2

I pray the gods to quit me
of my toils,
To close the watch I keep
this livelong year;
For as a watch-dog lying,
not at rest,
Propped on one arm, upon
the palace roof
Of Atreus' race, too long,
too well I know
The starry conclave of the
midnight sky,
Too well, the splendours of the firmament,
The lords of light, whose kingly aspect
shows—
What time they set or climb
the sky in turn—
The year's divisions, bringing frost or fire.

Aeschylus
Agamemnon

Sunrise from Earth orbit by the crew of the STS-47 Space Shuttle Mission.

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Patterns in the Sky

The world has always been an uncertain place. Within the fabric of unpredictable events, however, are reliable, reassuring natural patterns. And of all the aspects of nature, the most predictable and reliable are the patterns of the celestial bodies—Sun, Moon, stars, and planets. People have followed these patterns for much longer than the span of recorded history. The Moon's phases are among the earliest recorded events. The world is dotted with prehistoric observatories used to follow the annual changes in sunrise and sunset.

Today, people are probably less aware of the celestial patterns than they have been for thousands of years. The distractions of modern life conspire to keep us indoors at night. Most of us live in urban areas, where outdoor lighting and smog have led to poorer and poorer observing conditions. Very few of us have had the opportunity or interest to take regular notice of the night sky. The patterns that were so apparent to people of antiquity are now known only to a relative few.

Yet the importance of these patterns to the development of astronomy can hardly be overemphasized. After people first noticed the patterns, they began to seek their causes. Proposing explanations for observed patterns has always been a key step in the progress of science. From the beginning of recorded history, the central problem of astronomy was the explanation of the motions of the Sun, Moon, stars, and planets. The explanations that resulted eventually led, in the sixteenth century, to a radically different view of the world. The realization of the true nature of the Earth and its relation to the other planets and stars had profound spiritual and philosophical consequences.

Questions to Explore

- How do the apparent paths of stars depend on where we are on the Earth?
- How does the Sun's apparent motion differ from that of the stars?
- How do we use the Sun's motion to keep track of time?
- How are the phases of the Moon related to the apparent motion of the Moon?
- How are the apparent motions of the planets different from those of the Sun and the Moon?

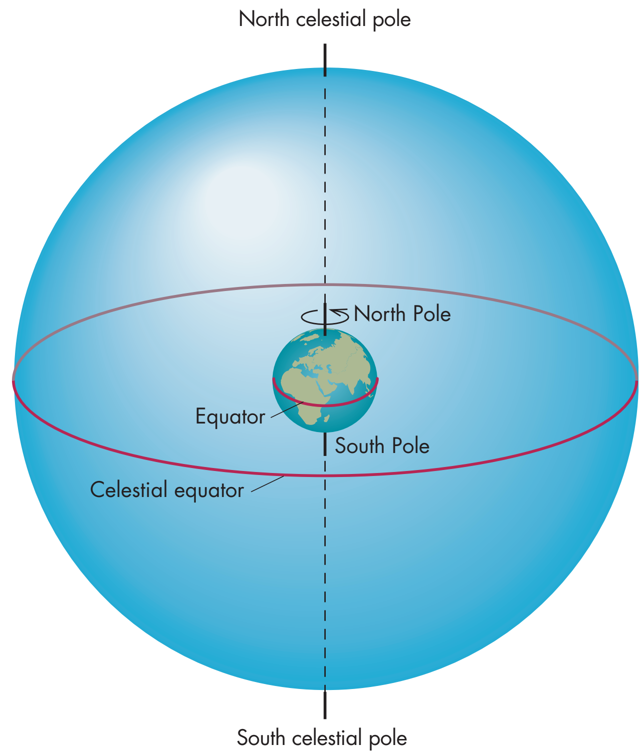
Later chapters of this book deal with the evolution of modern explanations of the patterns of celestial motion. This chapter concentrates on describing the motions themselves. The motions of the stars at night have been described briefly in Chapter 1. In this chapter our focus is on a fuller description of the motions of the stars as well as the patterns of motions of the Sun, Moon, and planets. The major emphasis is on the observations that must be made to detect the motions and to deduce their patterns.

2.1 THE DAILY MOTION OF THE SKY

As the observations of Chapter 1 showed, the **diurnal,** or daily, motion of the stars is westward and can be detected in only about a minute. The rate at which a star appears to move across the sky can be as large as 1° every 4 minutes. The path that a star appears to follow is called its **diurnal circle.** Usually, you can see only part of the diurnal circle of a star because the rest is below the horizon. However, stars near Polaris lie in the **north circumpolar region,** in which the entire diurnal circle lies above the horizon. Figure 2.1 is a time exposure taken while the camera pointed at Polaris. The picture shows that the diurnal circles are all centered at a point on the celestial sphere near Polaris.

FIGURE 2.1
A Time Exposure of the Northern Part of the Sky
The tracks of the stars are partial circles centered near the North Star, Polaris. The dome in the foreground houses the Canada-France-Hawaii 3.5-meter telescope on the summit of Mauna Kea, Hawaii. The yellow lines are the trails of motor vehicle lights during the time exposure. Note how low Polaris is when viewed from Mauna Kea.

FIGURE 2.2
The Earth and the Celestial Sphere
The Earth's rotation axis, extended outward, intersects the celestial sphere at the north and south celestial poles. The Earth's equator, extended outward, intersects the celestial sphere along the celestial equator.



