunar eclipse occurs during each eclipse season's full moon, and some type of solar eclipse occurs during its new moon.

If Figure 24 told the whole story, eclipse seasons would occur every 6 months and predicting eclipses would be easy. For example, if eclipse seasons always occurred in January and July, eclipses would always occur on the dates of new and full moons in those months. Actual eclipse prediction is

TABLE 1 **Lunar Eclipses 2013–2016***

Date	Type	Where You Can See It
April 25, 2013	partial	Europe, Africa, Asia, Australia
May 25, 2013	penumbral	Americas, Africa
Oct. 18, 2013	penumbral	Americas, Europe, Africa, Asia
April 15, 2014	total	Australia, Pacific, Americas
Oct. 8, 2014	total	Asia, Australia, Pacific, Americas
April 4, 2015	total	Asia, Australia, Pacific, Americas
Sept. 28, 2015	total	Americas, Europe, Africa
March 23, 2016	penumbral	Asia, Australia, Pacific, western Americas
Sept. 16, 2016	penumbral	Europe, Africa, Asia, Australia

*Dates are based on Universal Time and hence are those in Greenwich, England, at the time of the eclipse; check a news source for the local time and date. Eclipse predictions by Fred Espenak, NASA GSFC.

more difficult than this because of something the figure does not show: The nodes slowly move around the Moon's orbit, so the eclipse seasons occur slightly less than 6 months apart (about 173 days apart).

The combination of the changing dates of eclipse seasons and the $29\frac{1}{2}$-day cycle of lunar phases makes eclipses recur in a cycle of about 18 years, $11\frac{1}{3}$ days, called the **saros cycle.** Astronomers in many ancient cultures identified the saros cycle and used it to make eclipse predictions. For example, in the Middle East the Babylonians achieved remarkable success at predicting eclipses more than 2500 years ago, and the Mayans achieved similar success in Central America; in fact, the Mayan calendar includes a cycle (the *sacred round*) of 260 days—almost exactly $1\frac{1}{2}$ times the 173.32 days between successive eclipse seasons.

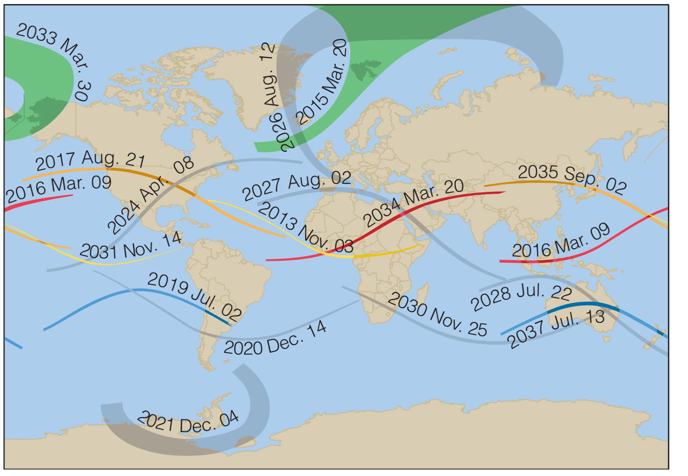


FIGURE 30 This map shows the paths of totality for solar eclipses from 2013 through 2037. Paths of the same color represent eclipses occurring in successive saros cycles, separated by 18 years 11 days. For example, the 2034 eclipse occurs 18 years 11 days after the 2016 eclipse (both shown in red). Eclipse predictions by Fred Espenak, NASA GSFC.

However, while the saros cycle allows you to predict when an eclipse will occur, it does not allow you to predict exactly where or the precise type of eclipse. For example, if a total solar eclipse occurred today, another would occur 18 years $11\frac{1}{3}$ days from now, but it would not be visible from the same places on Earth and might be annular or partial rather than total. No ancient culture achieved the ability to predict eclipses in every detail.

Today, we can predict eclipses because we know the precise details of the orbits of Earth and the Moon. **TABLE 1** lists upcoming lunar eclipses; notice that, as we expect, eclipses generally come a little less than 6 months apart. **FIGURE 30** shows paths of totality for upcoming total solar eclipses (but not for partial or annular eclipses), using color coding to show eclipses that repeat with the saros cycle.

THINK ABOUT IT

In Table 1, notice that there's one exception to the "rule" of eclipses coming a little less than 6 months apart: the 2013 lunar eclipses of April 25 and May 25. How can eclipses occur just a month apart? Explain.

SPECIAL TOPIC

Does the Moon Influence Human Behavior?

From myths of werewolves to stories of romance under the full moon, human culture is filled with claims that the Moon influences our behavior. Can we say anything scientific about such claims?

The Moon clearly has important influences on Earth, perhaps most notably through its role in creating tides. Although the Moon's tidal force cannot directly affect objects as small as people, the ocean tides have indirect effects. For example, fishermen, boaters, and surfers all adjust at least some of their activities to the cycle of the tides.

Another potential influence might come from the lunar phases. Physiological patterns in many species appear to follow the lunar phases; for example, some crabs and turtles lay eggs only at full moon. No human trait is so closely linked to lunar phases, but the average human menstrual cycle is so close in length to a lunar month that it is difficult to believe the similarity is mere coincidence.

Nevertheless, aside from the physiological cycles and the influence of tides on people who live near the oceans, claims that the lunar phase affects human behavior are difficult to verify scientifically. For example, although it is possible that the full moon brings out certain behaviors, it may also simply be that some behaviors are easier to engage in when the sky is bright. A beautiful full moon may bring out your desire to walk on the beach under the moonlight, but there is no scientific evidence to suggest that the full moon would affect you the same way if you were confined to a deep cave.

4 THE ANCIENT MYSTERY OF THE PLANETS

We've now covered the appearance and motion of the stars, Sun, and Moon in the sky. That leaves us with the planets yet to discuss. As you'll soon see, planetary motion posed an ancient mystery that played a critical role in the development of modern civilization.

Five planets are easy to find with the naked eye: Mercury, Venus, Mars, Jupiter, and Saturn. Mercury is visible infrequently, and only just after sunset or just before sunrise because it is so close to the Sun. Venus often shines brightly in the early evening in the west or before dawn in the east. If you see a very bright "star" in the early evening or early morning, it is probably Venus. Jupiter, when it is visible at night, is the brightest object in the sky besides the Moon and Venus. Mars is often recognizable by its reddish color, though you should check a star chart to make sure you aren't looking at a bright red star. Saturn is also easy to see with the naked eye, but because many stars are just as bright as Saturn, it helps to know where to look. (It also helps to know that planets tend not to twinkle as much as stars.) Sometimes several planets may appear close together in the sky, offering a particularly beautiful sight (**FIGURE 31**).

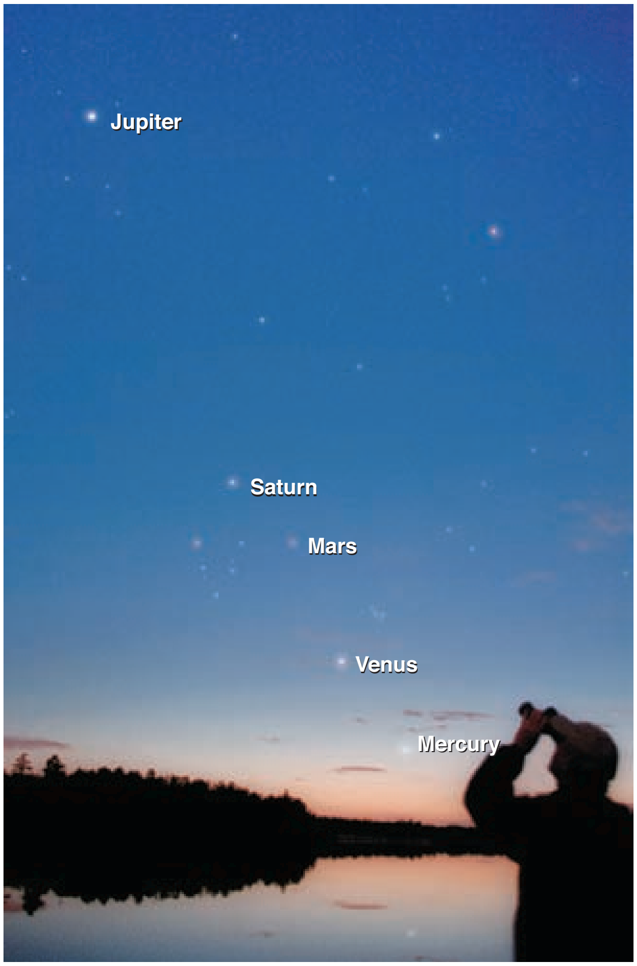


FIGURE 31 This photograph shows a grouping in our sky of all five planets that are easily visible to the naked eye. It was taken near Chatsworth, New Jersey, on April 23, 2002. The next such close grouping of these five planets in our sky will occur in September 2040.

SEE IT FOR YOURSELF

Using astronomical software or the Web, find out what planets are visible tonight and where to look for them, then go out and try to find them. Are they easy or difficult to identify?

Why was planetary motion so hard to explain?

Over the course of a single night, planets behave like all other objects in the sky: Earth's rotation makes them appear to rise in the east and set in the west. But if you continue to watch the planets night after night, you will notice that their movements among the constellations are quite complex. Instead of moving steadily eastward relative to the stars, like the Sun and Moon, the planets vary substantially in both speed and brightness; in fact, the word *planet* comes from the Greek for "wandering star." Moreover, while the planets *usually* move eastward through the constellations, they occasionally reverse course, moving westward through the zodiac (**FIGURE 32**). These periods of **apparent retrograde motion** (*retrograde* means "backward") last from a few weeks to a few months, depending on the planet.

For ancient people who believed in an Earth-centered universe, apparent retrograde motion was very difficult to explain; after all, what could make planets sometimes turn around and go backward if everything moves in circles around Earth? The ancient Greeks came up with some very clever ways to explain it, but their explanations were quite complex.

In contrast, apparent retrograde motion has a simple explanation in a Sun-centered solar system. You can demonstrate it for yourself with the help of a friend (**FIGURE 33a**). Pick a spot in an open area to represent the Sun. You can represent Earth by walking counterclockwise around the Sun, while your friend represents a more distant planet (such as Mars or Jupiter) by walking in the same direction around the Sun at a greater distance. Your friend should walk more slowly than you, because more distant planets orbit the Sun more slowly. As you walk, watch how your friend appears to

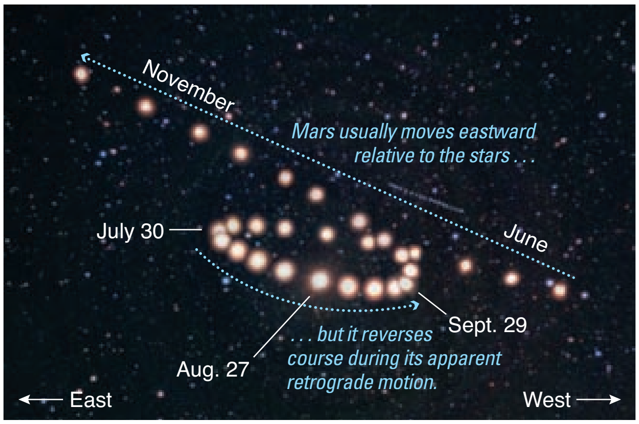
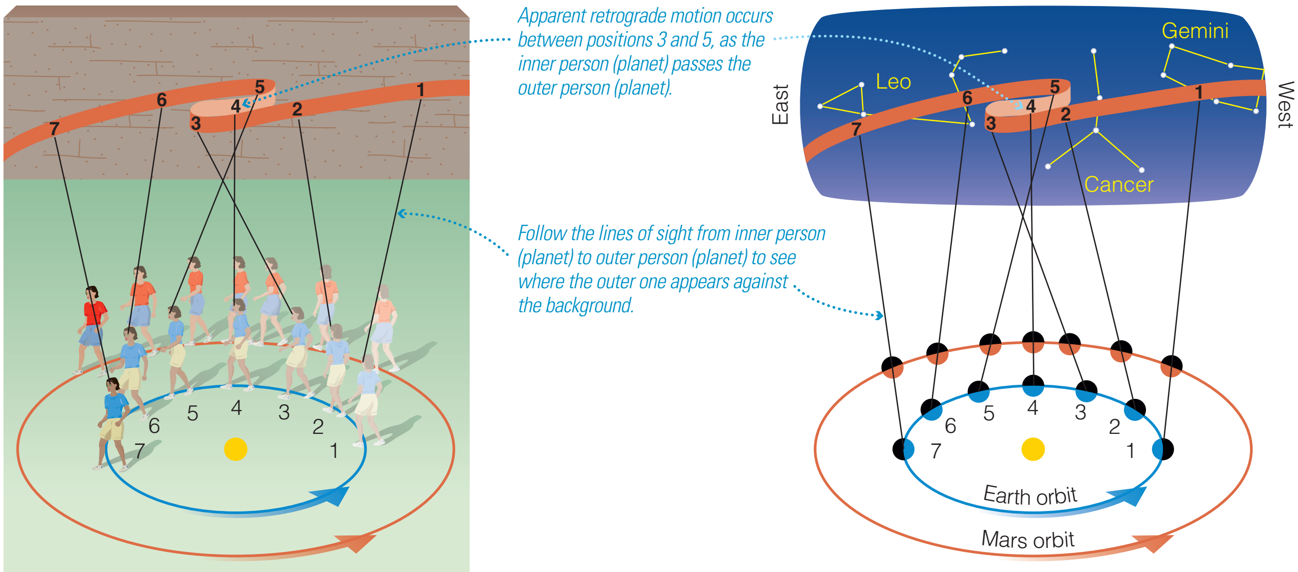


FIGURE 32 This composite of 29 individual photos (taken at 5- to 8-day intervals in 2003) shows a retrograde loop of Mars. Note that Mars is biggest and brightest in the middle of the retrograde loop, because that is where it is closest to Earth in its orbit. (The faint dots just right of center are images of the planet Uranus, which by coincidence was in the same part of the sky.)



a The retrograde motion demonstration: Watch how your friend (in red) usually appears to move forward against the background of the building in the distance but appears to move backward as you (in blue) catch up to and pass her in your "orbit."

b This diagram shows how the same idea applies to a planet. Follow the lines of sight from Earth to Mars in numerical order. Notice that Mars appears to move westward relative to the distant stars as Earth passes it by in its orbit (roughly from points 3 to 5).

FIGURE 33 interactive figure Apparent retrograde motion—the occasional "backward" motion of the planets relative to the stars—has a simple explanation in a Sun-centered solar system.

move relative to buildings or trees in the distance. Although both of you always walk the same way around the Sun, your friend will appear to move backward against the background during the part of your "orbit" in which you catch up to and pass him or her. **FIGURE 33b** shows how the same idea applies to Mars. Note that Mars never actually changes direction; it only *appears* to go backward as Earth passes Mars in its orbit. (To understand the apparent retrograde motions of Mercury and Venus, which are closer to the Sun than is Earth, simply switch places with your friend and repeat the demonstration.)

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

If the apparent retrograde motion of the planets is so readily explained by recognizing that Earth orbits the Sun, why wasn't this idea accepted in ancient times? In fact, the idea that Earth goes around the Sun was suggested as early as 260 B.C. by the Greek astronomer Aristarchus (see Special Topic). Nevertheless, Aristarchus's contemporaries rejected his idea, and the Sun-centered solar system did not gain wide acceptance until almost 2000 years later.

Although there were many reasons the Greeks were reluctant to abandon the idea of an Earth-centered universe, one of the most important was their inability to detect what we call **stellar parallax.** Extend your arm and hold up one finger. If you keep your finger still and alternately close your left eye and right eye, your finger will appear to jump back and forth against the background. This apparent shifting, called *parallax*, occurs because your two eyes view your finger from opposite sides of your nose. If you move your finger closer to your face, the parallax increases. If you look at a distant tree or flagpole instead of your finger, you may not notice any parallax at all. In other words, parallax depends on distance, with nearer objects exhibiting greater parallax than more distant objects.

If you now imagine that your two eyes represent Earth at opposite sides of its orbit around the Sun and that the tip of your finger represents a relatively nearby star, you have the idea of stellar parallax. That is, because we view the stars from different places in our orbit at different times of year, nearby stars should *appear* to shift back and forth against the background of more distant stars (**FIGURE 34**).

