Discovering the Universe for Yourself

LEARNING GOALS

2.1 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?

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

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- What causes eclipses?

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

▲ About the photo: This time-exposure photograph shows star paths at Arches National Park, Utah.
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. New and powerful telescopes are scanning the depths of the universe. Sophisticated space probes are exploring 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.

2.1 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 2.1). 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 2.2 shows the borders of the constellation Orion and several of its neighbors.

The names and borders of the 88 official constellations (Appendix H) 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, 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 (Appendix I), or sky-viewing apps.

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 [Section 1.1]. The ancient Greeks mistook this illusion for reality, imagining the stars and constellations to lie on a great celestial sphere that surrounds Earth (Figure 2.3).

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 two special points and two special circles on the celestial sphere (Figure 2.4).

- 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 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 2.5 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 [Section 5.2]).
Fig. 2.6 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 2.6 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 1/2° (Fig. 2.7a). Note that angular size does not by itself tell us an object’s true size,
because angular 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 2.7b). You can use your outstretched hand to make rough estimates of angles in the sky (FIGURE 2.7c).

For greater precision, we subdivide each degree into 60 arcminutes (symbolized by ′) and each arcminute into 60 arcseconds (symbolized by ″) as shown in FIGURE 2.8. For example, we read 35° 27′ 15″ as “35 degrees, 27 arcminutes, 15 arcseconds.”

### Mathematical Insight 2.1: 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 \(2\pi \times \text{distance}\)). That is,

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

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.

**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:

\[
\text{angular separation} = \text{physical separation} \times \frac{360°}{2\pi \times \text{distance}}
\]

\[
= 1.5 \text{ m} \times \frac{360°}{2\pi \times 500 \text{ m}} \approx 0.17°
\]

**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 × 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 \((2\pi \times \text{distance})/360°\):

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

**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.
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shows the idea for a typical Northern Hemisphere location (latitude 40°N). If you study the figure carefully, 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 (page 24) 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

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 2.9). 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 2.10

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.

Not to scale!

FIGURE 2.8 We subdivide each degree into 60 arcminutes and each arcminute into 60 arcseconds.

FIGURE 2.9 Earth rotates from west to east (black arrow), making the celestial sphere appear to rotate around us from east to west (red arrows).

FIGURE 2.10 The local sky for a location at latitude 40°N. The horizon slices through the celestial sphere at an angle to the celestial 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.

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circles. The circles grow larger for stars farther 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 counterclockwise.

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.

Variation with Latitude

Latitude measures north-south position on Earth, and longitude measures east-west position (FIGURE 2.11). Latitude is defined to be 0° at the equator, increasing to 90°N at the North Pole and 90° 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° 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 2.12 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 2.10 and 2.12. 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 2.3), 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.
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Find the south celestial pole with the aid of the Southern Cross (Figure 2.13b). We’ll discuss celestial navigation and how the sky varies with latitude in more detail in Chapter S1.

See it for yourself What is your latitude? Use Figure 2.13 to find the celestial pole in your sky, and estimate its altitude with your hand as shown in Figure 2.7c. Is its altitude what you expect?

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 2.13). Finding the north celestial pole is fairly easy, because it lies very close to the star Polaris, also known as the North Star (Figure 2.13a). In the Southern Hemisphere, you can find the south celestial pole with the aid of the Southern Cross (Figure 2.13b). We’ll discuss celestial navigation and how the sky varies with latitude in more detail in Chapter S1.

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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 2.14 shows how this works. From our vantage point on Earth, the annual orbit of Earth around the Sun makes the Sun appear 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 2.14 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.

See it for yourself  Based on Figure 2.14 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.

2.2 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 2.15 (pages 34–35) 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 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 (which is in July) than at its nearest (in January). The difference in the strength of sunlight due to this small change in distance is 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.

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**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.

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**Solstices and Equinoxes** To help us mark the changing seasons, we define four special moments in the year, each of which corresponds to one of the four special positions in Earth’s orbit shown in Figure 2.15.

- The **June solstice**, called the summer solstice by people in the Northern Hemisphere, occurs around June 21 and is the moment when the Northern Hemisphere is tipped most directly toward the Sun and receives the most direct sunlight.

- The **December solstice**, called the winter solstice by people in the Northern Hemisphere, occurs around December 21 and is the moment when the Northern Hemisphere receives the least direct sunlight.

- The March equinox, called the spring equinox (or vernal equinox) by people in the Northern Hemisphere, occurs around March 21 and is the moment when the Northern Hemisphere goes from being tipped slightly away from the Sun to being tipped slightly toward the Sun.