That point, about ¾° from Polaris, is called the **north celestial pole.** The north celestial pole is the point on the celestial sphere directly above the Earth's North Pole (Figure 2.2). In other words, if the Earth's rotation axis were extended into space, it would meet the celestial sphere at the north celestial pole. Extended above the Earth's South Pole, it would meet the celestial sphere at the **south celestial pole.** If there were a bright star directly at the north celestial pole, its diurnal circle would be a point. The star would remain in exactly the same place day and night. When we face north, the motion of the stars on their diurnal circles carries them counterclockwise around the north celestial pole (Figure 2.3). When we face south, the diurnal motion is clockwise. In either case the motions of the stars seem to be caused by the rotation of the celestial sphere about an axis that passes through the celestial poles.

Two important circles on the celestial sphere are the **meridian** and the **celestial equator.** As Figure 2.4 shows, the meridian passes through both celestial poles and your zenith. The half of the meridian that is above the horizon is a semicircle that divides the sky into eastern and western

FIGURE 2.3
Diurnal Circles
Whether we face north or south, the stars appear to move westward on their diurnal paths.

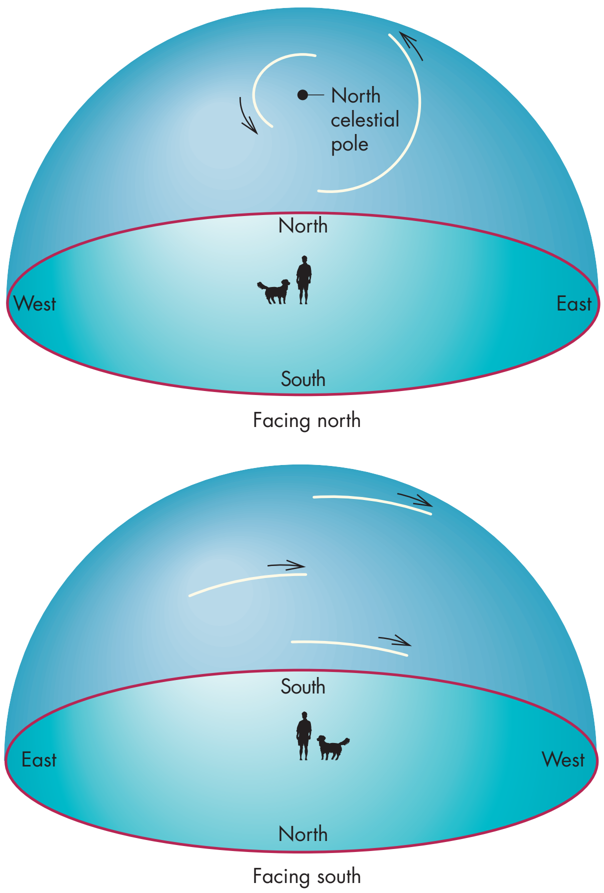
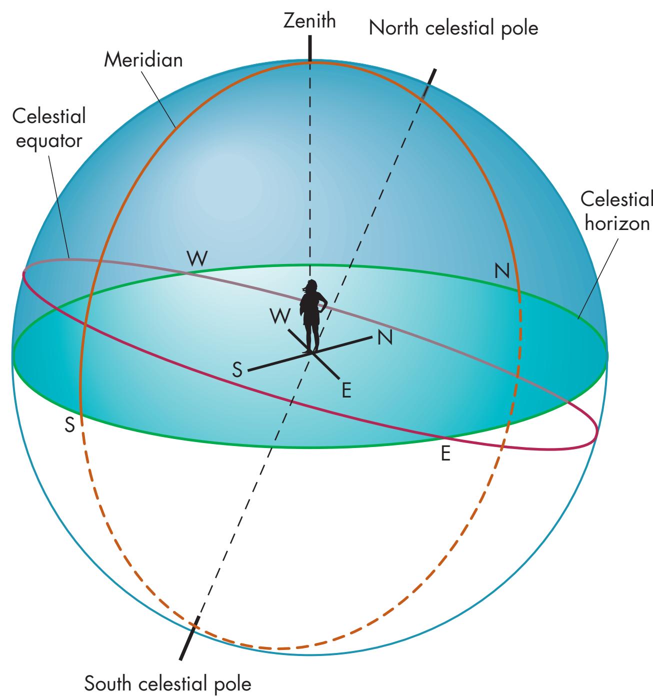


FIGURE 2.4
The Meridian and the Celestial Equator
The meridian is the circle on the celestial sphere that passes from the south celestial pole to the north celestial pole and through the observer's zenith. The part of the meridian that is below the horizon is shown as a dashed line. The north and south points on the observer's horizon lie where the meridian crosses the horizon. The celestial equator is the circle midway between the north and south celestial poles. It divides the celestial sphere into northern and southern halves.



halves. As time passes, the stars move with respect to your meridian. A star rises steadily higher in the eastern sky until it crosses the meridian, then it begins to sink toward the western horizon.

The apparent daily motion of a star is westward on a circle centered on the north celestial pole. The motion appears counterclockwise if we face north and clockwise if we face south. The pattern of diurnal motions makes it look as if the celestial sphere is rotating on an axis passing through the celestial poles.