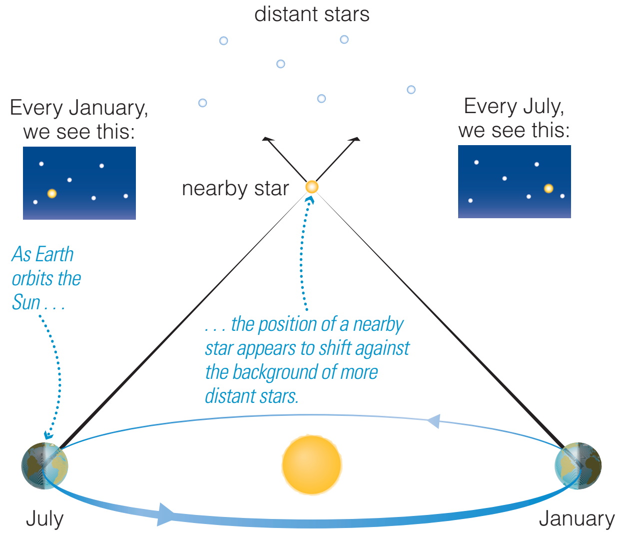


FIGURE 34 Stellar parallax is an apparent shift in the position of a nearby star as we look at it from different places in Earth's orbit. This figure is greatly exaggerated; in reality, the amount of shift is far too small to detect with the naked eye.

SPECIAL TOPIC

Who First Proposed a Sun-Centered Solar System?

You've probably heard of Copernicus, whose work in the 16th century started the revolution that ultimately overturned the ancient belief in an Earth-centered universe. However, the idea that Earth goes around the Sun was proposed much earlier by the Greek scientist Aristarchus (c. 310–230 B.C.).

Little of Aristarchus's work survives to the present day, so we cannot know what motivated him to suggest an idea so contrary to the prevailing view of an Earth-centered universe. However, it's likely that he was motivated by the fact that a Sun-centered system offers a much more natural explanation for the apparent retrograde motion of the planets. To account for the lack of detectable stellar parallax, Aristarchus suggested that the stars were extremely far away.

Aristarchus further strengthened his argument by estimating the sizes of the Moon and the Sun. By observing the shadow of Earth on the Moon during a lunar eclipse, he estimated the Moon's diameter to be about one-third of Earth's diameter—only slightly more than the actual value. He then used a geometric argument, based on measuring the angle between the Moon and the Sun at first- and third-quarter phases, to conclude that the Sun must be larger than Earth. (Aristarchus's measurements were imprecise, so he estimated the Sun's diameter to be about 7 times Earth's rather than the correct value of about 100 times.) His conclusion that the Sun is larger than Earth may have been another reason he believed that Earth should orbit the Sun, rather than vice versa.

Although Aristarchus was probably the first to suggest that Earth orbits the Sun, his ideas built on the work of earlier scholars. For example, Heracleides (c. 388–315 B.C.) had previously suggested that Earth rotates, which offered Aristarchus a way to explain the daily circling of the sky in a Sun-centered system. Heracleides also suggested that not all heavenly bodies circle Earth: Based on the fact that Mercury and Venus always stay fairly close to the Sun in the sky, he argued that these two planets must orbit the Sun. In suggesting that *all* the planets orbit the Sun, Aristarchus was extending the ideas of Heracleides and others before him.

Aristarchus gained little support among his contemporaries, but his ideas never died, and Copernicus was aware of them when he proposed his own version of the Sun-centered system. Thus, our modern understanding of the universe owes at least some debt to the remarkable vision of a man born more than 2300 years ago.

Because the Greeks believed that all stars lie on the same celestial sphere, they expected to see stellar parallax in a slightly different way. If Earth orbited the Sun, they reasoned, at different times of year we would be closer to different parts of the celestial sphere and would notice changes in the angular separation of stars. However, no matter how hard they searched, they could find no sign of stellar parallax. They concluded that one of the following must be true:

1. Earth orbits the Sun, but the stars are so far away that stellar parallax is undetectable to the naked eye.
2. There is no stellar parallax because Earth remains stationary at the center of the universe.

Aside from a few notable exceptions such as Aristarchus, the Greeks rejected the correct answer (the first one) because they could not imagine that the stars could be *that* far away. Today, we can detect stellar parallax with the aid of telescopes, providing direct proof that Earth really does orbit the Sun. Careful measurements of stellar parallax also provide the most reliable means of measuring distances to nearby stars.

THINK ABOUT IT

How far apart are opposite sides of Earth's orbit? How far away are the nearest stars? Using the 1-to-10-billion scale, describe the challenge of detecting stellar parallax.

The ancient mystery of the planets drove much of the historical debate over Earth's place in the universe. In many ways, the modern technological society we take for granted today can be traced directly to the scientific revolution that began in the quest to explain the strange wanderings of the planets among the stars in our sky.

The Big Picture

Putting This Chapter into Context

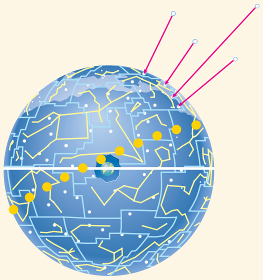
In this chapter, we surveyed the phenomena of our sky. Keep the following "big picture" ideas in mind as you continue your study of astronomy:

- You can enhance your enjoyment of astronomy by observing the sky. The more you learn about the appearance and apparent motions of the sky, the more you will appreciate what you can see in the universe.
- From our vantage point on Earth, it is convenient to imagine that we are at the center of a great celestial sphere—even though we really are on a planet orbiting a star in a vast universe. We can then understand what we see in the local sky by thinking about how the celestial sphere appears from our latitude.
- Most of the phenomena of the sky are relatively easy to observe and understand. The more complex phenomena—particularly eclipses and apparent retrograde motion of the planets—challenged our ancestors for thousands of years. The desire to understand these phenomena helped drive the development of science and technology.

SUMMARY OF KEY CONCEPTS

1 PATTERNS IN THE NIGHT SKY

- **What does the universe look like from Earth?** Stars and other celestial objects appear to lie on a great **celestial sphere** surrounding Earth. We divide the celestial sphere into **constellations** with well-defined borders. From any location on Earth, we see half the celestial sphere at any one time as the dome of our **local sky,** in which the **horizon** is the boundary between Earth and sky, the **zenith** is the point directly overhead, and the **meridian** runs from due south to due north through the zenith.

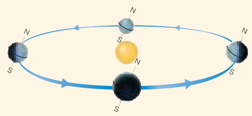


- **Why do stars rise and set?** Earth's rotation makes stars appear to circle around Earth each day. A star whose complete circle lies above our horizon is said to be **circumpolar.** Other stars have circles that cross the horizon, making them rise in the east and set in the west each day.

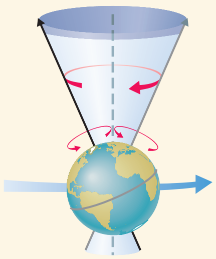
- **Why do the constellations we see depend on latitude and time of year?** The visible constellations vary with time of year because our night sky lies in different directions in space as we orbit the Sun. The constellations vary with **latitude** because your latitude determines the orientation of your horizon relative to the celestial sphere. The sky does not vary with **longitude.**

2 THE REASON FOR SEASONS

- **What causes the seasons?** The tilt of Earth's axis causes the seasons. The axis points in the same direction throughout the year, so as Earth orbits the Sun, sunlight hits different parts of Earth more directly at different times of year.

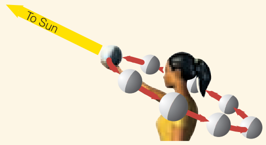


- **How does the orientation of Earth's axis change with time?** Earth's 26,000-year cycle of **precession** changes the orientation of the axis in space, although the tilt remains about $23\frac{1}{2}°$. The changing orientation of the axis does not affect the pattern of seasons, but it changes the identity of the North Star and shifts the locations of the solstices and equinoxes in Earth's orbit.



3 THE MOON, OUR CONSTANT COMPANION

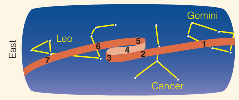
- **Why do we see phases of the Moon?** The **phase** of the Moon depends on its position relative to the Sun as it orbits Earth. The half of the Moon facing the Sun is always illuminated while the other half is dark, but from Earth we see varying combinations of the illuminated and dark faces.



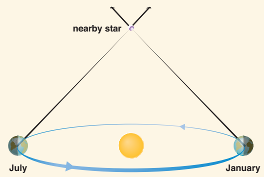
- **What causes eclipses?** We see a **lunar eclipse** when Earth's shadow falls on the Moon and a **solar eclipse** when the Moon blocks our view of the Sun. We do not see an eclipse at every new and full moon because the Moon's orbit is slightly inclined to the ecliptic plane.

4 THE ANCIENT MYSTERY OF THE PLANETS

- **Why was planetary motion so hard to explain?** Planets generally move eastward relative to the stars over the course of the year, but for weeks or months they reverse course during periods of **apparent retrograde motion.** This motion occurs when Earth passes by (or is passed by) another planet in its orbit, but it posed a major mystery to ancient people who assumed Earth to be at the center of the universe.

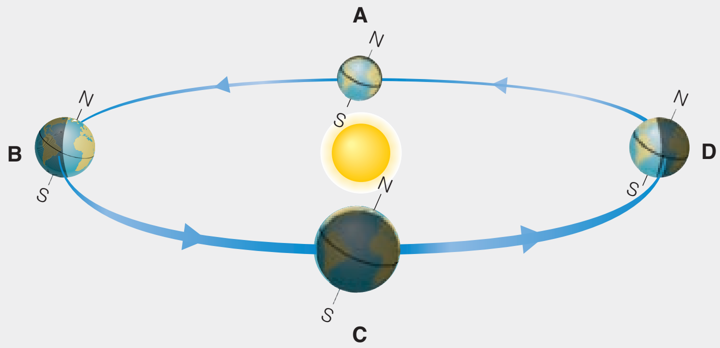


- **Why did the ancient Greeks reject the real explanation for planetary motion?** The Greeks rejected the idea that Earth goes around the Sun in part because they could not detect **stellar parallax**—slight apparent shifts in stellar positions over the course of the year. To most Greeks, it seemed truly unlikely that the stars could be so far away as to make parallax undetectable to the naked eye, even though that is, in fact, the case.



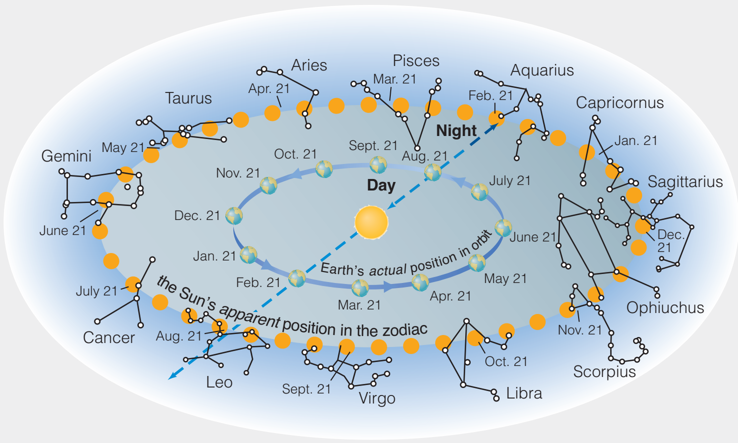
VISUAL SKILLS CHECK

Use the following questions to check your understanding of some of the many types of visual information used in astronomy. For additional practice, try the Visual Quiz at MasteringAstronomy®.



The figure above is a typical diagram used to describe Earth's seasons.

1. Which of the four labeled points (A through D) represents the beginning of summer for the Northern Hemisphere?
2. Which of the four labeled points represents the beginning of summer for the Southern Hemisphere?
3. Which of the four labeled points represents the beginning of spring for the Southern Hemisphere?
4. The diagram exaggerates the sizes of Earth and the Sun relative to the orbit. If Earth were correctly scaled relative to the orbit in the figure, how big would it be?
   a. about half the size shown b. about 2 millimeters across
   c. about 0.1 millimeter across d. microscopic
5. Given that Earth's actual distance from the Sun varies by less than 3% over the course of a year, why does the diagram look so elliptical?
   a. It correctly shows that Earth is closest to the Sun at points A and C and farthest at points B and D.
   b. The elliptical shape is an effect of perspective, since the diagram shows an almost edge-on view of a nearly circular orbit.
   c. The shape of the diagram is meaningless and is done only for artistic effect.



The figure above (based on Figure 14) shows the Sun's path through the constellations of the zodiac.

6. As viewed from Earth, in which zodiac constellation does the Sun appear to be located on April 21?
   a. Leo b. Aquarius c. Libra d. Aries
7. If the date is April 21, what zodiac constellation will be visible on your meridian at midnight?
   a. Leo b. Aquarius c. Libra d. Aries
8. If the date is April 21, what zodiac constellation will you see setting in the west shortly after sunset?
   a. Scorpius b. Pisces c. Taurus d. Virgo

EXERCISES AND PROBLEMS

MasteringAstronomy®

For instructor-assigned homework go to MasteringAstronomy®.

REVIEW QUESTIONS

Short-Answer Questions Based on the Reading

1. What are *constellations*? How did they get their names?
2. Suppose you were making a model of the celestial sphere with a ball. Briefly describe all the things you would need to mark on your celestial sphere.
3. On a clear, dark night, the sky may appear to be "full" of stars. Does this appearance accurately reflect the way stars are distributed in space? Explain.
4. Why does the *local sky* look like a dome? Define *horizon, zenith,* and *meridian.* How do we describe the location of an object in the local sky?
5. Explain why we can measure only *angular sizes* and *angular distances* for objects in the sky. What are *arcminutes* and *arcseconds*?
6. What are *circumpolar stars*? Are more stars circumpolar at the North Pole or in the United States? Explain.
7. What are *latitude* and *longitude*? Does the sky vary with latitude? Does it vary with longitude? Explain.
8. What is the *zodiac,* and why do we see different parts of it at different times of year?
9. Suppose Earth's axis had no tilt. Would we still have seasons? Why or why not?
10. Briefly describe key facts about the solstices and equinoxes.
11. What is *precession,* and how does it affect what we see in our sky?
12. Briefly describe the Moon's cycle of *phases.* Can you ever see a full moon at noon? Explain.
13. Why do we always see the same face of the Moon?
14. Why don't we see an *eclipse* at every new and full moon? Describe the conditions needed for a *solar* or *lunar eclipse.*
15. What do we mean by the *apparent retrograde motion* of the planets? Why was this motion difficult for ancient astronomers to explain? How do we explain it today?

16. What is *stellar parallax*? How did an inability to detect it support the ancient belief in an Earth-centered universe?

TEST YOUR UNDERSTANDING

Does It Make Sense?

Decide whether the statement makes sense (or is clearly true) or does not make sense (or is clearly false). Explain clearly; not all of these have definitive answers, so your explanation is more important than your chosen answer.

17. The constellation Orion didn't exist when my grandfather was a child.
18. When I looked into the dark lanes of the Milky Way with my binoculars, I saw what must have been a cluster of distant galaxies.
19. Last night the Moon was so big that it stretched for a mile across the sky.
20. I live in the United States, and during my first trip to Argentina I saw many constellations that I'd never seen before.
21. Last night I saw Jupiter right in the middle of the Big Dipper. (*Hint:* Is the Big Dipper part of the zodiac?)
22. Last night I saw Mars move westward through the sky in its apparent retrograde motion.
23. Although all the known stars rise in the east and set in the west, we might someday discover a star that will rise in the west and set in the east.
24. If Earth's orbit were a perfect circle, we would not have seasons.
25. Because of precession, someday it will be summer everywhere on Earth at the same time.
26. This morning I saw the full moon setting at about the same time the Sun was rising.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

27. Two stars that are in the same constellation (a) must both be part of the same cluster of stars in space. (b) must both have been discovered at about the same time. (c) may actually be very far away from each other.
28. The north celestial pole is 35° above your northern horizon. This tells you that (a) you are at latitude 35°N. (b) you are at longitude 35°E. (c) you are at latitude 35°S.
29. Beijing and Philadelphia have about the same latitude but very different longitudes. Therefore, tonight's night sky in these two places (a) will look about the same. (b) will have completely different sets of constellations. (c) will have partially different sets of constellations.
30. In winter, Earth's axis points toward the star Polaris. In spring, (a) the axis also points toward Polaris. (b) the axis points toward Vega. (c) the axis points toward the Sun.
31. When it is summer in Australia, the season in the United States is (a) winter. (b) summer. (c) spring.
32. If the Sun rises precisely due east, (a) you must be located at Earth's equator. (b) it must be the day of either the spring or the fall equinox. (c) it must be the day of the summer solstice.
33. A week after full moon, the Moon's phase is (a) first quarter. (b) third quarter. (c) new.
34. The fact that we always see the same face of the Moon tells us that (a) the Moon does not rotate. (b) the Moon's rotation period is the same as its orbital period. (c) the Moon looks the same on both sides.
35. If there is going to be a total lunar eclipse tonight, then you know that (a) the Moon's phase is full. (b) the Moon's phase is new. (c) the Moon is unusually close to Earth.
36. When we see Saturn going through a period of apparent retrograde motion, it means (a) Saturn is temporarily moving backward in its orbit of the Sun. (b) Earth is passing Saturn in its orbit, with both planets on the same side of the Sun. (c) Saturn and Earth must be on opposite sides of the Sun.