- The September equinox, called the fall equinox (or autumnal equinox) by people in the Northern Hemisphere, occurs around September 22 and is the moment when the Northern Hemisphere first starts to be tipped away from the Sun.

The exact dates and times of the solstices and equinoxes can vary by up to a couple days from the dates given above, depending on where we are in the leap year cycle. In fact, our modern calendar includes leap years (usually adding one day—February 29—every fourth year) specifically to keep the solstices and equinoxes around the same dates [Section S1.1].

We can mark the dates of the equinoxes and solstices by observing changes in the Sun’s path through our sky (Figure 2.16). The equinoxes occur on the only two days of the year on which the Sun rises precisely due east and sets precisely due west; these are also the two days when the Sun is above and below the horizon for equal times of 12 hours (equinox means “equal night”). 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 farthest to the north of due east and due west; it is also the day on which the Northern Hemisphere has its longest hours of daylight and the Sun rises highest in the midday sky. The opposite is true on the day of the December solstice, when the Sun rises and sets farthest to the south and the Northern Hemisphere has its shortest hours of daylight and lowest midday Sun. Figure 2.17 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 June solstice is usually called the “first day of summer” in the Northern Hemisphere. Notice, however, that the Northern Hemisphere has its maximum tilt toward the Sun at this time. You might then wonder why we consider the solstice to be the beginning rather than the midpoint of summer.
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.

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

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.

March Equinox: The Sun shines equally on both hemispheres.

September Equinox: The Sun shines equally on both hemispheres.

April 20: Noon rays of sunlight hit the ground at a shallower angle in the Southern Hemisphere, meaning less concentrated sunlight and longer shadows.

November 22: Noon rays of sunlight hit the ground at a steeper angle in the Northern Hemisphere, meaning more concentrated sunlight and shorter shadows.
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.

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

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.

June Solstice: The Northern Hemisphere is tipped most directly toward the Sun.

March Equinox: The Sun shines equally on both hemispheres.

September Equinox: The Sun shines equally on both hemispheres.

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.

Noon rays of sunlight hit the ground at a steeper angle in the Southern Hemisphere, meaning more concentrated sunlight and shorter shadows.

Noon rays of sunlight hit the ground at a shallower angle in the Northern Hemisphere, meaning less concentrated sunlight and longer shadows.

December Solstice: The Southern Hemisphere is tipped most directly toward the Sun.

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.

The variation in Earth's orientation relative to the Sun means that the seasons are linked to four special points in Earth's orbit: Solstices are the two points at which sunlight becomes most extreme for the two hemispheres. Equinoxes are the two points at which the hemispheres are equally illuminated.
part I Developing Perspective

has much longer summer days and much longer winter nights than Florida. At the Arctic Circle (latitude 66½°), the Sun remains above the horizon all day long on the June solstice (Fig. 2.18), and never rises on the December solstice (although bending of light by the atmosphere makes the Sun appear to be about a half-degree higher than it really is). 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.

Seasons also differ in equatorial regions, because the equator gets its most direct sunlight on the two equinoxes and its least direct sunlight on the solstices. As a result, instead of the four seasons experienced at higher latitudes, equatorial regions generally have rainy and dry seasons, with the rainy seasons coming when the Sun is higher in the sky.

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 Earth is closer to the Sun and summer when Earth is farther away (see the lower left diagram in Figure 2.15), 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.

Seasons Around the World The seasons have different characteristics in different parts of the world. High latitudes have more extreme seasons. For example, Vermont has much longer summer days and much longer winter nights than Florida. At the Arctic Circle (latitude 66½°), the Sun remains above the horizon all day long on the June solstice (Fig. 2.18), and never rises on the December solstice (although bending of light by the atmosphere makes the Sun appear to be about a half-degree higher than it really is). 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.

Seasons also differ in equatorial regions, because the equator gets its most direct sunlight on the two equinoxes and its least direct sunlight on the solstices. As a result, instead of the four seasons experienced at higher latitudes, equatorial regions generally have rainy and dry seasons, with the rainy seasons coming when the Sun is higher in the sky.

Why Orbital Distance Doesn’t Affect Our Seasons
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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 (see Figure 10.24).

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

Our calendar keeps the solstices and equinoxes around the same dates each year, but the constellations associated with them change gradually over time. The reason 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 2.20a). 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 2.20b). Each cycle of Earth’s precession takes about 26,000 years. This gradually changes the direction in which the axis points in space.

Think about it ➤ Was Polaris the North Star in ancient times? Explain.