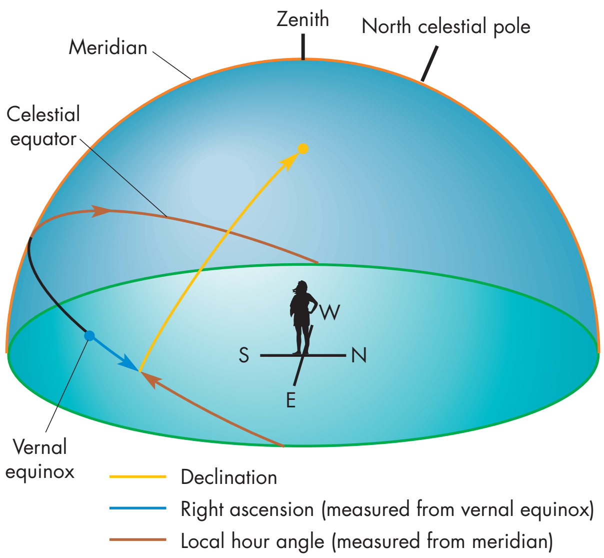
The celestial equator also is shown in Figure 2.4. Every point on the celestial equator is 90° from both celestial poles. Just as the Earth's equator divides the Earth's surface into northern and southern hemispheres, the celestial equator divides the sky into northern and southern halves. A star that lies on the celestial equator rises due east and sets due west.

Like the horizon, the celestial equator is used as the basis of a coordinate system, the **equatorial system.** The equatorial system is very similar to the terrestrial coordinate system, which is based on the Earth's equator. The two coordinates that give the position of a star in the equatorial system are shown in Figure 2.5. One is **declination,** a north-south coordinate equal to the angular distance of a star from the celestial equator. The other is **right ascension,** the angular distance measured eastward along the celestial equator from the **vernal equinox** to the point on the celestial equator nearest the star's position. The vernal equinox is the position of the Sun on the celestial sphere on the first day of spring. The vernal equinox moves with the stars as the celestial sphere rotates, so the right ascension and declination of a star remain the same throughout a night, just as the longitude and latitude of a city remain

FIGURE 2.5

The Equatorial Coordinate System

Declination is the angular distance of a star north or south of the celestial equator. Right ascension is measured from the vernal equinox eastward around the celestial equator to the point on the equator nearest the star. Local hour angle is measured westward around the celestial equator from the meridian to the point nearest the star. During a night, the declination and right ascension of a star remain constant while its hour angle changes as the star appears to move with respect to the meridian.



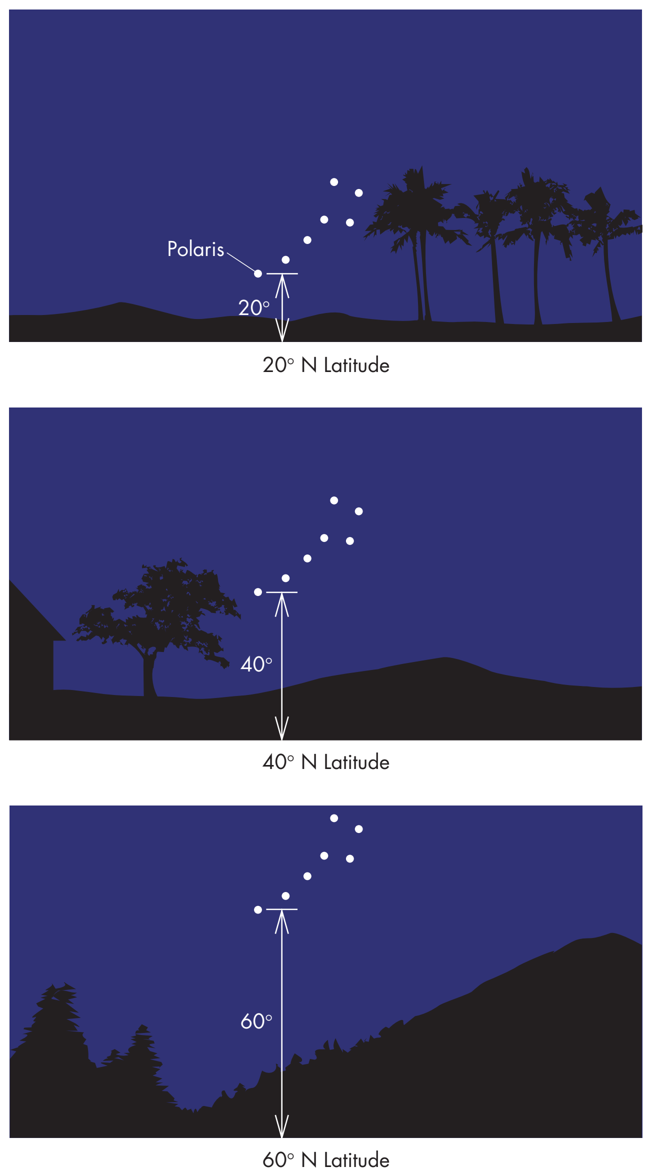
To use right ascension and declination to find a star, an astronomer needs to know where on the celestial sphere the vernal equinox is located. To do this, special clocks, **sidereal clocks,** are used to keep track of the local hour angle of the vernal equinox. A sidereal clock reads 0^h (zero hours) when the vernal equinox crosses the meridian. The sidereal clock reaches 24^h when the vernal equinox returns to the meridian. Once the vernal equinox is located, the same as the Earth rotates. Declination is measured in degrees, minutes, and seconds of arc while right ascension is measured in hours, minutes, and seconds. One hour of right ascension corresponds to 15°.