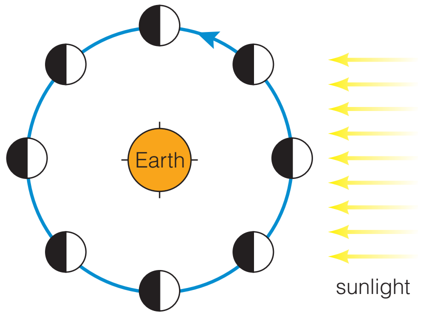
PROCESS OF SCIENCE

Examining How Science Works

37. *Earth-Centered or Sun-Centered?* Decide whether each of the following phenomena is consistent or inconsistent with a belief in an Earth-centered system. If consistent, describe how. If inconsistent, explain why, and also explain why the inconsistency did not immediately lead people to abandon the Earth-centered model.
a. The daily paths of stars through the sky **b.** Seasons **c.** Phases of the Moon **d.** Eclipses **e.** Apparent retrograde motion of the planets
38. *Shadow Phases.* Many people incorrectly guess that the phases of the Moon are caused by Earth's shadow falling on the Moon. How would you convince a friend that the phases of the Moon have nothing to do with Earth's shadow? Describe the observations you would use to show that Earth's shadow can't be the cause of phases.

GROUP WORK EXERCISE

39. *Lunar Phases and Time of Day.* Before you begin, assign the following roles to the people in your group: *Scribe* (takes notes on the group's activities), *Proposer* (proposes explanations to the group), *Skeptic* (points out weaknesses in proposed explanations), and *Moderator* (leads group discussion and makes sure everyone contributes). Then each member of the group should draw a copy of the following diagram, which represents the Moon's orbit as seen from above Earth's North Pole (not to scale):



Discuss and answer the following questions as a group:
a. How would the Moon appear from Earth at each of the eight Moon positions? Label each one with the corresponding phase. **b.** What time of day corresponds to each of the four tick marks on Earth? Label each tick mark accordingly. **c.** Why doesn't the Moon's phase change during the course of one night? Explain your reasoning. **d.** At what times of day would a full moon be visible to someone standing on Earth? Write down when a full moon rises and explain why it appears to rise at that time. **e.** At what times of day would a third-quarter moon be visible to someone standing on Earth? Write down when a third-quarter moon sets and explain why it appears to set at that time. **f.** At what times of day would a waxing crescent moon be visible to someone standing on Earth? Write down when a waxing crescent moon rises and explain why it appears to rise at that time.

INVESTIGATE FURTHER

In-Depth Questions to Increase Your Understanding

Short-Answer/Essay Questions

40. *New Planet.* A planet in another solar system has a circular orbit and an axis tilt of 35°. Would you expect this planet to have seasons? If so, would you expect them to be more extreme than the seasons on Earth? If not, why not?
41. *Your View of the Sky.*
a. What are your latitude and longitude? **b.** Where does the north (or south) celestial pole appear in your sky? **c.** Is Polaris a circumpolar star in your sky? Explain.
42. *View from the Moon.* Assume you live on the Moon, near the center of the face that looks toward Earth.
a. Suppose you see a full earth in your sky. What phase of the Moon would people on Earth see? Explain. **b.** Suppose people on Earth see a full moon. What phase would you see for Earth? Explain. **c.** Suppose people on Earth see a waxing gibbous moon. What phase would you see for Earth? Explain. **d.** Suppose people on Earth are viewing a total lunar eclipse. What would you see from your home on the Moon? Explain.
43. *View from the Sun.* Suppose you lived on the Sun (and could ignore the heat). Would you still see the Moon go through phases as it orbits Earth? Why or why not?
44. *A Farther Moon.* Suppose the distance to the Moon were twice its actual value. Would it still be possible to have a total solar eclipse? Why or why not?
45. *A Smaller Earth.* Suppose Earth were smaller. Would solar eclipses be any different? If so, how? What about lunar eclipses?
46. *Observing Planetary Motion.* Find out which planets are currently visible in your evening sky. At least once a week, observe the planets and draw a diagram showing the position of each visible planet relative to stars in a zodiac constellation. From week to week, note how the planets are moving relative to the stars. Can you see any of the apparently wandering features of planetary motion? Explain.
47. *A Connecticut Yankee.* Find the book *A Connecticut Yankee in King Arthur's Court* by Mark Twain. Read the portion that deals with the Connecticut Yankee's prediction of an eclipse. In a one- to two-page essay, summarize the episode and explain how it helped the Connecticut Yankee gain power.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

48. *Arcminutes and Arcseconds.* There are 360° in a full circle.
a. How many arcminutes are in a full circle? **b.** How many arcseconds are in a full circle? **c.** The Moon's angular size is about $\frac{1}{2}°$. What is this in arcminutes? In arcseconds?
49. *Latitude Distance.* Earth's radius is approximately 6370 km.
a. What is Earth's circumference? **b.** What distance is represented by each degree of latitude? **c.** What distance is represented by each arcminute of latitude? **d.** Can you give similar answers for the distances represented by a degree or arcminute of longitude? Why or why not?
50. *Angular Conversions I.* The following angles are given in degrees and fractions of degrees. Rewrite them in degrees, arcminutes, and arcseconds.
a. 24.3° **b.** 1.59° **c.** 0.1° **d.** 0.01° **e.** 0.001°
51. *Angular Conversions II.* The following angles are given in degrees, arcminutes, and arcseconds. Rewrite them in degrees and fractions of degrees.
a. 7°38′42″ **b.** 12′54″ **c.** 1°59′59″ **d.** 1′ **e.** 1″
52. *Angular Size of Your Finger.* Measure the width of your index finger and the length of your arm. Based on your measurements, calculate the angular width of your index finger at arm's length. Does your result agree with the approximations shown in Figure 7c? Explain.
53. *Find the Sun's Diameter.* The Sun has an angular diameter of about 0.5° and an average distance of about 150 million km. What is the Sun's approximate physical diameter? Compare your answer to the actual value of 1,390,000 km.
54. *Find a Star's Diameter.* Estimate the diameter of the supergiant star Betelgeuse, using its angular diameter of about 0.05 arcsecond and distance of about 600 light-years. Compare your answer to the size of our Sun and the Earth-Sun distance.
55. *Eclipse Conditions.* The Moon's precise equatorial diameter is 3476 km, and its orbital distance from Earth varies between 356,400 and 406,700 km. The Sun's diameter is 1,390,000 km, and its distance from Earth ranges between 147.5 and 152.6 million km.
a. Find the Moon's angular size at its minimum and maximum distances from Earth. **b.** Find the Sun's angular size at its minimum and maximum distances from Earth. **c.** Based on your answers to parts a and b, is it possible to have a total solar eclipse when the Moon and Sun are both at their maximum distance? Explain.

Discussion Questions

56. *Earth-Centered Language.* Many common phrases reflect the ancient Earth-centered view of our universe. For example, the phrase "the Sun rises each day" implies that the Sun is really moving over Earth. We know that the Sun only *appears* to rise as the rotation of Earth carries us to a place where we can see the Sun in our sky. Identify other common phrases that imply an Earth-centered viewpoint.
57. *Flat Earth Society.* Believe it or not, there is an organization called the Flat Earth Society. Its members hold that Earth is flat and that all indications to the contrary (such as pictures of Earth from space) are fabrications made as part of a conspiracy to hide the truth from the public. Discuss the evidence for a round Earth and how you can check it for yourself. In light of the evidence, is it possible that the Flat Earth Society is correct? Defend your opinion.

Web Projects

58. *Sky Information.* Search the Web for sources of daily information about sky phenomena (such as lunar phases, times of sunrise and sunset, or dates of equinoxes and solstices). Identify and briefly describe your favorite source.
59. *Constellations.* Search the Web for information about the constellations and their mythology. Write a short report about one or more constellations.
60. *Upcoming Eclipse.* Find information about an upcoming solar or lunar eclipse. Write a short report about how you could best observe the eclipse, including any necessary travel to a viewing site, and what you could expect to see. Bonus: Describe how you could photograph the eclipse.

ANSWERS TO VISUAL SKILLS CHECK QUESTIONS

1. B
2. D
3. C
4. D
5. B
6. D
7. C
8. C

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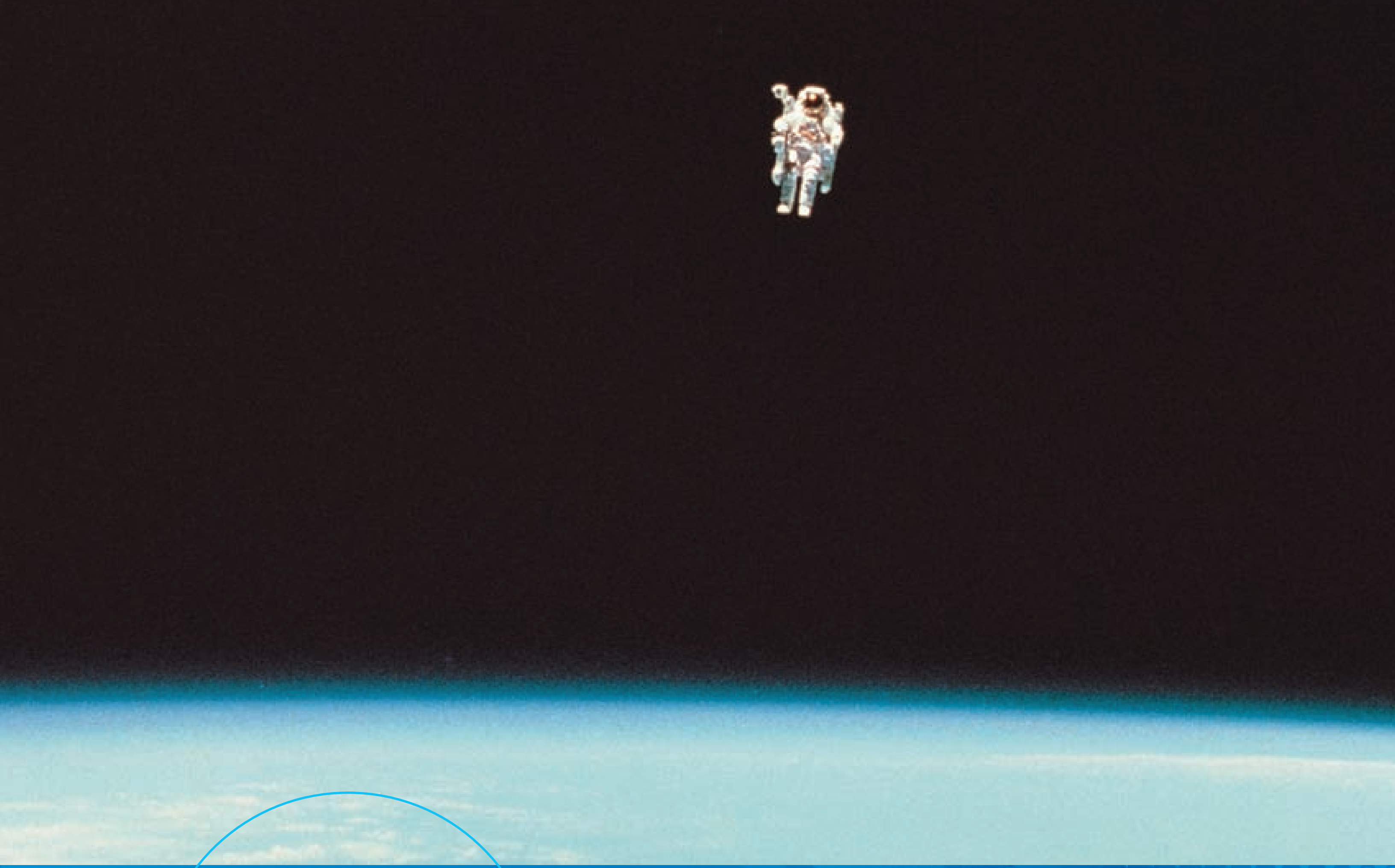
Quote from Mark Twain, *Adventures of Huckleberry Finn,* 1884.



THE SCIENCE OF ASTRONOMY

LEARNING GOALS

1 THE ANCIENT ROOTS OF SCIENCE
- In what ways do all humans use scientific thinking?
- How is modern science rooted in ancient astronomy?

2 ANCIENT GREEK SCIENCE
- Why does modern science trace its roots to the Greeks?
- How did the Greeks explain planetary motion?

3 THE COPERNICAN REVOLUTION
- How did Copernicus, Tycho, and Kepler challenge the Earth-centered model?
- What are Kepler's three laws of planetary motion?
- How did Galileo solidify the Copernican revolution?

4 THE NATURE OF SCIENCE
- How can we distinguish science from nonscience?
- What is a scientific theory?

5 ASTROLOGY
- How is astrology different from astronomy?
- Does astrology have any scientific validity?

We especially need imagination in science. It is not all mathematics, nor all logic, but is somewhat beauty and poetry.

—Maria Mitchell (1818–1889), astronomer and the first woman elected to the American Academy of Arts and Sciences

Today we know that Earth is a planet orbiting a rather ordinary star, in a galaxy of more than a hundred billion stars, in an incredibly vast universe. We know that Earth, along with the entire cosmos, is in constant motion. We know that, on the scale of cosmic time, human civilization has existed for only the briefest moment. How did we manage to learn these things?

It wasn't easy. In this chapter, we will trace how modern astronomy grew from its roots in ancient observations, including those of the Greeks. We'll pay special attention to the unfolding of the Copernican revolution, which overturned the ancient belief in an Earth-centered universe and laid the foundation for the rise of our technological civilization. Finally, we'll explore the nature of modern science and how science can be distinguished from nonscience.

1 THE ANCIENT ROOTS OF SCIENCE

The rigorous methods of modern science have proven to be among the most valuable inventions in human history. These methods have enabled us to discover almost everything we now know about nature and the universe, and they also have made our modern technology possible. In this section, we will explore the ancient roots of science, which grew out of experiences common to nearly all people and all cultures.

In what ways do all humans use scientific thinking?

Scientific thinking comes naturally to us. By about a year of age, a baby notices that objects fall to the ground when she drops them. She lets go of a ball—it falls. She pushes a plate of food from her high chair—it falls, too. She continues to drop all kinds of objects, and they all plummet to Earth. Through her powers of observation, the baby learns about the physical world, finding that things fall when they are unsupported. Eventually, she becomes so certain of this fact that, to her parents' delight, she no longer needs to test it continually.

One day someone gives the baby a helium balloon. She releases it, and to her surprise it rises to the ceiling! Her understanding of nature must be revised. She now knows that the principle "all things fall" does not represent the whole truth, although it still serves her quite well in most situations. It will be years before she learns enough about the atmosphere, the force of gravity, and the concept of density to understand *why* the balloon rises when most other objects fall. For now, she is delighted to observe something new and unexpected.

The baby's experience with falling objects and balloons exemplifies scientific thinking. In essence, science is a way of learning about nature through careful observation and trial-and-error experiments. Rather than thinking differently than other people, modern scientists simply are trained to organize everyday thinking in a way that makes it easier for them to share their discoveries and use their collective wisdom.

THINK ABOUT IT

Describe a few cases where you have learned by trial and error while cooking, participating in sports, fixing something, or working at a job.

Just as learning to communicate through language, art, or music is a gradual process for a child, the development of science has been a gradual process for humanity. Science in its modern form requires painstaking attention to detail, relentless testing of each piece of information to ensure its reliability, and a willingness to give up old beliefs that are not consistent with observed facts about the physical world. For professional scientists, these demands are the "hard work" part of the job. At heart, professional scientists are like the baby with the balloon, delighted by the unexpected and motivated by those rare moments when they—and all of us—learn something new about the universe.

How is modern science rooted in ancient astronomy?

Astronomy has been called the oldest of the sciences, because its roots stretch deepest into antiquity. Ancient civilizations did not always practice astronomy in the same ways or for the same reasons that we study it today, but they nonetheless had some amazing achievements. Understanding this ancient astronomy can give us a greater appreciation of how and why science developed through time.

Practical Benefits of Astronomy No one knows exactly how or when humans first began making careful observations of the sky, but we know observation has been going on for many thousands of years. This interest in astronomy probably comes in part from our inherent curiosity as humans, but ancient cultures also discovered that astronomy had practical benefits for timekeeping, keeping track of seasonal changes, and navigation.

One amazing example comes from people of central Africa. Although we do not know exactly when they developed the skill, people in some regions learned to predict rainfall patterns by making careful observations of the Moon. **FIGURE 1** shows how the method works. The orientation of the "horns" of a waxing crescent moon (relative to the horizon) varies over the course of the year, primarily because the angle at which the ecliptic intersects the horizon changes during the year. (The orientation also depends on latitude.) In tropical regions in which there are distinct rainy and dry seasons—rather than the four seasons familiar at temperate latitudes—the orientation of the crescent moon can be used to predict how much rainfall should be expected over coming days and weeks.