Note that precession does not change the amount of the axis tilt (which stays close to 23.5°) and therefore does not affect the pattern of the seasons. However, it changes the points in Earth’s orbit at which the solstices and equinoxes occur, and therefore changes the constellations that we see at those times. For example, a couple thousand years
ago the June solstice occurred when the Sun appeared in the constellation Cancer, but it now occurs when the Sun appears in Gemini. This explains something you can see on any world map: The latitude at which the Sun is directly overhead on the June solstice (23.5°N) is called the Tropic of Cancer, telling us that it was named back when the Sun appeared in Cancer on this solstice.

Precession is caused by gravity’s effect on a tilted, rotating object. 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 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 [Section 4.3]). 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 23.5° 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 straightening out 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 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.)

**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, astrological Sun signs are off by nearly a month from the actual positions of the Sun among the constellations today.
2.3 The Moon, Our Constant Companion

Aside from the Sun, the Moon is the brightest and most noticeable object in our sky. The Moon is our constant companion in space, traveling with us as we orbit the Sun.

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 29.5 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 29.5-day period is also the origin of the word *month* (think “moonth”).

**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 1°—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 first step in understanding phases is to recognize that sunlight essentially comes at both Earth and the Moon from the same direction. You can see why by studying **Figure 2.21**, which shows the Moon’s orbit on the same scale we used for the model solar system in Chapter 1. Recall that the Sun is located 15 meters away from Earth and the Moon on this scale, which is far enough that the Sun would seem to be in almost precisely the same direction no matter whether you looked at it from Earth or from the Moon.

You can now understand the lunar phases with the simple demonstration illustrated in **Figure 2.22**. 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 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 2.22 show how the phases look. (The new moon photo shows blue sky, because a new moon is nearly in line with the Sun and therefore hidden from view in the bright daytime sky.)

The Moon’s phase also determines the times of day at which we see it in the sky. 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 sunset, and set around midnight, because it occurs when the Moon is about 90° east of the Sun in our sky.

**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?
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 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

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*Because the Moon’s orbital speed varies (in accord with Kepler’s second law [Section 3.3]) 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.
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 (FIGURE 2.23). The only way you can face the ball at all times is by completing exactly one rotation while you complete one orbit. Note that the Moon’s synchronous rotation is not a coincidence; it is a consequence of Earth’s gravity affecting the Moon in much the same way the Moon’s gravity causes tides on Earth [Section 4.5].

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.

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.

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 again at Figure 2.22. 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 2.22 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 2.24**. 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 in Figure 2.24) throughout the year, which means they lie along a nearly straight line with the Sun and Earth about twice each year. Eclipses can occur only during these periods, because these are the only times when the Moon can be directly in line with the Sun and Earth. In other words, eclipses can occur only when

1. the phase of the Moon is full (for a lunar eclipse) or new (for a solar eclipse), and
2. the new or full moon occurs at a time when the Moon is very close to a node.

**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.

Moon can be directly in line with the Sun and Earth. In other words, eclipses can occur only when

1. the phase of the Moon is full (for a lunar eclipse) or new (for a solar eclipse), and
2. the new or full moon occurs at a time when the Moon is very close to a node.
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 (Fig 2.27). 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 (Fig 2.28). If a solar eclipse occurs when the Moon is in a part of its orbit where it is relatively close to Earth (see Figure 2.21), 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, leading to 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 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 homes.
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 2.29). 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.

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 2.24, focusing on the two periods—called eclipse seasons—in which the nodes of the Moon’s orbit are closely aligned with the Sun. Each eclipse season lasts a little less than five weeks, which means there is generally one lunar eclipse (at full moon) and one solar eclipse (at new moon) during each eclipse season. Because the eclipse season is slightly longer than the cycle of phases, there can occasionally be a third eclipse during a single eclipse season.
TABLE 2.1 Lunar Eclipses 2016–2019*

<table>
<thead>
<tr>
<th>Date</th>
<th>Type</th>
<th>Where You Can See It</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 23, 2016</td>
<td>penumbral</td>
<td>Asia, Australia, Pacific, western Americas</td>
</tr>
<tr>
<td>Sept. 16, 2016</td>
<td>penumbral</td>
<td>Europe, Africa, Asia, Australia</td>
</tr>
<tr>
<td>Feb. 11, 2017</td>
<td>penumbral</td>
<td>Americas, Europe, Africa, Asia</td>
</tr>
<tr>
<td>Aug. 7, 2017</td>
<td>partial</td>
<td>Europe, Africa, Asia, Australia</td>
</tr>
<tr>
<td>Jan. 31, 2018</td>
<td>total</td>
<td>Asia, Australia, Pacific, western N. America</td>
</tr>
<tr>
<td>July 27, 2018</td>
<td>total</td>
<td>S. America, Europe, Africa, Asia, Australia</td>
</tr>
<tr>
<td>Jan. 21, 2019</td>
<td>total</td>
<td>Pacific, Americas, Europe, Africa</td>
</tr>
<tr>
<td>Jul. 16, 2019</td>
<td>partial</td>
<td>S. America, Europe, Africa, Asia, Australia</td>
</tr>
</tbody>
</table>

*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.