Because the equatorial coordinates of a star don't depend on the time or place where observations are made, they can be used to arrange the stars in order in catalogues. Catalogues are used by astronomers to find a particular star to observe. The fact that right ascension and declination don't vary with time or place is an advantage in this case. It means, however, that these coordinates don't directly tell you where to look to find a star. To actually locate a star in the sky, astronomers must find the star's **local hour angle.** This is the angular distance westward around the celestial equator from the meridian to the point on the equator nearest the star. The name "hour angle" suggests that there is a relationship between that coordinate and time. In fact, there is. The local hour angle of a star is zero when the star crosses the meridian and increases steadily until it next crosses the meridian. Local hour angle tells how long it has been since the star last crossed the meridian. The relationship between local hour angle and time is explored further later in this chapter.

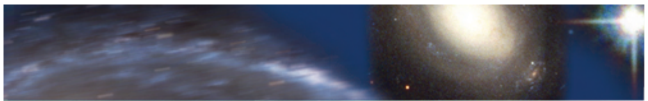
FIGURE 2.6

Latitude and the Altitude of the North Celestial Pole

The altitude of the north celestial pole is the same angle as the observer's latitude. The more northerly the observer, the higher the north celestial pole is in the sky. The Little Dipper, in which Polaris is located, is also shown.



right ascension and declination of a star can be used to find the star. The relationship between right ascension and hour angle is shown in Figure 2.5.



Right ascension (or hour angle) and declination are used to locate stars in the equatorial system, which resembles the terrestrial system of longitude and latitude.

So far, the night sky has been described as it would appear to someone at the Riverside Observatory. Actually, the sky would look about the same for other stargazers in most of the United States. For those observers, only a relatively small part of the sky is contained in the north circumpolar cap, and the north celestial pole is about one-third of the way to halfway from the horizon to the zenith.

However, the appearance of the sky and the motions of the stars depend on the latitude where you are observing. The north celestial pole has an altitude equal to the observer's latitude (Figure 2.6). This means that you can use Polaris not only to find which direction is north but also to find your latitude. If you travel northward to higher latitudes, the north celestial pole climbs higher in the sky. As this happens, the circumpolar region grows in size. On reaching the terrestrial pole, you would see the north celestial pole directly overhead. Both your latitude and the altitude of the north celestial pole would be 90°. The celestial equator would lie along the horizon. Only the northern half of the celestial sphere could ever be seen, but that half would always be above the horizon. The diurnal circles of the stars, as shown in Figure 2.7, would be parallel to the horizon.

By traveling south toward the equator, you would see different changes in the sky. Polaris would sink behind you and the circumpolar region would grow smaller. At the terrestrial equator, the north celestial pole would lie on the horizon. A panoramic view of star trails at the equator is shown in Figure 2.8. Stars near the celestial

FIGURE 2.7
Observing at the North Pole
The north celestial pole is at the zenith; the celestial equator is on the horizon. The diurnal circles of stars are parallel to the horizon.

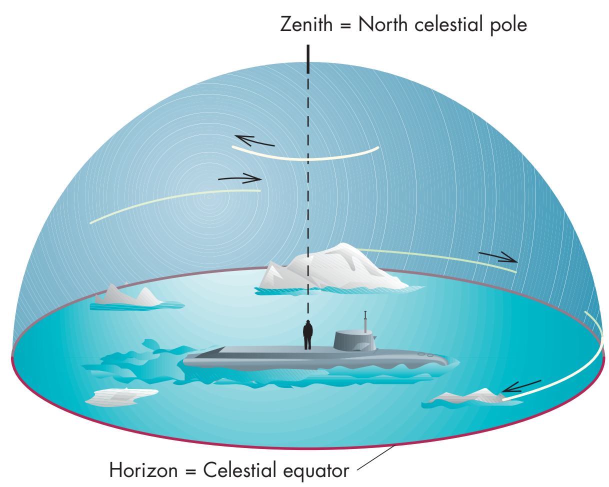
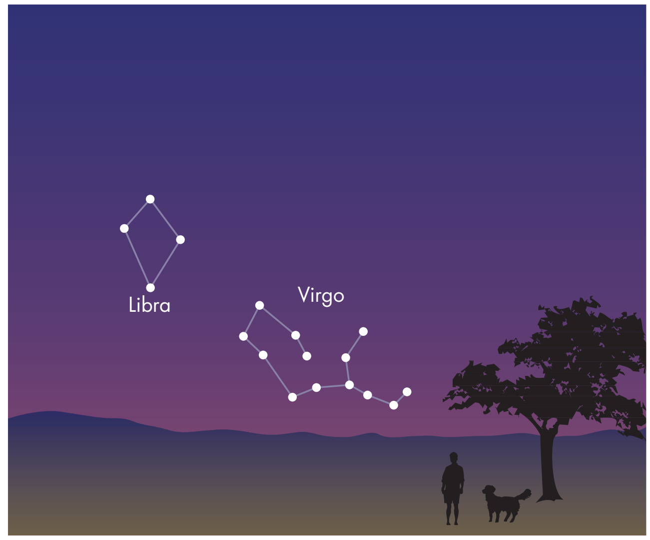


FIGURE 2.8
Star Trails at the Equator
This panoramic view shows star trails as seen from Kenya. South is at the left, west at the center, and north at the right. Star trails near the celestial poles are semicircles whereas those near the celestial equator set straight down in the west.

equator rise straight up from the horizon, pass nearly overhead, and set straight down in the west. The south celestial pole would be on the southern horizon. Half of every diurnal circle would be above the horizon and each star would spend half its time above the horizon. At the Earth's equator there is no circumpolar region. Every star in both the northern and southern hemisphere can be seen half the time. If you continued south, the north celestial pole would sink below the horizon and the south celestial pole would rise, bringing with it the south circumpolar region. Unfortunately for navigators in the southern hemisphere, there is no southern counterpart of Polaris to make it easy to find which way is south and to determine latitude. The changes in the sky as you continued south would be like those of your northern trip except that the stars and constellations would probably be unfamiliar to those of us who have spent most of our lives in the northern hemisphere.