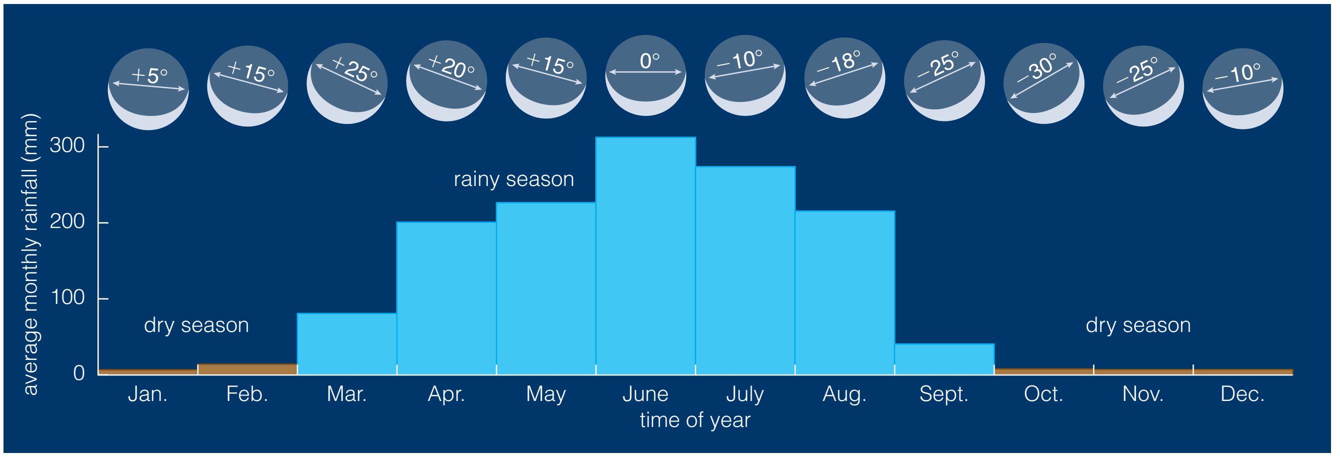


FIGURE 1 In central Nigeria, the orientation of the "horns" of a waxing crescent moon (shown along the top) correlates with the average amount of rainfall at different times of year. Local people could use this fact to predict the weather with reasonable accuracy. (Adapted from *Ancient Astronomers* by Anthony F. Aveni.)

Astronomy and Measures of Time The impact of ancient astronomical observations is still with us in our modern measures of time. The length of our day is the time it takes the Sun to make one full circuit of the sky. The length of a month comes from the Moon's cycle of phases, and our year is based on the cycle of the seasons. The seven days of the week were named after the seven "planets" of ancient times (**TABLE 1**), which were the Sun, the Moon, and the five planets that are easily visible to the naked eye: Mercury, Venus, Mars, Jupiter, Saturn. Note that the ancient definition of *planet*, which comes from a Greek word meaning "wanderer," applied to any object that appeared to wander among the fixed stars. That is why the Sun and Moon were on the list while Earth was not, because we don't see our own planet moving in the sky.

THINK ABOUT IT

Uranus is faintly visible to the naked eye, but it was not recognized as a planet in ancient times. If Uranus had been brighter, would we now have eight days in a week? Defend your opinion.

TABLE 1 The Seven Days of the Week and the Astronomical Objects They Honor

The seven days were originally linked directly to the seven objects. The correspondence is no longer perfect, but the overall pattern is clear in many languages; some English names come from Germanic gods.

Object	Germanic God	English	French	Spanish
Sun	—	Sunday	dimanche	domingo
Moon	—	Monday	lundi	lunes
Mars	Tiw	Tuesday	mardi	martes
Mercury	Woden	Wednesday	mercredi	miércoles
Jupiter	Thor	Thursday	jeudi	jueves
Venus	Fria	Friday	vendredi	viernes
Saturn	—	Saturday	samedi	sábado

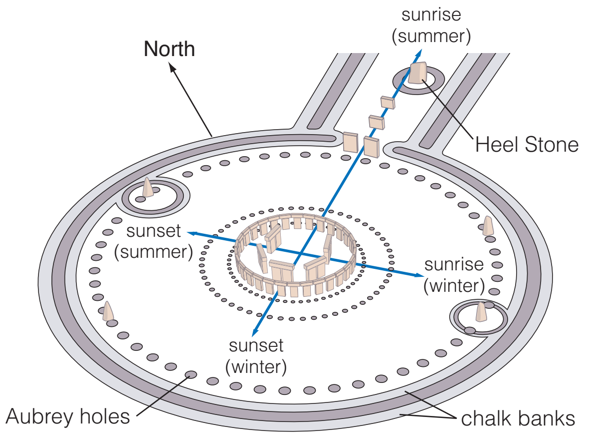
Because timekeeping was so important and required precise observations, many ancient cultures built structures or created special devices to help with it. Let's briefly investigate a few of the ways in which ancient cultures kept track of time.

Determining the Time of Day In the daytime, ancient peoples could tell time by observing the Sun's path through the sky. Many cultures probably used sticks and the shadows they cast as simple sundials. The ancient Egyptians built huge obelisks, often decorated in homage to the Sun, which probably also served as simple clocks (**FIGURE 2**).

At night, ancient people could estimate the time from the position and phase of the Moon or by observing the constellations visible at a particular time. For example, ancient Egyptian star clocks, often found painted on the coffin lids

FIGURE 2 This ancient Egyptian obelisk, which stands 83 feet tall and weighs 331 tons, resides in St. Peter's Square at the Vatican in Rome. It is one of 21 surviving obelisks from ancient Egypt, most of which are now scattered around the world. Shadows cast by the obelisks may have been used to tell time.

a The remains of Stonehenge today.



b This sketch shows how archaeologists believe Stonehenge looked upon its completion in about 1550 B.C. Several astronomical alignments are shown as they appear from the center. For example, the Sun rises directly over the Heel Stone on the summer solstice.

FIGURE 3 Stonehenge, in southern England, was built in stages from about 2750 B.C. to about 1550 B.C.

of Egyptian pharaohs, cataloged where particular stars appeared in the sky at various times of night throughout the year. By knowing the date from their calendar and observing the positions of the cataloged stars in the sky, the Egyptians could use the star clocks to estimate the time of night.

In fact, we can trace the origins of our modern clock to ancient Egypt, some 4000 years ago. The Egyptians divided daytime and nighttime into 12 equal parts each, which is how we got our 12 hours each of a.m. and p.m. The abbreviations *a.m.* and *p.m.* stand for the Latin terms *ante meridiem* and *post meridiem,* respectively, which mean "before the middle of the day" and "after the middle of the day."

By about 1500 B.C., Egyptians had abandoned star clocks in favor of clocks that measure time by the flow of water through an opening of a particular size, just as hourglasses measure time by the flow of sand through a narrow neck.* These *water clocks* had the advantage of working even when the sky was cloudy. They eventually became the primary timekeeping instruments for many cultures, including the Greeks, Romans, and Chinese. Water clocks, in turn, were replaced by mechanical clocks in the 17th century and by electronic clocks in the 20th century. Despite the availability of other types of clocks, sundials were common throughout ancient times and remain popular today both for their decorative value and as reminders that the Sun and stars once were our only guides to time.

Marking the Seasons Many ancient cultures built structures to help them mark the seasons. Stonehenge (**FIGURE 3**) is a well-known example that served both as an astronomical device and as a social and religious gathering place. In the Americas, one of the most spectacular structures was the Templo Mayor (**FIGURE 4**) in the Aztec city of Tenochtitlán (in modern-day Mexico City), which featured twin temples on a flat-topped pyramid. From the vantage point of a royal observer watching from the opposite side of the plaza, the Sun rose through the notch between the temples on the equinoxes. Before the Conquistadors destroyed it, Spanish visitors reported elaborate rituals at the Templo Mayor, sometimes including human sacrifice, that were held at times determined by astronomical observations. After its destruction, stones from the Templo Mayor were used to build a cathedral in the great plaza of Mexico City.

Many cultures aligned their buildings and streets with the cardinal directions (north, south, east, and west), which made it easier to keep track of the changing rise and set positions of the Sun over the course of the year. This type of alignment is found at such diverse sites as the Egyptian pyramids and the

FIGURE 4 This scale model shows the Templo Mayor and the surrounding plaza as they are thought to have looked before the Spanish Conquistadors destroyed them. The structure was used to help mark the seasons.

*Hourglasses using sand were not invented until about the 8th century A.D., long after the advent of water clocks. Natural sand grains vary in size, so making accurate hourglasses required technology for making uniform grains of sand.

FIGURE 5 This large structure, more than 20 meters in diameter, is a kiva in Chaco Canyon, New Mexico. It was built by Ancestral Pueblo People approximately 1000 years ago. Its main axis is aligned almost precisely north-south.

Forbidden City in China and among ceremonial kivas built by the Ancestral Pueblo People of the American southwest (**FIGURE 5**). Many modern cities retain this layout, which is why you'll find so many streets that run directly north-south or east-west.

Other structures were used to mark the Sun's position on special dates such as the winter or summer solstice. Many such structures can be found around the world, but one of the most amazing is the *Sun Dagger*, made by the Ancestral Pueblo People in Chaco Canyon, New Mexico (**FIGURE 6**). Three large slabs of rock lie in front of a carved spiral in such a way that they produced special patterns of light and shadow at different times of year. For example, a single dagger of sunlight pierced the center of the spiral only at noon on the summer solstice, while two daggers of light bracketed the spiral at the winter solstice.

FIGURE 6 The Sun Dagger. Three large slabs of rock in front of the carved spiral produced patterns of light and shadow that varied throughout the year. Here, we see the single dagger of sunlight that pierced the center of the spiral only at noon on the summer solstice. (Unfortunately, within just 12 years of the site's 1977 discovery, the rocks shifted so that the effect no longer occurs; the shifts probably were due to erosion of the trail below the rocks caused by large numbers of visitors.)

The Sun Dagger may also have been used to mark a special cycle of the Moon that had ritual significance to the Ancestral Pueblo People. The rise and set positions of the full moon vary in an 18.6-year cycle (the cycle of precession of the Moon's orbit), so the full moon rises at its most southerly point along the eastern horizon only once every 18.6 years. At this time, known as a "major lunar standstill," the shadow of the full moon passes through the slabs of rock to lie tangent to the edge of the spiral in the Sun Dagger; then, 9.3 years later, the lunar shadow cuts through the center of the spiral. The major lunar standstill can also be observed with structures at nearby Chimney Rock and in cliff dwellings at Colorado's Mesa Verde National Park.

Solar and Lunar Calendars The tracking of the seasons eventually led to the advent of written calendars. Today, we use a *solar calendar*, meaning a calendar that is synchronized with the seasons so that seasonal events such as the solstices and equinoxes occur on approximately the same dates each year. The origins of our modern solar calendar go back to ancient Egypt, though many details (such as the timing of leap years) have been refined throughout history to keep the calendar well synchronized to the seasons.

Solar calendars are not the only option. Many cultures created *lunar calendars* that aimed to stay synchronized with the Moon's $29\frac{1}{2}$-day cycle of phases, so that the Moon's phase was always the same on the first day of each month. A basic lunar calendar has 12 months, with some months lasting 29 days and others lasting 30 days; the lengths are chosen to make the average agree with the approximately $29\frac{1}{2}$-day lunar cycle. A 12-month lunar calendar therefore has only 354 or 355 days, or about 11 days fewer than a calendar based on the Sun. Such a calendar is still used in the Muslim religion. That is why the month-long fast of Ramadan (the ninth month) begins about 11 days earlier with each subsequent year.

Some cultures that used lunar calendars apparently did not like the idea of having their months cycle through the seasons over time, so they modified their calendars to take advantage of an interesting coincidence: 19 years on a solar calendar is almost precisely 235 months on a lunar calendar. As a result, the lunar phases repeat on the same dates about every 19 years (a pattern known as the *Metonic cycle*, so named because it was recognized by the Greek astronomer Meton in 432 B.C.). For example, there was a full moon on December 28, 2012, and there will be a full moon 19 years later, on December 28, 2031. Because an ordinary lunar calendar has only $19 \times 12 = 228$ months in a 19-year period, adding 7 extra months (to make 235) can keep the lunar calendar roughly synchronized to the seasons. One way of adding the 7 months is used in the Jewish calendar, which adds a thirteenth month in the third, sixth, eighth, eleventh, fourteenth, seventeenth, and nineteenth years of each 19-year cycle. This scheme keeps the dates of Jewish holidays within about a 1-month range on a solar calendar, with precise dates repeating every 19 years. It also explains why the date of Easter changes from year to year: The New Testament ties the date of Easter to the Jewish festival of Passover. In a slight modification of the original scheme, most Western Christians now celebrate Easter on the

FIGURE 7 This photo shows a model of the celestial sphere and other instruments on the roof of the ancient astronomical observatory in Beijing. The observatory was built in the 15th century; the instruments shown here were built later and show a European influence brought by Jesuit missionaries.

first Sunday after the first full moon after March 21. If the full moon falls on Sunday, Easter is the following Sunday. (Eastern Orthodox churches calculate the date of Easter differently, because they base the date on the Julian rather than the Gregorian calendar.)

Learning About Ancient Achievements The study of ancient astronomical achievements is a rich field of research. Many ancient cultures made careful observations of planets and stars, and some left remarkably detailed records. The Chinese, for example, began recording astronomical observations at least 5000 years ago, allowing ancient Chinese astronomers to make many important discoveries. By the 15th century, the Chinese had built a great observatory in Beijing, which still stands today (**FIGURE 7**). We can also study written records from ancient Middle Eastern civilizations such as those of Egypt and Babylonia.

Other cultures either did not leave clear written records or had records that were lost or destroyed, so we must piece together their astronomical achievements by studying the physical evidence they left behind. This type of study is usually called *archaeoastronomy,* a word that combines archaeology and astronomy. The astronomical uses of most of the structures we've discussed so far were discovered by researchers working in archaeoastronomy.

The cases we've discussed to this point have been fairly straightforward for archaeoastronomers to interpret, but many other cases are more ambiguous. For example, ancient people in what is now Peru etched hundreds of lines and patterns in the sand of the Nazca desert. Many of the lines point to places where the Sun or bright stars rise at particular times of year, but that doesn't prove anything: With hundreds of lines, random chance ensures that many will have astronomical alignments no matter how or why they were made. The patterns, many of which are large figures of animals (**FIGURE 8**), have evoked even more debate. Some people think they may be representations of constellations recognized by the people who lived in the region, but we do not know for sure.

FIGURE 8 Hundreds of lines and patterns are etched in the sand of the Nazca desert in Peru. This aerial photo shows a large figure of a hummingbird.

THINK ABOUT IT

Animal figures like that in Figure 8 show up clearly only when seen from above. As a result, some UFO enthusiasts argue that the patterns must have been created by aliens. What do you think of this argument? Defend your opinion.

In some cases, scientists studying archaeoastronomy can use other clues to establish the intentions of ancient builders. For example, lodges built by the Pawnee people in Kansas feature strategically placed holes for observing the passage of constellations that figure prominently in Pawnee folklore. The correspondence between the folklore and the structural features provides a strong case for deliberate intent rather than coincidence. Similarly, traditions of the Inca Empire of South America held that its rulers were descendents of the Sun and therefore demanded close watch of the movements of the Sun and stars. This fact supports the idea that astronomical alignments in Inca cities and ceremonial centers, such as the World Heritage Site of Machu Picchu (**FIGURE 9**), were deliberate rather than accidental.

FIGURE 9 The World Heritage Site of Machu Picchu has structures aligned with sunrise at the winter and summer solstices.

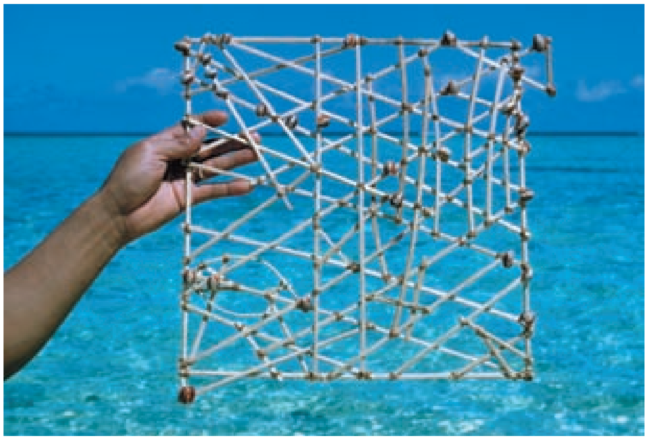


FIGURE 10 A Micronesian stick chart, an instrument used by Polynesian Navigators to represent swell patterns around islands.