If Figure 2.24 told the whole story, eclipse seasons would always occur 6 months apart and predicting eclipses would be easy. For example, if the eclipse seasons occurred in January and July, eclipses would always occur on the dates of new and full moons in those months. Actual eclipse prediction is more difficult than this because of something the figure does not show: The nodes slowly move around the Moon's orbit (often called "precession of the nodes," which has a period of 18.6 years), causing the eclipse seasons to occur slightly less than 6 months apart (about 173 days apart).

The combination of the changing dates of eclipse seasons and the 29 1/2-day cycle of lunar phases makes eclipses recur in a cycle of about 18 years, 11 1/2 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 1/2 times the 173.32 days between successive eclipse seasons.

Note that while the saros cycle allows you to predict when an eclipse will occur, the approximately 1/4 day in the cycle length means that the locations where an eclipse will be visible shift about 1/4 of the way around the world with each cycle. This and other subtleties of eclipses (such as whether a solar eclipse is total or annular, which depends on the Moon's orbital distance at the time of the eclipse) make exact eclipse prediction very difficult, and 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 2.1 lists upcoming lunar eclipses; notice that, as we expect, eclipses generally come a little less than 6 months apart. FIGURE 2.30 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.

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 [Section 4.5]. 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.
2.4 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 2.31).

![Figure 2.31](image1.png)

**FIGURE 2.31** 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.

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**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 a Greek term meaning “wandering star.” Moreover, while the planets usually move eastward through the constellations, they occasionally reverse course, moving westward through the zodiac (FIGURE 2.32). 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 (which we’ll study in Chapter 3) 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 2.33a). 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 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 her or him. Figure 2.33b shows how the same idea applies to Mars. Note that Mars never actually changes direction; it only appears to go backward as Earth passes it 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 the Special Topic, page 48). 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. 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 2.34).
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 [Section 3.3]. 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—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 [Section 15.1].

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 from Chapter 1, 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. We will turn our attention to this revolution in the next chapter.

The BIG Picture

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.

MY COSMIC PERSPECTIVE

No matter how abstract or esoteric the study of astronomy may sometimes seem to be, you can always connect it back to your own personal experience of the sky around us.
Summary of Key Concepts

2.1 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**.

2.2 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 23½°. 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.

2.3 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.

2.4 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 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 Chapter 2 Visual Quiz at MasteringAstronomy®.

![Diagram of Earth's seasons]

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 day with the most hours of daylight for the Northern Hemisphere?
2. Which of the four labeled points represents the day with the most hours of daylight 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.

Exercises and Problems

MasteringAstronomy® For instructor-assigned homework and other learning materials, 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.

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? 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 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 a trip to Argentina I saw many constellations that I’d never seen before.
21. Last night I saw Jupiter 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 part of the same cluster of stars in space.
28. The north celestial pole is 35° above your northern horizon. This tells you that you are at (a) latitude 35°N. (b) longitude 35°E. (c) latitude 35°S.
29. Beijing and Philadelphia have about the same latitude but different longitudes. Therefore, tonight’s night sky in these two places will (a) look about the same. (b) have completely different sets of constellations. (c) have partially different sets of constellations.
30. In winter, Earth’s axis points toward the star Polaris. In spring, the axis points toward (a) Polaris. (b) Vega. (c) 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 March or the September equinox. (c) it must be the day of the June 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 the Moon (a) does not rotate. (b) rotates with the same period that it orbits Earth. (c) 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. Roles: Scribe (takes notes on the group’s activities), Proposer (proposes explanations to the group), Skeptic (points out weaknesses in proposed explanations), Moderator (leads group discussion and makes sure everyone contributes). Activity: The diagram below represents the Moon’s orbit as seen from above Earth’s North Pole (not to scale). Each group member should draw a copy of the diagram and label it as you work together on the following questions.

   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. Your View of the Sky.

41. 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.

42. 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?

43. 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?

44. A Smaller Earth. Suppose Earth were smaller. Would solar eclipses be any different? If so, how? What about lunar eclipses?

45. 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.

46. 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, arcminutes, and arcseconds. Rewrite them in degrees and fractions of degrees.
   a. 24°30′ b. 1°59′ c. 0.1° d. 0.01°

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 2.7c? 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.