FIGURE 2.9
The Constellations as They Appear Above the Western Horizon Just After Sunset in Early September



2.2 THE APPARENT MOTION OF THE SUN

ANIMATION *Different constellations at different times of the year*

Although the Sun, Moon, and planets share the westerly diurnal motion of the stars, they have individual motions of their own with respect to the stars. For the Sun the motion with respect to the stars isn't usually very obvious because there is no starry background visible during the day. One way to see that the Sun changes its position with respect to the stars is to observe the stars above the western horizon just after sunset on different days of the year. (Observing before dawn above the eastern horizon will also work, but the time of day is less popular.)

Imagine facing west just after sunset in early September when the sky first gets dark enough to see the stars, just as in the imaginary trip to Riverside Observatory in Chapter 1. The lowest constellation you could see above the place on the horizon where the Sun had just set is Virgo, as shown in Figure 2.9. Above Virgo, and slightly to the south, would be Libra. Now repeat the observation a month later, in October. Virgo isn't visible. Instead Libra is just above the horizon. Above Libra and slightly to the south is Scorpius. In November, Scorpius is the lowest visible constellation above the place where the Sun has set. Above Scorpius in the sky are Sagittarius and Capricornus.

Throughout the fall, the constellation just east of the Sun, the one we can see just after the Sun sets, changes at the rate of one constellation per month, as shown in Figure 2.10. If we regard the stars' positions on the celestial sphere as fixed, then it appears that the Sun moves steadily eastward among the constellations. Between September and October the Sun moves into Virgo, then by November it moves into Libra. By December it moves eastward into Scorpius, making Sagittarius the constellation low in the southwestern sky after sunset. During a year, the Sun appears to move through the **zodiacal constellations:** Virgo, Libra, Scorpius, Sagittarius, Capricornus, Aquarius, Pisces, Aries, Taurus, Gemini, Cancer, and Leo. The length of time it takes for the Sun to move through the constellations and return to the same spot on the celestial sphere is defined as the **year.** Because there are 360° in a circle and 365 days per year, the Sun moves with respect to the stars at a rate of slightly less than 1° per day.

The path that the Sun follows among the stars is called the **ecliptic.** Although the annual motion of the Sun is primarily eastward, the ecliptic is tilted, or inclined, to the celestial equator, as shown in Figure 2.11. Thus the Sun's movement on the ecliptic also carries it north and south of the celestial equator during the year. The Sun spends about half of the year in the northern hemisphere of the celestial sphere and half in the southern hemisphere. The angle between the equator and the ecliptic is 23.5°, so the Sun's declination varies from +23.5° (north of the celestial equator) to −23.5° (south of the celestial equator) during the year. When the Sun has a declination of +23.5°, it is directly overhead at a latitude of 23.5° north. This latitude is called the Tropic of Cancer. The corresponding southern latitude, 23.5° south, is called the Tropic of Capricorn.

The point on the ecliptic where the Sun's declination is most northerly is called the **summer solstice.** The point where it is most southerly is the **winter solstice.**

FIGURE 2.10
The Apparent Path of the Sun During Autumn
The Sun appears to move eastward, relative to the stars, at the rate of one constellation per month.

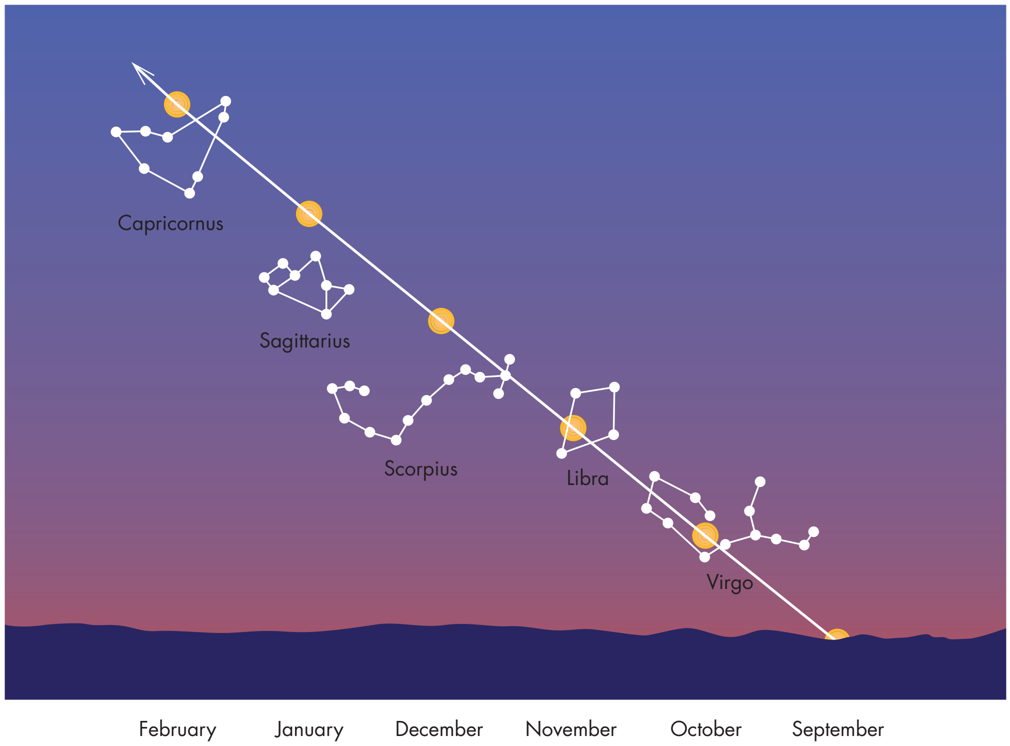
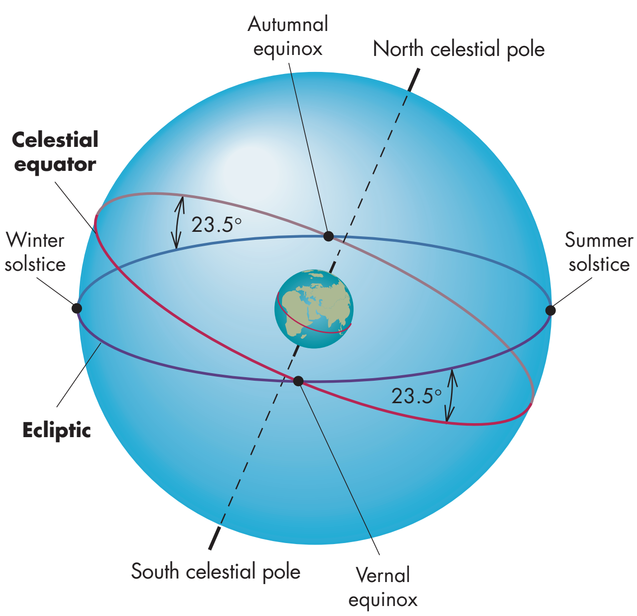