A different type of evidence makes a convincing case for the astronomical sophistication of ancient Polynesians, who lived and traveled among the islands of the mid- and South Pacific. Navigation was crucial to their survival because the next island in a journey usually was too distant to be seen. The most esteemed position in Polynesian culture was that of the Navigator, a person who had acquired the knowledge necessary to navigate great distances among the islands. Navigators used a combination of detailed knowledge of astronomy and an understanding of the patterns of waves and swells around different islands (**FIGURE 10**). The stars provided the broad navigational sense, while wave and swell patterns guided them to a precise landing point. A Navigator memorized all his knowledge and passed it to the next generation through a well-developed training program. Unfortunately, with the advent of modern navigational technology, many of the skills of the Navigators have been lost.

2 ANCIENT GREEK SCIENCE

Before a structure such as Stonehenge or the Templo Mayor could be built, careful observations had to be made and repeated over and over to ensure their accuracy. Careful, repeatable observations also underlie modern science. Elements of modern science were therefore present in many early human cultures. If the circumstances of history had been different, almost any culture might have been the first to develop what we consider to be modern science. In the end, however, history takes only one of countless possible paths. The path that led to modern science emerged from the ancient civilizations of the Mediterranean and the Middle East—especially from ancient Greece.

Greece gradually rose as a power in the Middle East beginning around 800 B.C. and was well established by about 500 B.C. Its geographical location placed it at a crossroads for travelers, merchants, and armies from northern Africa, Asia, and Europe. Building on the diverse ideas brought forth by the meeting of these many cultures, ancient Greek philosophers soon began their efforts to move human understanding of nature from the mythological to the rational.

Why does modern science trace its roots to the Greeks?

Greek philosophers developed at least three major innovations that helped pave the way for modern science. First, they developed a tradition of trying to understand nature without relying on supernatural explanations and of working communally to debate and challenge each other's ideas. Second, the Greeks used mathematics to give precision to their ideas, which allowed them to explore the implications of new ideas in much greater depth than would have otherwise been possible. Third, while much of their philosophical activity consisted of subtle debates grounded only in thought and was not scientific in the modern sense, the Greeks also saw the power of reasoning from observations. They understood that an explanation could not be right if it disagreed with observed facts.

Models of Nature Perhaps the greatest Greek contribution to science came from the way they synthesized all three innovations into the idea of creating models of nature, a practice that is central to modern science. Scientific models differ somewhat from the models you may be familiar with in everyday life. In our daily lives, we tend to think of models as miniature physical representations, such as model cars or airplanes. In contrast, a scientific **model** is a conceptual representation created to explain and predict observed phenomena. For example, a model of Earth's climate uses logic and mathematics to represent what we know about how the climate works. Its purpose is to explain and predict climate changes, such as the changes that may occur with global warming. Just as a model airplane does not faithfully represent every aspect of a real airplane, a scientific model may not fully explain all our observations of nature. Nevertheless, even the failings of a scientific model can be useful, because they often point the way toward building a better model.

From Greece to the Renaissance The Greeks created models that sought to explain many aspects of nature, including the properties of matter and the principles of motion. For our purposes, the most important of the Greek models was their Earth-centered model of the universe. Before we turn to its details, however, it's worth briefly discussing how ancient Greek philosophy was passed to Europe, where it ultimately grew into the principles of modern science.

Greek philosophy first began to spread widely with the conquests of Alexander the Great (356–323 B.C.). Alexander had a deep interest in science, perhaps in part because Aristotle (see Special Topic) had been his personal tutor. Alexander founded the city of Alexandria in Egypt, and shortly after his death the city commenced work on a great research center and library. The Library of Alexandria (**FIGURE 11**) opened in about 300 B.C. and remained the world's preeminent center of research for some 700 years. At its peak, it may have held as many as a half million books, handwritten on papyrus scrolls. Most of these scrolls were ultimately burned when the library was destroyed, their contents lost forever.

a This rendering shows an artist's reconstruction of the Great Hall of the ancient Library of Alexandria.

b A rendering similar to part a, showing a scroll room in the ancient library.

c The New Library of Alexandria in Egypt, which opened in 2003.

FIGURE 11 The ancient Library of Alexandria thrived for some 700 years, starting in about 300 B.C.

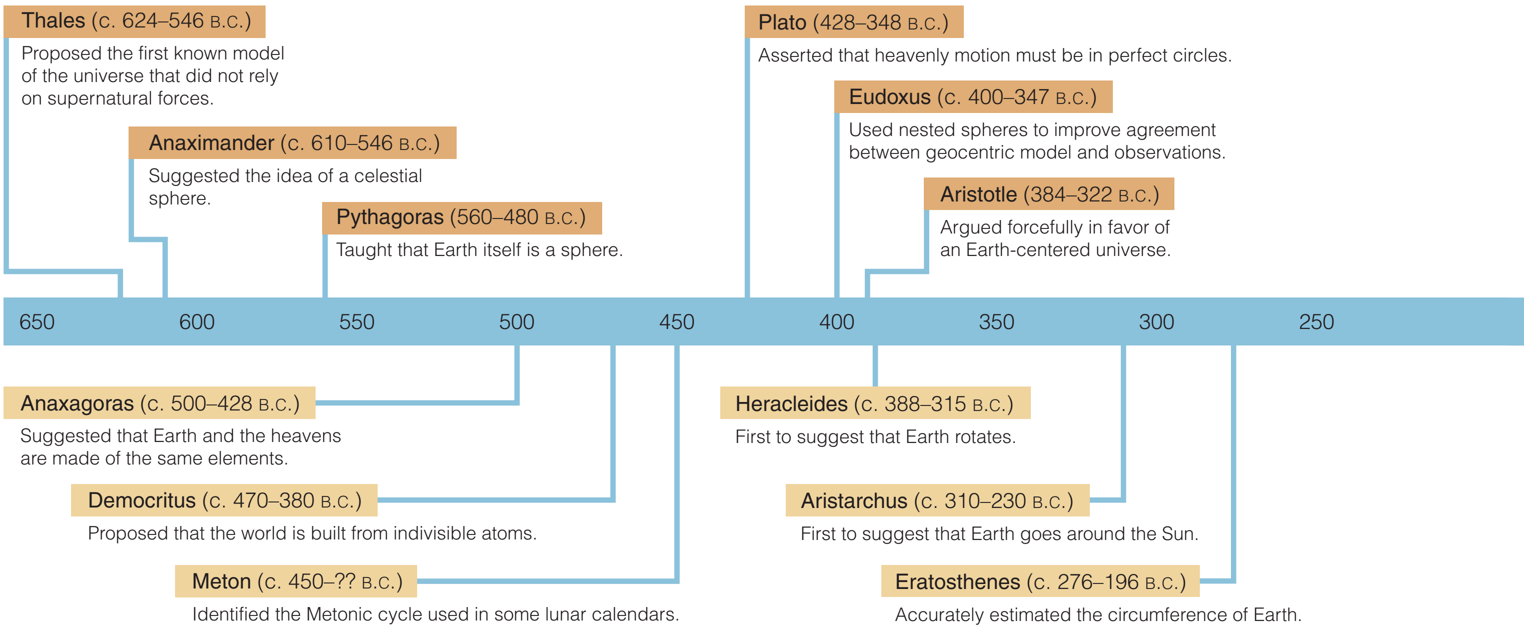
THINK ABOUT IT

Estimate the number of books you're likely to read in your lifetime, and compare this number to the half million books once housed in the Library of Alexandria. Can you think of other ways to put into perspective the loss of ancient wisdom resulting from the destruction of the Library of Alexandria?

Much of the Library of Alexandria's long history remains unknown today, in part because the books that recorded its history were destroyed along with the library. Nevertheless, historians are confident that the library's demise was intertwined with the life and death of a woman named Hypatia (A.D. 370–415), one of the few prominent female scholars of the ancient world. Hypatia was one of the last resident scholars of the library, as well as the director of the observatory in Alexandria and one of the leading mathematicians and astronomers of her time. Tragically, she became a scapegoat during a time of rising sentiment against free inquiry and was murdered in A.D. 415. The final destruction of the library took place not long after her death. In commemoration of the ancient library, Egypt built a New Library of Alexandria (the *Bibliotheca Alexandrina*, which opened in 2003), with hopes that it will once again make Alexandria a global center for scientific research.

The relatively few books that survived the destruction of the Library of Alexandria were preserved primarily thanks to the rise of a new center of intellectual inquiry in Baghdad (in present-day Iraq). While European civilization fell into the period of intellectual decline known as the Dark Ages, scholars of the new religion of Islam sought knowledge of mathematics and astronomy in hopes of better understanding the wisdom of Allah. During the 8th and 9th centuries A.D., scholars working in the Muslim Empire translated and thereby saved many ancient Greek works.

Around A.D. 800, the Islamic leader Al-Mamun (A.D. 786–833) established a "House of Wisdom" in Baghdad with a mission



SPECIAL TOPIC

Aristotle

Aristotle (384–322 B.C.) is among the best-known philosophers of the ancient world. Both his parents died when he was a child, and he was raised by a family friend. In his 20s and 30s, he studied under Plato (428–348 B.C.) at Plato's Academy. He later founded his own school, called the Lyceum, where he studied and lectured on virtually every subject. Historical records tell us that his lectures were collected and published in 150 volumes. About 50 of these volumes survive to the present day.

Many of Aristotle's scientific discoveries were about the nature of plants and animals. He studied more than 500 animal species in detail, dissecting specimens of nearly 50 species, and came up with a strikingly modern classification system. For example, he was the first person to recognize that dolphins should be classified with land mammals rather than with fish. In mathematics, he is known for laying the foundations of mathematical logic. Unfortunately, he was far less successful in physics and astronomy, areas in which many of his claims turned out to be wrong.

Despite his wide-ranging discoveries and writings, Aristotle's philosophies were not particularly influential until many centuries after his death. His books were preserved and valued by Islamic scholars but were unknown in Europe until they were translated into Latin in the 12th and 13th centuries. Aristotle's work gained great influence only after his philosophy was integrated into Christian theology by St. Thomas Aquinas (1225–1274). In the ancient world, Aristotle's greatest influence came indirectly, through his role as the tutor of Alexander the Great.

much like that of the destroyed Library of Alexandria. Founded in a spirit of openness and tolerance, the House of Wisdom employed Jews, Christians, and Muslims, all working together in scholarly pursuits. Using the translated Greek scientific manuscripts as building blocks, these scholars developed the mathematics of algebra and many new instruments and techniques for astronomical observation. Most of the official names of constellations and stars come from Arabic because of the work of the scholars at Baghdad. If you look at a star chart, you will see that the names of many bright stars begin with *al* (e.g., Aldebaran, Algol), which means "the" in Arabic.

The Islamic world of the Middle Ages was in frequent contact with Hindu scholars from India, who in turn brought knowledge of ideas and discoveries from China. Hence, the intellectual center in Baghdad achieved a synthesis of the surviving work of the ancient Greeks and that of the Indians and the Chinese. The accumulated knowledge of the Baghdad scholars spread throughout the Byzantine empire (part of the former Roman Empire). When the Byzantine capital of Constantinople (modern-day Istanbul) fell to the Turks in 1453, many Eastern scholars headed west to Europe, carrying with them the knowledge that helped ignite the European Renaissance.

How did the Greeks explain planetary motion?

The Greek **geocentric model** of the cosmos—so named because it placed a spherical Earth at the center of the universe—developed gradually over a period of several centuries. Because this model was so important in the history of science, let's briefly trace its development. FIGURE 12 will help you keep track of some of the personalities we will encounter.

Early Development of the Geocentric Model

We generally trace the origin of Greek science to the philosopher Thales (c. 624–546 B.C.; pronounced *thay-lees*). We encountered Thales earlier because of his legendary prediction

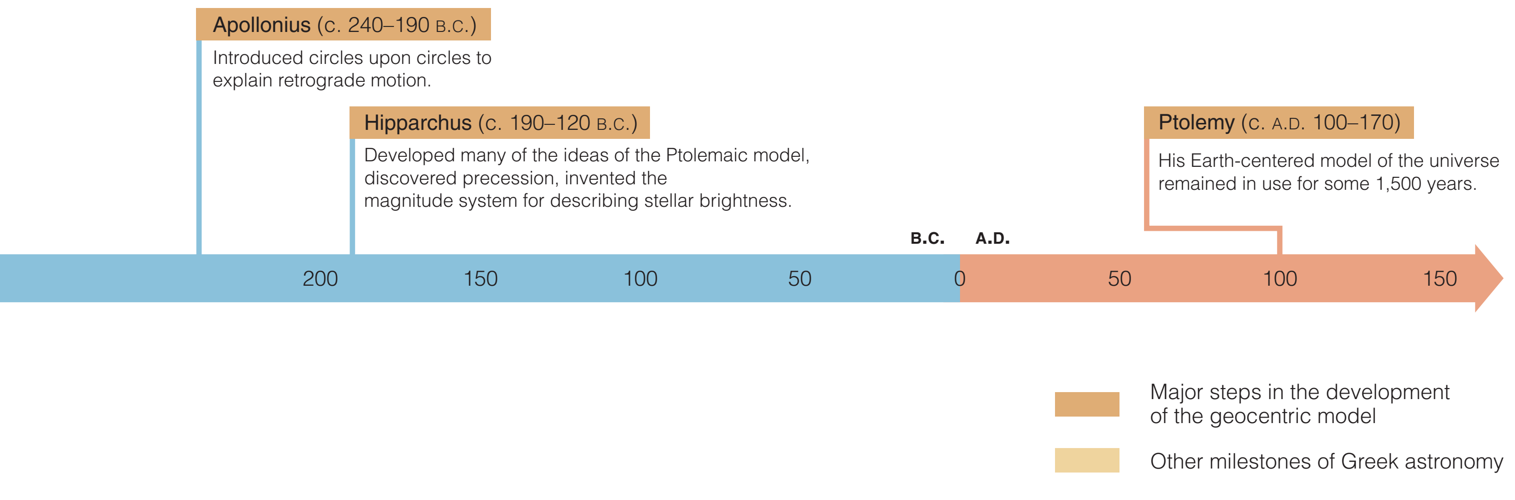


FIGURE 12 Timeline for major Greek figures in the development of astronomy.

of a solar eclipse. Thales was the first person known to have addressed the question "What is the universe made of?" without resorting to supernatural explanations. His own guess—that the universe fundamentally consists of water and that Earth is a flat disk floating in an infinite ocean—was not widely accepted even in his own time. Nevertheless, just by asking the question he suggested that the world is inherently understandable and thereby inspired others to come up with better models for the structure of the universe.

A more sophisticated idea followed soon after, proposed by a student of Thales named Anaximander (c. 610–546 B.C.). Anaximander suggested that Earth floats in empty space surrounded by a sphere of stars and two separate rings along which the Sun and Moon travel. We therefore credit him with inventing the idea of a celestial sphere. Interestingly, Anaximander imagined Earth itself to be cylindrical rather than spherical in shape. He probably chose this shape because he knew Earth had to be curved in a north-south direction to explain changes in the constellations with latitude. Because the visible constellations do not change with longitude, he saw no need for curvature in the east-west direction.

We do not know precisely when the Greeks first began to think that Earth is round, but this idea was taught as early as about 500 B.C. by the famous mathematician Pythagoras (c. 560–480 B.C.). He and his followers envisioned Earth as a sphere floating at the center of the celestial sphere. Much of their motivation for adopting a spherical Earth probably was philosophical: The Pythagoreans had a mystical interest in mathematical perfection, and they considered a sphere to be geometrically perfect. More than a century later, Aristotle cited observations of Earth's curved shadow on the Moon during lunar eclipses as evidence for a spherical Earth.

The Pythagorean interest in "heavenly perfection" became deeply ingrained in most Greek philosophers. It took on even more significance after Plato (428–348 B.C.) asserted that all heavenly objects move in perfect circles at constant speeds and therefore must reside on huge spheres encircling Earth (FIGURE 13). The Platonic belief in perfection influenced astronomical models for the next 2000 years. Of course, those Greeks who made observations found Plato's model problematic: The apparent retrograde motion of the planets, already well known by that time, clearly showed that planets do *not* move at constant speeds around Earth.

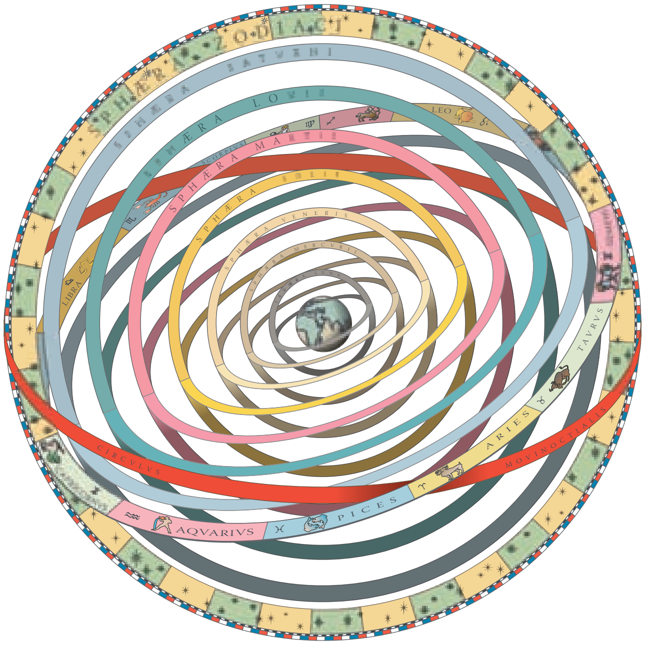


FIGURE 13 This model represents the Greek idea of the heavenly spheres (c. 400 B.C.). Earth is a sphere that rests in the center. The Moon, the Sun, and the planets all have their own spheres. The outermost sphere holds the stars.

An ingenious solution came from Plato's colleague Eudoxus (c. 400–347 B.C.), who created a model in which the Sun, the Moon, and the planets each had their own spheres nested within several other spheres. Individually, the nested spheres turned in perfect circles. By carefully choosing the sizes, rotation axes, and rotation speeds for the invisible spheres, Eudoxus was able to make them work together in a way that reproduced many of the observed motions of the Sun, Moon, and planets in our sky. Other Greeks refined the model by comparing its predictions to observations and adding more spheres to improve the agreement.

This is how things stood when Aristotle (384–322 B.C.) arrived on the scene. Whether Eudoxus and his followers thought of the nested spheres as real physical objects is not clear, but Aristotle certainly did. In Aristotle's model, all the spheres responsible for celestial motion were transparent and interconnected like the gears of a giant machine. Earth's position at the center was explained as a natural consequence of gravity. Aristotle argued that gravity pulled heavy things toward the center of the universe (and allowed lighter things to float toward the heavens), thereby causing all the dirt, rock, and water of the universe to collect at the center and form the spherical Earth. We now know that Aristotle was wrong about both gravity and Earth's location. However, largely because of his persuasive arguments for an Earth-centered universe, the geocentric view dominated Western thought for almost 2000 years.

COMMON MISCONCEPTIONS

Columbus and a Flat Earth

A widespread myth gives credit to Columbus for learning that Earth is round, but knowledge of Earth's shape predated Columbus by nearly 2000 years. Not only were scholars of Columbus's time well aware that Earth is round, but they even knew its approximate size: Earth's circumference was first measured in about 240 B.C. by the Greek scientist Eratosthenes. In fact, a likely reason Columbus had so much difficulty finding a sponsor for his voyages was that he tried to argue a point on which he was wrong: He claimed the distance by sea from western Europe to eastern Asia to be much less than scholars knew it to be. When he finally found a patron in Spain and left on his journey, he was so woefully underprepared that the voyage would almost certainly have ended in disaster if the Americas hadn't stood in his way.

Ptolemy's Synthesis Greek modeling of the cosmos culminated in the work of Claudius Ptolemy (c. A.D. 100–170; pronounced *TOL-e-mee*). Ptolemy's model still placed Earth at the center of the universe, but it differed in significant ways from the nested spheres of Eudoxus and Aristotle. We refer to Ptolemy's geocentric model as the **Ptolemaic model** to distinguish it from earlier geocentric models.

To explain the apparent retrograde motion of the planets, the Ptolemaic model applied an idea first suggested by Apollonius (c. 240–190 B.C.). This idea held that each planet moved around Earth on a small circle that turned upon a larger circle (FIGURE 14). (The small circle is sometimes called an *epicycle,* and the larger circle is called a *deferent.*) A planet following this circle-upon-circle motion would trace a loop as seen from Earth, with the backward portion of the loop mimicking apparent retrograde motion.

Ptolemy also relied heavily on the work of Hipparchus (c. 190–120 B.C.), considered one of the greatest of the Greek astronomers. Among his many accomplishments, Hipparchus developed the circle-upon-circle idea of Apollonius into a model that could predict planetary positions. To do this, Hipparchus had to add several features to the basic idea; for example, he included even smaller circles that moved upon the original set of small circles, and he positioned the large circles slightly off-center from Earth.

Ptolemy's great accomplishment was to adapt and synthesize earlier ideas into a single system that agreed quite well with the astronomical observations available at the time. In the end, he created and published a model that could correctly forecast future planetary positions to within a few degrees of arc, which is about the angular size of your hand held at arm's length against the sky. This was sufficiently accurate to keep the model in use for the next 1500 years. When Ptolemy's book describing the model was translated by Arabic scholars around A.D. 800, they gave it the title *Almagest*, derived from words meaning "the greatest compilation."

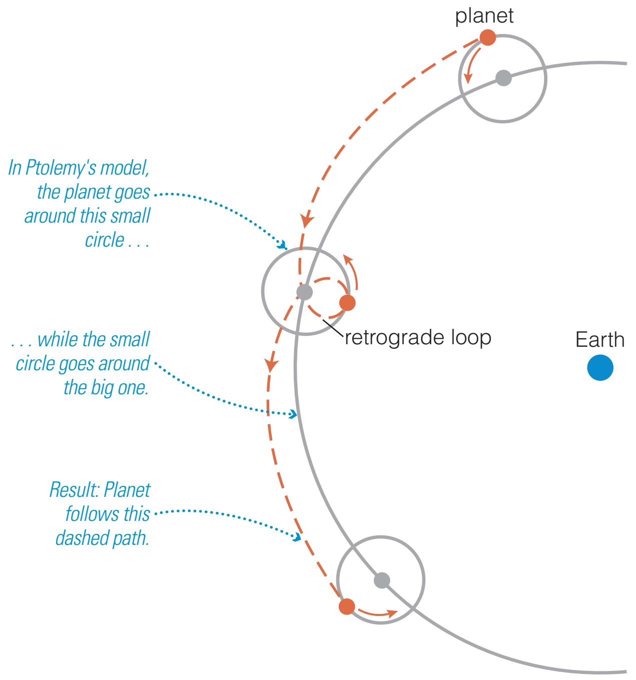


FIGURE 14 interactive figure This diagram shows how the Ptolemaic model accounted for apparent retrograde motion. Each planet is assumed to move around a small circle that turns upon a larger circle. The resulting path (dashed) includes a loop in which the planet goes backward as seen from Earth.

SPECIAL TOPIC

Eratosthenes Measures Earth

In a remarkable feat, the Greek scientist Eratosthenes accurately estimated the size of Earth in about 240 B.C. He did it by comparing the altitude of the Sun on the summer solstice in the Egyptian cities of Syene (modern-day Aswan) and Alexandria.

Eratosthenes knew that the Sun passed directly overhead in Syene on the summer solstice. He also knew that in Alexandria, to the north, the Sun came within only 7° of the zenith on the summer solstice. He therefore reasoned that Alexandria must be 7° of latitude to the north of Syene (FIGURE 1). Because 7° is $\frac{7}{360}$ of a circle, he concluded that the north-south distance between Alexandria and Syene must be $\frac{7}{360}$ of the circumference of Earth.

Eratosthenes estimated the north-south distance between Syene and Alexandria to be 5000 stadia (the *stadium* was a Greek unit of distance). Thus, he concluded that

$$\frac{7}{360} \times \text{circumference of Earth} = 5000 \text{ stadia}$$

From this he found Earth's circumference to be about 250,000 stadia.

We don't know exactly what distance a stadium meant to Eratosthenes, but from sizes of actual Greek stadiums, it must have been about $\frac{1}{6}$ kilometer. Thus, Eratosthenes estimated the circumference of Earth to be about $\frac{250{,}000}{6} = 42{,}000$ kilometers—impressively close to the real value of just over 40,000 kilometers.

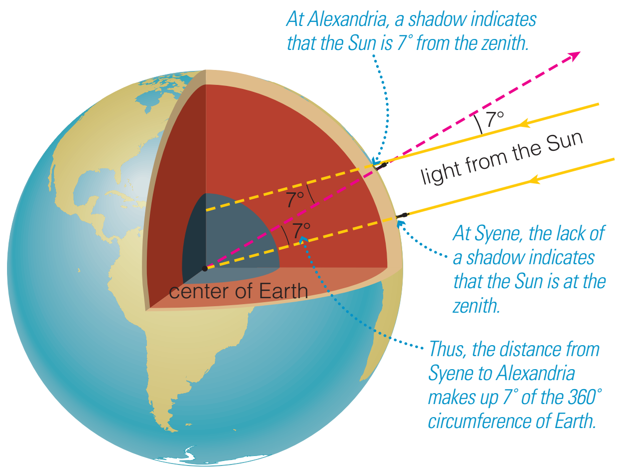


FIGURE 1 At noon on the summer solstice, the Sun appears at the zenith in Syene but 7° shy of the zenith in Alexandria. Thus, 7° of latitude, which corresponds to a distance of $\frac{7}{360}$ of Earth's circumference, must separate the two cities.

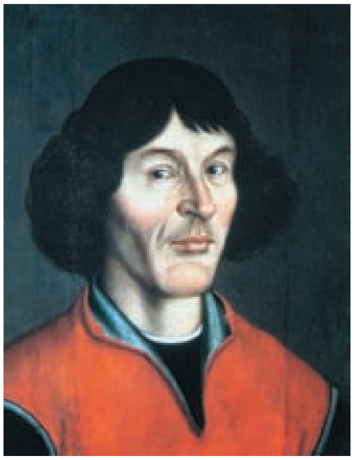
3 THE COPERNICAN REVOLUTION

The Greeks and other ancient peoples developed many important scientific ideas, but what we now think of as science arose during the European Renaissance. Within a half century after the fall of Constantinople, Polish scientist Nicholas Copernicus began the work that ultimately overturned the Earth-centered Ptolemaic model.

How did Copernicus, Tycho, and Kepler challenge the Earth-centered model?

The ideas introduced by Copernicus fundamentally changed the way we perceive our place in the universe. The story of this dramatic change, known as the **Copernican revolution**, is in many ways the story of the origin of modern science. It is also the story of several key personalities, beginning with Copernicus himself.

Copernicus Nicholas Copernicus was born in Toruń, Poland, on February 19, 1473. His family was wealthy and he received an education in mathematics, medicine, and law. He began studying astronomy in his late teens.



Copernicus (1473–1543)

By that time, tables of planetary motion based on the Ptolemaic model had become noticeably inaccurate. But few people were willing to undertake the difficult calculations required to revise the tables. The best tables available had been compiled some two centuries earlier under the guidance of Spanish monarch Alphonso X (1221–1284). Commenting on the tedious nature of the work, the monarch is said to have complained, "If I had been present at the creation, I would have recommended a simpler design for the universe."

In his quest for a better way to predict planetary positions, Copernicus decided to try Aristarchus's Sun-centered idea, first proposed more than 1700 years earlier. He had read of Aristarchus's work, and recognized the much simpler explanation for apparent retrograde motion offered by a Sun-centered system. But he went far beyond Aristarchus in working out mathematical details of the model. Through this process, Copernicus discovered simple geometric relationships that allowed him to calculate each planet's orbital period around the Sun and its relative distance from the Sun in terms of the Earth-Sun distance. The model's success in providing a geometric layout for the solar system convinced him that the Sun-centered idea must be correct.

Despite his own confidence in the model, Copernicus was hesitant to publish his work, fearing that his suggestion that Earth moved would be considered absurd. However, he discussed his system with other scholars, including high-ranking officials of the Catholic Church, who urged him to publish a book. Copernicus saw the first printed copy of his book, *De Revolutionibus Orbium Coelestium* ("Concerning the Revolutions of the Heavenly Spheres"), on the day he died—May 24, 1543.

Publication of the book spread the Sun-centered idea widely, and many scholars were drawn to its aesthetic advantages. Nevertheless, the Copernican model gained relatively few converts over the next 50 years, for a good reason: It didn't work all that well. The primary problem was that while Copernicus had been willing to overturn Earth's central place in the cosmos, he had held fast to the ancient belief that heavenly motion must occur in perfect circles. This incorrect assumption forced him to add numerous complexities to his system (including circles on circles much like those used by Ptolemy) to get it to make decent predictions. In the end, his complete model was no more accurate and no less complex than the Ptolemaic model, and few people were willing to throw out thousands of years of tradition for a new model that worked just as poorly as the old one.

Tycho Part of the difficulty faced by astronomers who sought to improve either the Ptolemaic or the Copernican system was a lack of quality data. The telescope had not yet been invented, and existing naked-eye observations were not very accurate. Better data were needed, and they were provided by the Danish nobleman Tycho Brahe (1546–1601), usually known simply as Tycho (pronounced *tie-koe*).

Tycho became interested in astronomy as a young boy, but his family discouraged this interest. He therefore kept his passion secret, learning the constellations from a miniature model of a celestial sphere that he kept hidden. As he grew older, Tycho was often arrogant about both his noble birth and his intellectual abilities. At age 20, he fought a duel with another student over which of them was the better mathematician. Part of Tycho's nose was cut off, and he designed a replacement piece made of silver and gold.

Tycho Brahe (1546–1601)

In 1563, Tycho decided to observe a widely anticipated alignment of Jupiter and Saturn. To his surprise, the alignment occurred nearly 2 days later than the date Copernicus had predicted. Resolving to improve the state of astronomical prediction, he set about compiling careful observations of stellar and planetary positions in the sky.

Tycho's fame grew after he observed what he called a *nova,* meaning "new star," in 1572. By measuring its parallax and comparing it to the parallax of the Moon, he proved that the nova was much farther away than the Moon. (Today, we know that Tycho saw a *supernova*—the explosion of a distant star.) In 1577, Tycho made similar observations of a comet and proved that it too lay in the realm of the heavens. Others, including Aristotle, had argued that comets were phenomena of Earth's atmosphere. King Frederick II of Denmark decided to sponsor Tycho's ongoing work, providing him with money to build an unparalleled observatory for naked-eye observations (**FIGURE 15**). After Frederick II died in 1588, Tycho moved to Prague, where his work was supported by German emperor Rudolf II.

Over a period of three decades, Tycho and his assistants compiled naked-eye observations accurate to within less than 1 arcminute—less than the thickness of a fingernail viewed at arm's length. Because the telescope was invented shortly after his death, Tycho's data remain the best set of naked-eye observations ever made. Despite the quality of his observations, Tycho never succeeded in coming up with a satisfying explanation for planetary motion. He was convinced that the *planets* must orbit the Sun, but his inability to detect stellar parallax led him to conclude that Earth must remain stationary. He therefore advocated a model in which the Sun orbits Earth while all other planets orbit the Sun. Few people took this model seriously.

FIGURE 15 Tycho Brahe in his naked-eye observatory, which worked much like a giant protractor. He could sit and observe a planet through the rectangular hole in the wall as an assistant used a sliding marker to measure the angle on the protractor.

Kepler Tycho failed to explain the motions of the planets satisfactorily, but he succeeded in finding someone who could: In 1600, he hired the young German astronomer Johannes Kepler (1571–1630). Kepler and Tycho had a strained relationship, but Tycho recognized the talent of his young apprentice. In 1601, as he lay on his deathbed, Tycho begged Kepler to find a system that would make sense of his observations so "that it may not appear I have lived in vain."*

Johannes Kepler (1571–1630)

Kepler was deeply religious and believed that understanding the geometry of the heavens would bring him closer to God. Like Copernicus, he believed that planetary orbits should be perfect circles, so he worked diligently to match circular motions to Tycho's data.

Kepler labored with particular intensity to find an orbit for Mars, which posed the greatest difficulties in matching the data to a circular orbit. After years of calculation, Kepler found a circular orbit that matched all of Tycho's observations of Mars's position along the ecliptic (east-west) to within 2 arcminutes. However, the model did not correctly predict Mars's positions north or south of the ecliptic. Because Kepler sought a physically realistic orbit for Mars, he could not (as Ptolemy and Copernicus had done) tolerate one model for the east-west positions and another for the north-south positions. He attempted to find a unified model with a circular orbit. In doing so, he found that some of his predictions differed from Tycho's observations by as much as 8 arcminutes.

Kepler surely was tempted to ignore these discrepancies and attribute them to errors by Tycho. After all, 8 arcminutes is barely one-fourth the angular diameter of the full moon. But Kepler trusted Tycho's careful work. The small discrepancies finally led Kepler to abandon the idea of circular orbits—and to find the correct solution to the ancient riddle of planetary motion. About this event, Kepler wrote:

> *If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy.*

*For a particularly moving version of the story of Tycho and Kepler, see Episode 3 of Carl Sagan's *Cosmos* video series.