FIGURE 2.11
The Ecliptic
The Sun appears to move eastward along the ecliptic relative to the stars. The ecliptic is inclined 23.5° with respect to the celestial equator. The solstices occur when the Sun is farthest north or south of the celestial equator. The equinoxes occur when the Sun crosses the celestial equator.

ANIMATION *The Sun's motion north and south in the sky as the seasons change*



The points where the Sun crosses the celestial equator and has zero declination are called the **autumnal equinox** and the vernal equinox. Recall that the vernal equinox, one of the points where the ecliptic and the celestial equator cross, is the zero point from which right ascension is measured in the equatorial coordinate system (Figure 2.5).

The Seasons

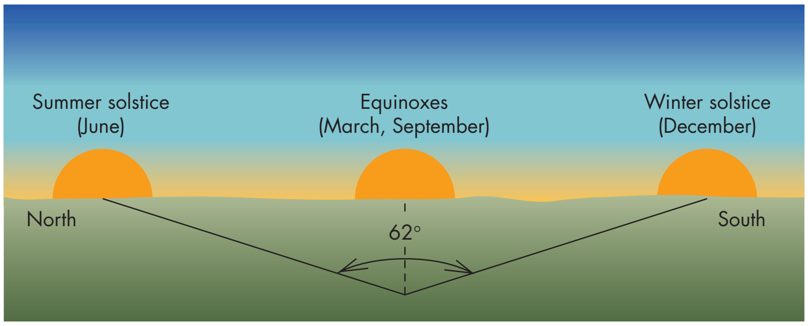
ANIMATION *The change in number of hours of daylight as seasons change*

ANIMATION *The Earth's rotation axis*

INTERACTIVE *Seasons*

The changing declination of the Sun affects the point on the horizon where the Sun rises (the azimuth of sunrise) and the duration of daylight. When it is north of the celestial equator, the Sun rises in the northeast and daylight lasts for more than half the day for people in the northern hemisphere. When south of the equator, the Sun rises in the southeast and day is shorter than night. On the summer solstice, the declination of the Sun is +23.5°. At a latitude of 40°, the azimuth of sunrise is 59° (Figure 2.12). At the winter solstice, the azimuth of sunrise is 121°. This means that at a latitude of 40° the direction of sunrise changes by 62°, more than one-third of the way from due north to due south, between the

FIGURE 2.12
The Annual Variation in the Azimuth of Sunrise
For a latitude of 40°, the azimuth of sunrise increases by more than 60° between the summer solstice and the winter solstice. The annual variation in azimuth is even greater for more northerly latitudes, but is only 47° at the equator.



summer and winter solstices. The annual migration of sunrise northward and southward along the horizon was noticed by people in prehistoric times. We know this because they built monuments that helped them use the annual changes in the azimuth of sunrise and sunset to determine when the solstices occur. In other words, they kept track of the seasons.

To see how this might work, imagine that you were given a pile of rocks, a willing coworker, and an assignment to set up a system for determining the approximate date of the winter solstice. You could begin by marking the position of sunrise on a day in autumn. Just before dawn, you could stand at a chosen location and direct your assistant (who would be carrying a rock) to move back and forth in azimuth until the rock was aligned with the rising Sun. Your assistant would then place the rock to mark the azimuth of sunrise. If the exercise were repeated day after day, the two of you would build up a group of rocks, as shown in Figure 2.13, which would extend farther south as the weeks passed.

One day, however, you would notice that the newly placed rock was north of the one from the previous day. Because the most southerly sunrise occurs on the winter solstice, you would know that the winter solstice had occurred on the previous day. If you piled up all the other rocks on the site of the most southerly rock, you would have a monument that could be used in later years to find the date of the winter solstice. A similar procedure could be used in the spring to locate the azimuth of the most northerly sunrise, which happens when the Sun is at the summer solstice. People at many times and many places did just this. The earliest known solar observatory, at Nabta in southern Egypt, is 7000 years old. In the Americas, a 4200 year-old temple in Peru is aligned to the azimuth of sunrise on the December solstice. Probably the most famous prehistoric solar observatory is at Stonehenge, in England, shown in Figure 2.14. At Stonehenge there are a number of alignments of standing stones to mark sunrise at

FIGURE 2.13
Determining the Solstice
Your assistant, aligned with the rising Sun, places a rock to mark the azimuth of sunrise.