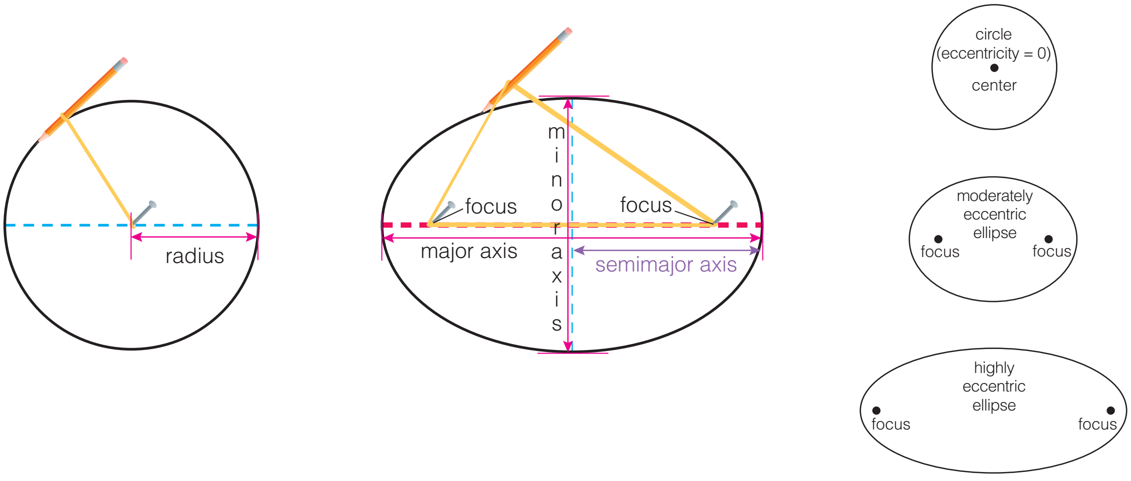


FIGURE 16 **interactive figure** An ellipse is a special type of oval. These diagrams show how an ellipse differs from a circle and how different ellipses vary in their eccentricity.

a Drawing a circle with a string of fixed length.

b Drawing an ellipse with a string of fixed length.

c Eccentricity describes how much an ellipse deviates from a perfect circle.

Kepler's key discovery was that planetary orbits are not circles but instead are a special type of oval called an **ellipse**. You can draw a circle by putting a pencil on the end of a string, tacking the string to a board, and pulling the pencil around (**FIGURE 16a**). Drawing an ellipse is similar, except that you must stretch the string around *two* tacks (**FIGURE 16b**). The locations of the two tacks are called the **foci** (singular, **focus**) of the ellipse. The long axis of the ellipse is called its *major axis,* each half of which is called a **semimajor axis**; as you'll see shortly, the length of the semimajor axis is particularly important in astronomy. The short axis is called the *minor axis.* By altering the distance between the two foci while keeping the length of string the same, you can draw ellipses of varying **eccentricity**, a quantity that describes how much an ellipse is stretched out compared to a perfect circle (**FIGURE 16c**). A circle is an ellipse with zero eccentricity, and greater eccentricity means a more elongated ellipse.

Kepler's decision to trust the data over his preconceived beliefs marked an important transition point in the history of science. Once he abandoned perfect circles in favor of ellipses, Kepler soon came up with a model that could predict planetary positions with far greater accuracy than Ptolemy's Earth-centered model. Kepler's model withstood the test of time and became accepted not only as a model of nature but also as a deep, underlying truth about planetary motion.

MA® **Orbits and Kepler's Laws Tutorial, Lessons 2–4**

What are Kepler's three laws of planetary motion?

Kepler summarized his discoveries with three simple laws that we now call **Kepler's laws of planetary motion**. He published the first two laws in 1609 and the third in 1619.

Kepler's First Law Kepler's first law tells us that *the orbit of each planet around the Sun is an ellipse with the Sun at one focus* (**FIGURE 17**). (Nothing is at the other focus.) In essence,

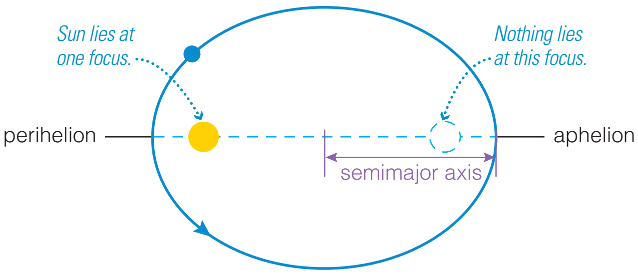


FIGURE 17 **interactive figure** Kepler's first law: The orbit of each planet about the Sun is an ellipse with the Sun at one focus. (The eccentricity shown here is exaggerated compared to the actual eccentricities of the planets.)

this law tells us that a planet's distance from the Sun varies during its orbit. It is closest at the point called **perihelion** (from the Greek for "near the Sun") and farthest at the point called **aphelion** (from the Greek for "away from the Sun"). The *average* of a planet's perihelion and aphelion distances is the length of its semimajor axis. We will refer to this simply as the planet's average distance from the Sun.

Kepler's Second Law Kepler's second law states that *as a planet moves around its orbit, it sweeps out equal areas in equal times.* As shown in **FIGURE 18**, this means the planet moves a greater distance when it is near perihelion than it does in the same amount of time near aphelion. That is, the planet travels faster when it is nearer to the Sun and slower when it is farther from the Sun.

Kepler's Third Law Kepler's third law tells us that *more distant planets orbit the Sun at slower average speeds, obeying a precise mathematical relationship.* The relationship is written

$$p^2 = a^3$$

where p is the planet's orbital period in years and a is its average distance from the Sun in astronomical units. **FIGURE 19a** shows the $p^2 = a^3$ law graphically. Notice that the square of

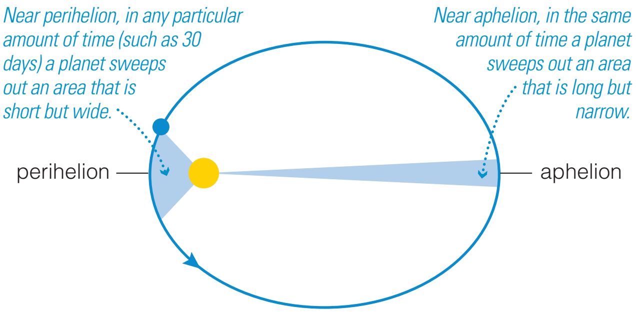


FIGURE 18 **interactive figure** Kepler's second law: As a planet moves around its orbit, an imaginary line connecting it to the Sun sweeps out equal areas (the shaded regions) in equal times.

each planet's orbital period (p^2) is indeed equal to the cube of its average distance from the Sun (a^3). Because Kepler's third law relates a planet's orbital distance to its orbital time (period), we can use the law to calculate a planet's average orbital speed.* **FIGURE 19b** shows the result, confirming that more distant planets orbit the Sun more slowly.

The fact that more distant planets move more slowly led Kepler to suggest that planetary motion might be the result of a force from the Sun. He even speculated about the nature of this force, guessing that it might be related to magnetism. (This idea, shared by Galileo, was first suggested by William Gilbert [1544–1603], an early believer in the Copernican system.) Kepler was right about the existence of a force but wrong in his guess of magnetism. A half century later, Isaac Newton finally explained planetary motion as a consequence of gravity.

*To calculate orbital speed from Kepler's third law, remember that speed = distance/time. For a planetary orbit, the distance is the orbital circumference, or $2\pi a$ (where a is the semimajor axis, roughly the "radius" of the orbit), and the time is the orbital period p, so the orbital speed is $(2\pi a)/p$. From Kepler's third law, $p = a^{3/2}$. Plugging this value for p into the orbital speed equation, we find that a planet's orbital speed is $2\pi/\sqrt{a}$; the graph of this equation is the curve in Figure 19b.

THINK ABOUT IT

Suppose a comet has an orbit that brings it quite close to the Sun at its perihelion and beyond Mars at its aphelion, but with an average distance (semimajor axis) of 1 AU. According to Kepler's laws, how long does the comet take to complete each orbit? Does it spend most of its time close to the Sun, far from the Sun, or somewhere in between? Explain.

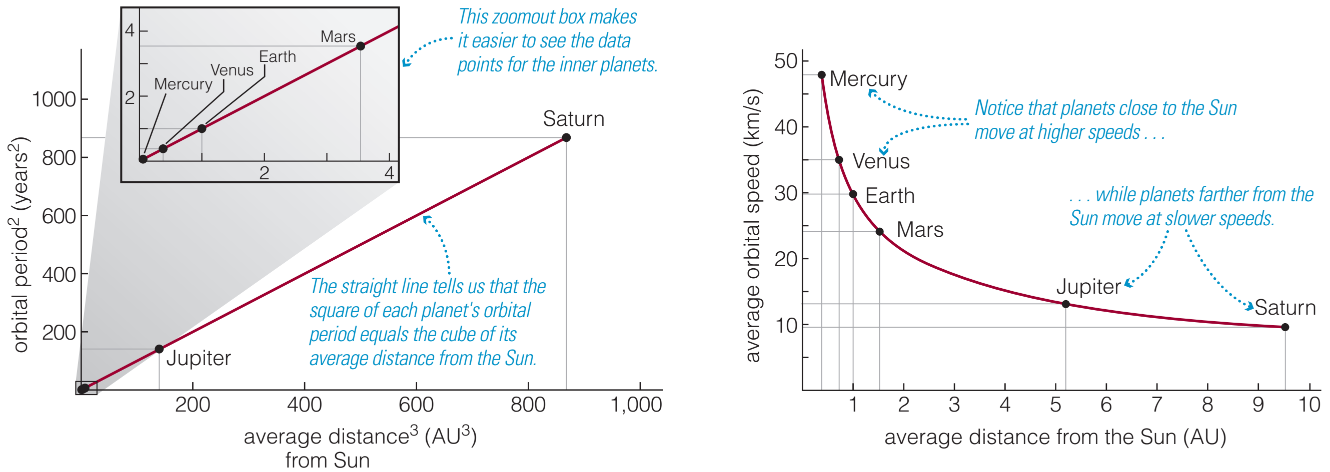
How did Galileo solidify the Copernican revolution?

The success of Kepler's laws in matching Tycho's data provided strong evidence in favor of Copernicus's placement of the Sun, rather than Earth, at the center of the solar system. Nevertheless, many scientists still voiced reasonable objections to the Copernican view. There were three basic objections, all rooted in the 2000-year-old beliefs of Aristotle and other ancient Greeks.

- First, Aristotle had held that Earth could not be moving because, if it were, objects such as birds, falling stones, and clouds would be left behind as Earth moved along its way.
- Second, the idea of noncircular orbits contradicted Aristotle's claim that the heavens—the realm of the Sun, Moon, planets, and stars—must be perfect and unchanging.
- Third, no one had detected the stellar parallax that should occur if Earth orbits the Sun.

Galileo Galilei (1564–1642), usually known by only his first name, answered all three objections.

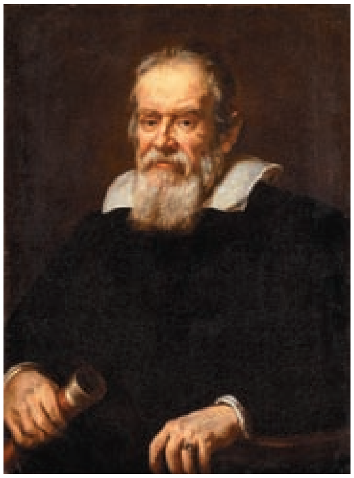
Galileo's Evidence Galileo defused the first objection with experiments that almost single-handedly overturned the Aristotelian view of physics. In particular, he used experiments with rolling balls to demonstrate that a moving object remains in motion *unless* a force acts to stop it (an idea now codified in Newton's first law of motion). This



a This graph shows that Kepler's third law ($p^2 = a^3$) holds true; the graph shows only the planets known in Kepler's time.

b This graph, based on Kepler's third law and modern values of planetary distances, shows that more distant planets orbit the Sun more slowly.

FIGURE 19 Graphs based on Kepler's third law.



Galileo (1564–1642)

insight explained why objects that share Earth's motion through space—such as birds, falling stones, and clouds—should *stay* with Earth rather than falling behind as Aristotle had argued. This same idea explains why passengers stay with a moving airplane even when they leave their seats.

The second objection had already been challenged by Tycho's supernova and comet observations, which proved that the heavens could change. Galileo then shattered the idea of heavenly perfection after he built a telescope in late 1609. (Galileo did not invent the telescope; it was patented by Hans Lippershey in 1608. However, Galileo took what was little more than a toy and turned it into a scientific instrument.) Through his telescope, Galileo saw sunspots on the Sun, which were considered "imperfections" at the time. He also used his telescope to prove that the Moon has mountains and valleys like the "imperfect" Earth by noticing the shadows cast near the dividing line between the light and dark portions of the lunar face (**FIGURE 20**). If the heavens were in fact not perfect, then the idea of elliptical orbits (as opposed to "perfect" circles) was not so objectionable.

The third objection—the absence of observable stellar parallax—had been of particular concern to Tycho. Based on his estimates of the distances of stars, Tycho believed that his naked-eye observations were sufficiently precise to detect stellar parallax if Earth did in fact orbit the Sun. Refuting Tycho's argument required showing that the stars were more distant than Tycho had thought and therefore too distant for him to have observed stellar parallax. Although Galileo didn't actually prove this fact, he provided strong evidence in its favor. For example, he saw with his telescope that the Milky Way

MATHEMATICAL INSIGHT 1

Eccentricity and Planetary Orbits

We describe how much a planet's orbit differs from a perfect circle by stating its orbital eccentricity. There are several equivalent ways to define the eccentricity of an ellipse, but the simplest is shown in **FIGURE 1**. We define c to be the distance from each focus to the center of the ellipse and a to be the length of the semimajor axis. The eccentricity, e, is then defined to be

$$e = \frac{c}{a}$$

Notice that $c = 0$ for a perfect circle, because a circle is an ellipse with both foci *in* the center, so this formula gives an eccentricity of 0 for a perfect circle, just as we expect.

You can find the orbital eccentricities for the planets in tables. Once you know the eccentricity, the following formulas allow you to calculate the planet's perihelion and aphelion distances (**FIGURE 2**):

$$\text{perihelion distance} = a(1 - e)$$
$$\text{aphelion distance} = a(1 + e)$$

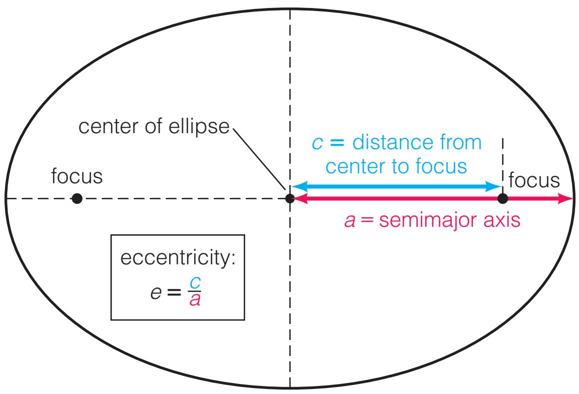


FIGURE 1

EXAMPLE: What are Earth's perihelion and aphelion distances?

SOLUTION:

Step 1 Understand: To use the given formulas, we need to know Earth's orbital eccentricity and semimajor axis length. Earth's orbital eccentricity is $e = 0.017$ and its semimajor axis (average distance from the Sun) is 1 AU, or $a = 149.6$ million km.

Step 2 Solve: We plug these values into the equations:

$$\begin{aligned}\text{Earth's perihelion distance} &= a(1 - e)\\ &= (149.6 \times 10^6 \text{ km})(1 - 0.017)\\ &= 147.1 \times 10^6 \text{ km}\end{aligned}$$

$$\begin{aligned}\text{Earth's aphelion distance} &= a(1 + e)\\ &= (149.6 \times 10^6 \text{ km})(1 + 0.017)\\ &= 152.1 \times 10^6 \text{ km}\end{aligned}$$

Step 3 Explain: Earth's perihelion (nearest to the Sun) distance is 147.1 million kilometers and its aphelion (farthest from the Sun) distance is 152.1 million kilometers. In other words, Earth's distance from the Sun varies between 147.1 and 152.1 million kilometers.