FIGURE 2.14
Stonehenge, a Prehistoric Solar Observatory
As viewed from the center of Stonehenge on the summer solstice, the rising Sun is aligned with the heel stone, which lies outside the circle of standing stones.

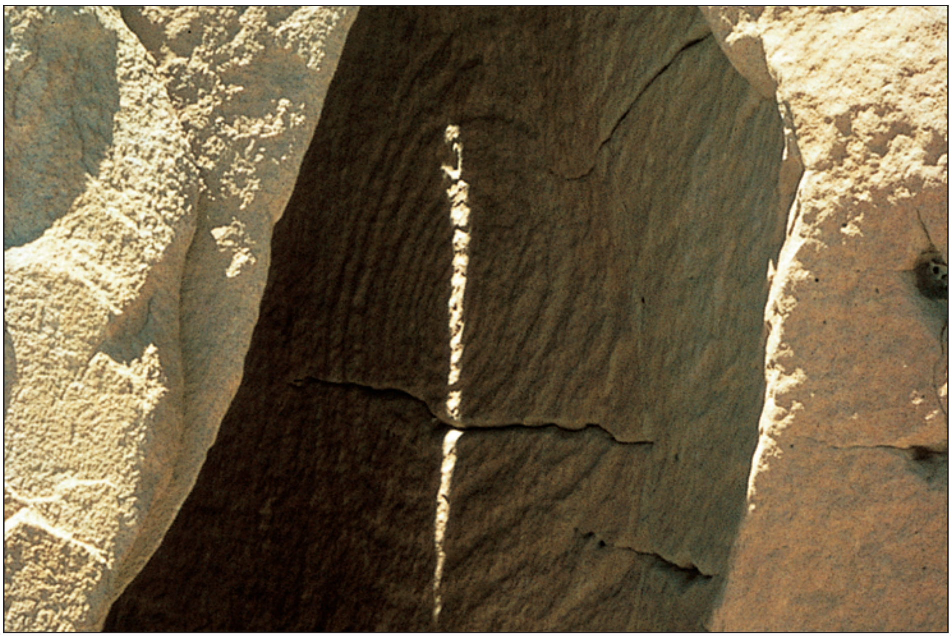


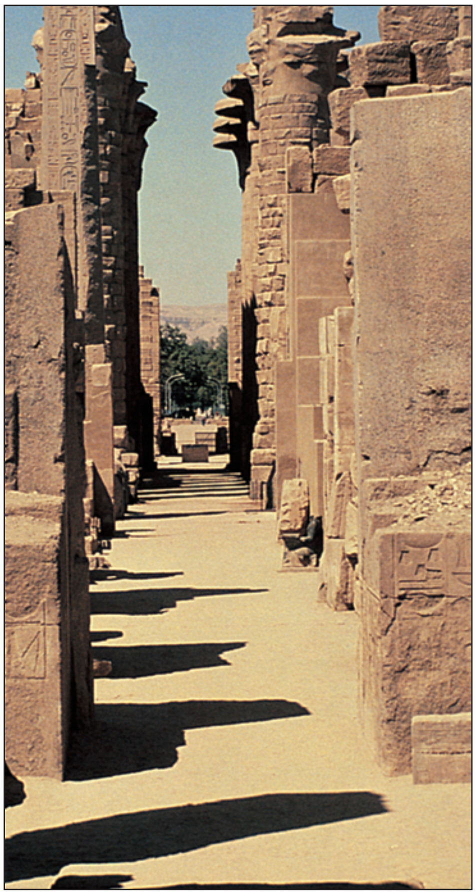
FIGURE 2.15
The Fajada Butte Sun Dagger on the Summer Solstice
A shaft of light passing between sandstone slabs produces the "sun dagger" that bisects the spiral petroglyph. Other distinctive patterns are produced at the winter solstice and at the equinoxes.

the solstices. The most famous of these is marked by the heel stone, over which the Sun rises on the summer solstice. Northwestern Europe is dotted with other stone monuments from which sunrises on the solstices and equinoxes could have been observed.

In North America there are solar monuments of a different sort. These are the sun daggers, built by the Native Americans as long as a thousand years ago. The most famous sun dagger is one built by the Anasazi at Fajada Butte in Chaco Canyon, New Mexico (Figure 2.15). The sun dagger is formed when narrow shafts of sunlight shine through the gaps between three sandstone slabs. At the solstices and equinoxes, the shafts (daggers) of sunlight create highly distinctive patterns on spiral petroglyphs carved on the rock wall. Early people must have been strongly motivated to expend the enormous effort required to build monuments such as Stonehenge or the sun daggers. Their motivation may have been religious or, perhaps, related to practical matters such as the timing of harvests and animal migration. Whatever the reason, it is obvious that they considered marking the seasons to be important.