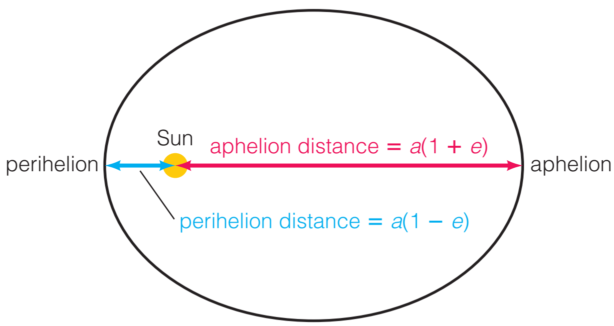


FIGURE 2

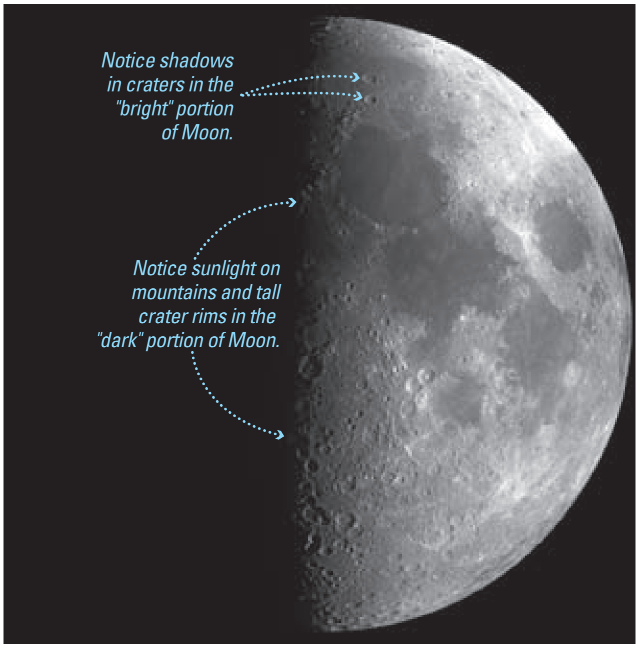


FIGURE 20 The shadows cast by mountains and crater rims near the dividing line between the light and dark portions of the lunar face prove that the Moon's surface is not perfectly smooth.

resolved into countless individual stars. This discovery helped him argue that the stars were far more numerous and more distant than Tycho had believed.

Sealing the Case In hindsight, the final nails in the coffin of the Earth-centered model came with two of Galileo's earliest discoveries through the telescope. First, he observed four moons clearly orbiting Jupiter, *not* Earth (**FIGURE 21**). By itself, this observation still did not rule out a stationary, central Earth. However, it showed that moons can orbit a moving planet like Jupiter, which overcame some critics' complaints that the Moon could not stay with a moving Earth. Soon thereafter, he observed that Venus goes through phases in a way that makes sense only if it orbits the Sun and not Earth (**FIGURE 22**).

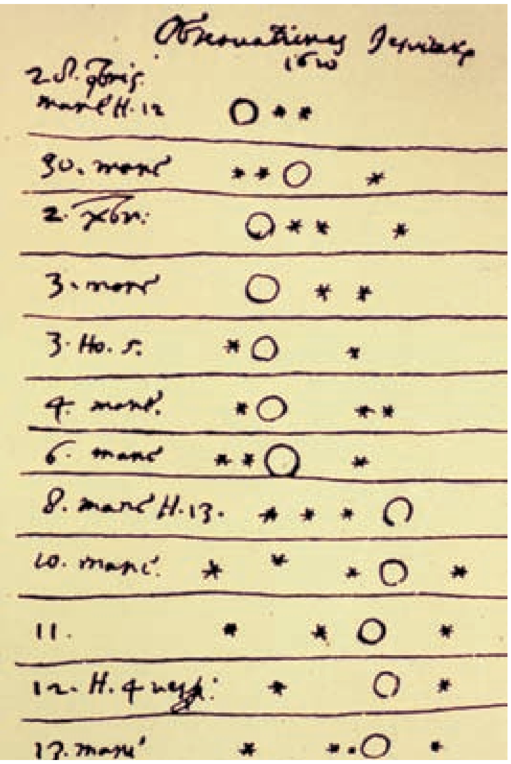
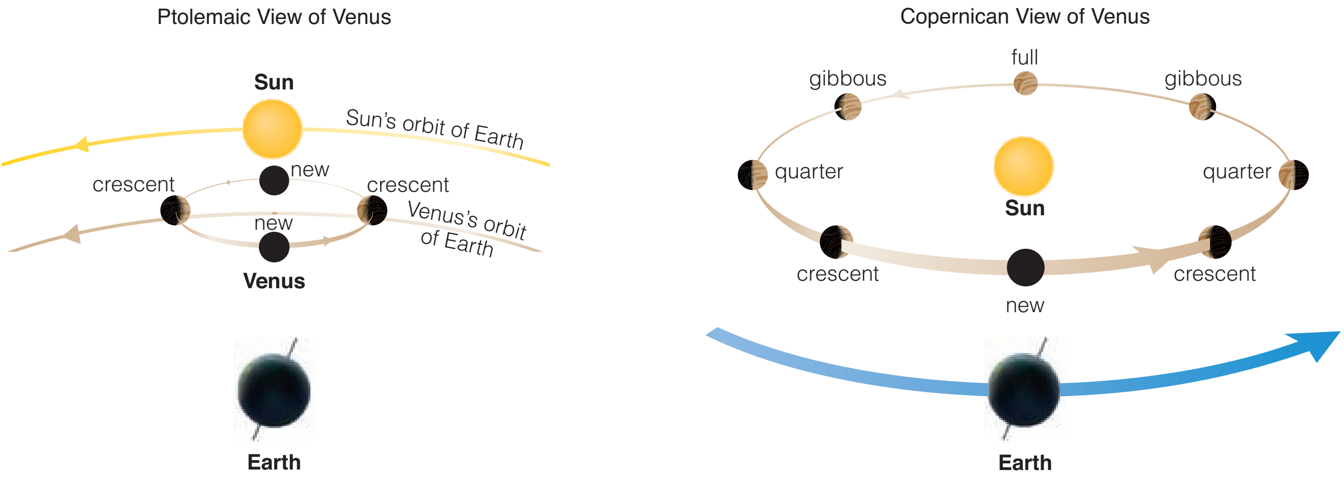


FIGURE 21 A page from Galileo's notebook written in 1610. His sketches show four "stars" near Jupiter (the circle) but in different positions at different times (with one or more sometimes hidden from view). Galileo soon realized that the "stars" were actually moons orbiting Jupiter.

With Earth clearly removed from its position at the center of the universe, the scientific debate turned to the question of whether Kepler's laws were the correct model for our solar system. The most convincing evidence came in 1631, when astronomers observed a transit of Mercury across the Sun's



a In the Ptolemaic system, Venus orbits Earth, moving around a smaller circle on its larger orbital circle; the center of the smaller circle lies on the Earth-Sun line. If this view were correct, Venus's phases would range only from new to crescent.

b In reality, Venus orbits the Sun, so from Earth we can see it in many different phases. This is just what Galileo observed, allowing him to prove that Venus orbits the Sun.

FIGURE 22 Galileo's telescopic observations of Venus proved that it orbits the Sun rather than Earth.

face. Kepler's laws had predicted the transit with overwhelmingly better success than any competing model.

Galileo and the Church Although we now recognize that Galileo won the day, the story was more complex in his own time, when Catholic Church doctrine still held Earth to be the center of the universe. On June 22, 1633, Galileo was brought before a Church inquisition in Rome and ordered to recant his claim that Earth orbits the Sun. Nearly 70 years old and fearing for his life, Galileo did as ordered and his life was spared. However, legend has it that as he rose from his knees he whispered under his breath, *Eppur si muove*—Italian for "And yet it moves." (Given the likely consequences if Church officials had heard him say this, most historians doubt the legend; see Special Topic.)

The Church did not formally vindicate Galileo until 1992, but Church officials gave up the argument long before that: In 1757, all works backing the idea of a Sun-centered solar system were removed from the Church's index of banned books. Today, Catholic scientists are at the forefront of much astronomical research, and official Church teachings are compatible not only with Earth's planetary status but also with the theories of the Big Bang and the subsequent evolution of the cosmos and of life.

4 THE NATURE OF SCIENCE

The story of how our ancestors gradually figured out the basic architecture of the cosmos exhibits many features of what we now consider "good science." For example, we have seen how models were formulated and tested against observations and modified or replaced when they failed those tests. The story also illustrates some classic mistakes, such as the apparent failure of anyone before Kepler to question the belief that orbits must be circles. The ultimate success of the Copernican revolution led scientists, philosophers, and theologians to reassess the various modes of thinking that played a role in the 2000-year process of discovering Earth's place in the universe. Let's examine how the principles of modern science emerged from the lessons learned in the Copernican revolution.

How can we distinguish science from nonscience?

It's surprisingly difficult to define the term *science* precisely. The word comes from the Latin *scientia,* meaning "knowledge," but not all knowledge is science. For example, you may know what music you like best, but your musical taste is not a result of scientific study.

Approaches to Science One reason science is difficult to define is that not all science works in the same way. For example, you've probably heard that science is supposed to proceed according to something called the "scientific method." As an idealized illustration of this method, consider what you would do if your flashlight suddenly stopped working. In hopes of fixing the flashlight, you might *hypothesize* that its batteries have died. This type of tentative explanation,

MATHEMATICAL INSIGHT 2

Kepler's Third Law

When Kepler discovered his third law, $p^2 = a^3$, he did so only by looking at planet orbits. In fact, it applies much more generally. Even in its original form we can apply it to any object *if*

1. the object is *orbiting the Sun* or another star of the same mass as the Sun and
2. we measure orbital *periods in years* and *distances in AU.*

EXAMPLE 1: What is the orbital period of the dwarf planet (and largest asteroid) Ceres, which orbits the Sun at an average distance (semimajor axis) of 2.77 AU?

SOLUTION:

Step 1 Understand: We can apply Kepler's third law because both conditions above are met. The first is met because Ceres orbits the Sun. The second is met because we are given the orbital distance in AU, which means Kepler's third law will tell us the orbital period in years.

Step 2 Solve: We want the period p, so we solve Kepler's third law for p by taking the square root of both sides; we then substitute the given value $a = 2.77$ AU:

$$p^2 = a^3 \Rightarrow p = \sqrt{a^3} = \sqrt{2.77^3} = 4.6$$

Note that because of the special conditions attached to the use of Kepler's third law in its original form, we do *not* include units when working with it; we know we'll get a period in years as long as we start with a distance in AU.

Step 3 Explain: Ceres has an orbital period of 4.6 years, meaning it takes 4.6 years to complete each orbit around the Sun.

EXAMPLE 2: A new planet is discovered to be orbiting a star with the same mass as our Sun. The planet orbits the star every 3 months. What is its average distance from its star?

SOLUTION:

Step 1 Understand: We can use Kepler's third law in its original form if the problem meets the two conditions above. The first condition is met because the planet is orbiting a star with the same mass as our Sun. To meet the second condition, we must convert the orbital period from 3 months to $p = 0.25$ year.

Step 2 Solve: We want the distance a, so we solve Kepler's third law for a by taking the cube root of both sides; we then substitute the orbital period $p = 0.25$ year:

$$p^2 = a^3 \Rightarrow a = \sqrt[3]{p^2} = \sqrt[3]{0.25^2} = 0.40$$

Step 3 Explain: The planet orbits its star at an average distance of 0.4 AU. By comparing this result to the distances of planets in our own solar system, we find that this planet's average orbital distance is just slightly larger than that of the planet Mercury in our own solar system.

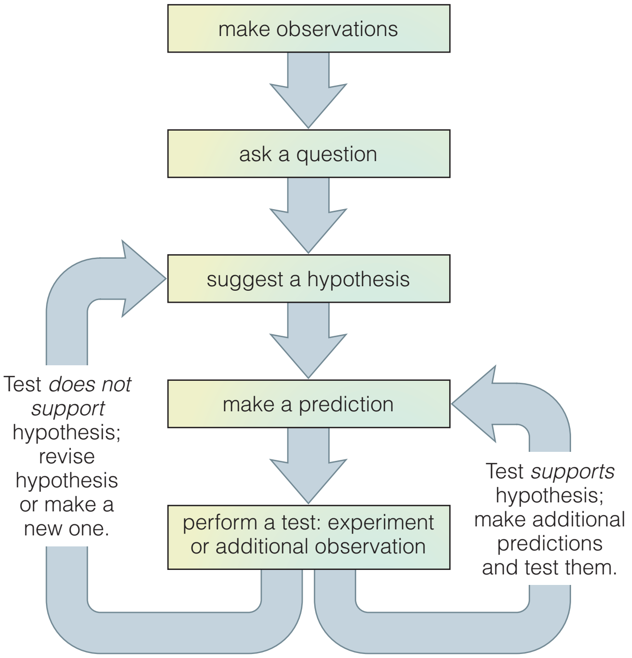


FIGURE 23 This diagram illustrates what we often call the scientific method.

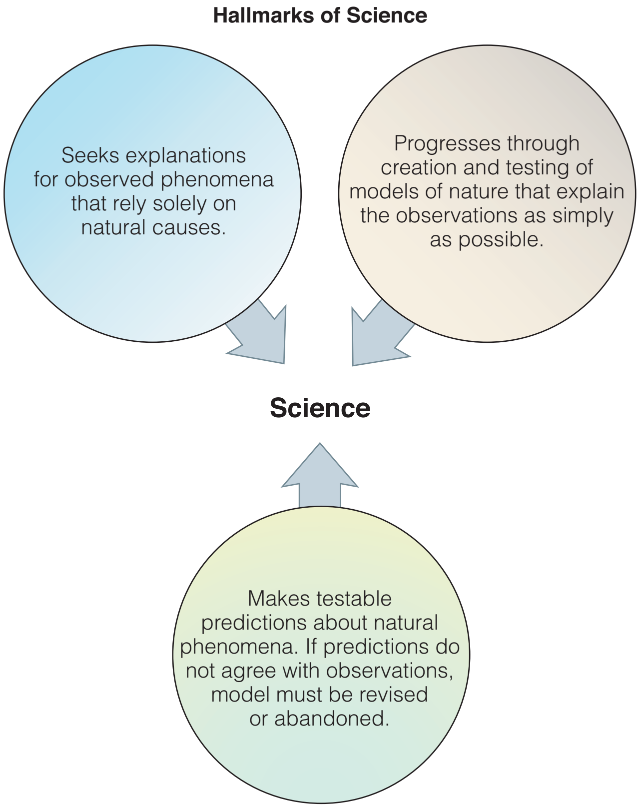


FIGURE 24 **interactive figure** Hallmarks of science.

or **hypothesis**, is sometimes called an *educated guess*—in this case, it is "educated" because you already know that flashlights need batteries. Your hypothesis allows you to make a simple prediction: If you replace the batteries with new ones, the flashlight should work. You can test this prediction by replacing the batteries. If the flashlight now works, you've confirmed your hypothesis. If it doesn't, you must revise or discard your hypothesis, perhaps in favor of some other one that you can also test (such as that the bulb is burned out). **FIGURE 23** illustrates the basic flow of this process.

The scientific method can be a useful idealization, but real science rarely progresses in such an orderly way. Scientific progress often begins with someone going out and looking at nature in a general way, rather than conducting a careful set of experiments. For example, Galileo wasn't looking for anything in particular when he pointed his telescope at the sky and made his first startling discoveries. Furthermore, scientists are human beings, and their intuition and personal beliefs inevitably influence their work. Copernicus, for example, adopted the idea that Earth orbits the Sun not because he had carefully tested it but because he believed it made more sense than the prevailing view of an Earth-centered universe. While his intuition guided him to the right general idea, he erred in the specifics because he still held Plato's ancient belief that heavenly motion must be in perfect circles.

Given that the idealized scientific method is an overly simplistic characterization of science, how can we tell what is science and what is not? To answer this question, we must look a little deeper into the distinguishing characteristics of scientific thinking.

Hallmarks of Science One way to define scientific thinking is to list the criteria that scientists use when they judge competing models of nature. Historians and philosophers of science have examined (and continue to examine) this issue in great depth, and different experts express different viewpoints on the details. Nevertheless, everything we now consider to be science shares the following three basic characteristics, which we will refer to as the "hallmarks" of science (**FIGURE 24**):

- Modern science seeks explanations for observed phenomena that rely solely on natural causes.
- Science progresses through the creation and testing of models of nature that explain the observations as simply as possible.
- A scientific model must make testable predictions about natural phenomena that will force us to revise or abandon the model if the predictions do not agree with observations.

Each of these hallmarks is evident in the story of the Copernican revolution. The first shows up in the way Tycho's careful measurements of planetary motion motivated Kepler to come up with a better explanation for those motions. The second is evident in the way several competing models were compared and tested, most notably those of Ptolemy, Copernicus, and Kepler. We see the third in the fact that each model could make precise predictions about the future motions of the Sun, Moon, planets, and stars in our sky. Kepler's model gained acceptance because it worked, while the competing models lost favor because their predictions failed to match the observations. The Cosmic Context spread in **FIGURE 25** summarizes the key scientific changes that occurred with the Copernican revolution and explains how they illustrate the hallmarks of science.