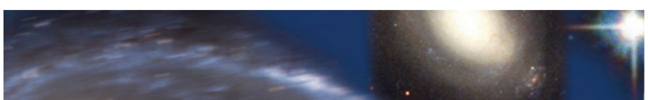
Even after recorded history began, people built monuments to mark the azimuths of sunrise and sunset at the solstices and equinoxes. A dramatic early example is the Temple of Amen-Ra at Karnak, Egypt. The temple, shown in Figure 2.16, was begun more than 4000 years ago. It is built around a series of doorways and halls of columns, which define an axis almost 600 meters (about 2000 feet) long. From the innermost chamber of the temple, only a small part of the northwestern horizon can be seen. The distant doorways framed the setting Sun on midsummer's day (the summer solstice). Equinoctial alignments, in which the main axis of a building is aligned east-west,

FIGURE 2.16
The Temple of Amen-Ra at Karnak, Egypt
The temple was aligned so that its main axis points to the position of sunset on the summer solstice.



are common in temples and churches from the Temple in Jerusalem to St. Peter's Cathedral in Rome.

As the azimuth of sunrise changes, so do the altitude of the Sun at noon and the length of time that the Sun spends above the horizon. The lower the altitude of the Sun, the more widely spread out is the sunlight that strikes the ground. In the northern hemisphere, the altitude of the Sun at noon is highest at the summer solstice and lowest at the winter solstice. For a latitude of 40° (that of Philadelphia and Denver), the noonday Sun has an altitude of 73.5° at the summer solstice and only 26.5° at the winter solstice. Daylight lasts for only a little more than 9 hours at the winter solstice, but 15 hours at the summer solstice. Also, the Earth's atmosphere absorbs more sunlight when the Sun is low in the sky because sunlight's path through the atmosphere is longer. As a result of the length of the day, the spreading out of sunlight, and absorption by the atmosphere, only one-sixth as much solar energy falls on a horizontal patch of ground at the winter solstice as at the summer solstice. For latitudes more northerly than 40°, the seasonal differences are even larger. It isn't surprising that the seasons often correspond to very different temperature conditions or that other aspects of the weather should change with the seasons. The annual variation in the amount of sunlight is particularly strong above the Arctic and Antarctic Circles, at 66.5° north and south latitudes. On the Arctic Circle, the Sun never sets at the summer solstice and never rises at the winter solstice. Closer to the poles, the period of winter darkness and the period of continuous summer sunlight both increase in length until they both reach 6 months at the poles.



The Sun appears to move eastward among the stars on the ecliptic, which is inclined with respect to the celestial equator. The annual changes in the declination of the Sun cause changes in the rising and setting directions of the Sun and its altitude at noon. These changes are responsible for seasonal differences in temperature.

Time

People have wanted to keep track of time since prehistory. Sundials, water clocks, and other devices have been used for thousands of years to coordinate the many activities of the day and night. In some religions, the beginning of each lunar month is a very important event. Mariners have long known that tides are related to the phases of the Moon. The agricultural necessity of keeping track of the passage of the year has been recognized at least since the time of the earliest civilizations.

Two of our basic units of time, the day and the year, are both related to the motion of the Sun. The **solar day** is the amount of time that passes between successive appearances of the Sun on the meridian—in other words, the amount of time from high noon to high noon. The average length of the solar day is defined as 24 hours, and is the basis for ordinary (civil) timekeeping.

Astronomers, on the other hand, often find it convenient to use the **sidereal day,** which is the length of time it takes for a star to return to the meridian. The sidereal day is obviously related to the positions of stars in the sky. If an astronomer wants to observe a given star as it crosses the meridian, the observations need to be carried out at intervals of a sidereal day. We have already seen that the Sun moves with respect to the stars, so the solar day and the sidereal day have different lengths. Suppose the Sun and a star cross the meridian at the same moment. Before either crosses the meridian again, the Sun has moved eastward along its annual path on the ecliptic. Thus, as Figure 2.17 shows, the star returns to the meridian first, ending the sidereal day slightly earlier than the solar day ends. The length of the sidereal day is $23^h\ 56^m\ 4^s$ (or 23 hours, 56 minutes, and 4 seconds).

A complication in timekeeping arises because the rate at which the Sun moves along the ecliptic varies slightly throughout the year. Because of this, the length of the solar day changes during the year as well. The longest solar day is about 1 minute longer than the shortest solar day. Differences of this size, although small, accumulate during the parts of the year for which

FIGURE 2.17
The Sidereal and Solar Days
A, The Sun and a star cross the meridian at the same time. **B,** The following day the Sun and the star cross the meridian at different times. Because the Sun appears to move eastward relative to the stars, it recrosses the meridian later than the star. Thus, the solar day is longer than the sidereal day.

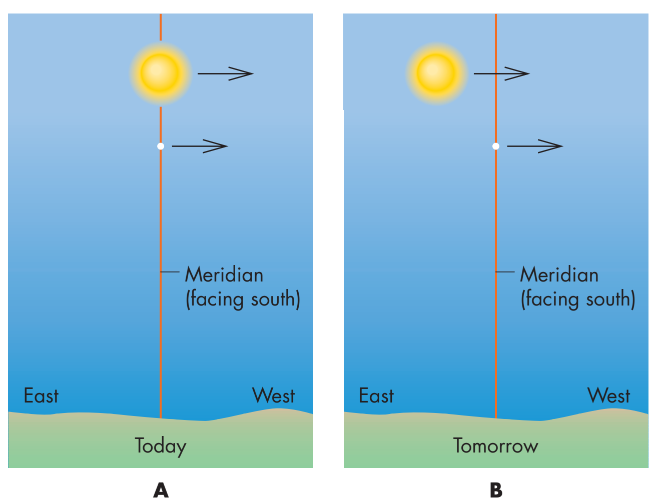
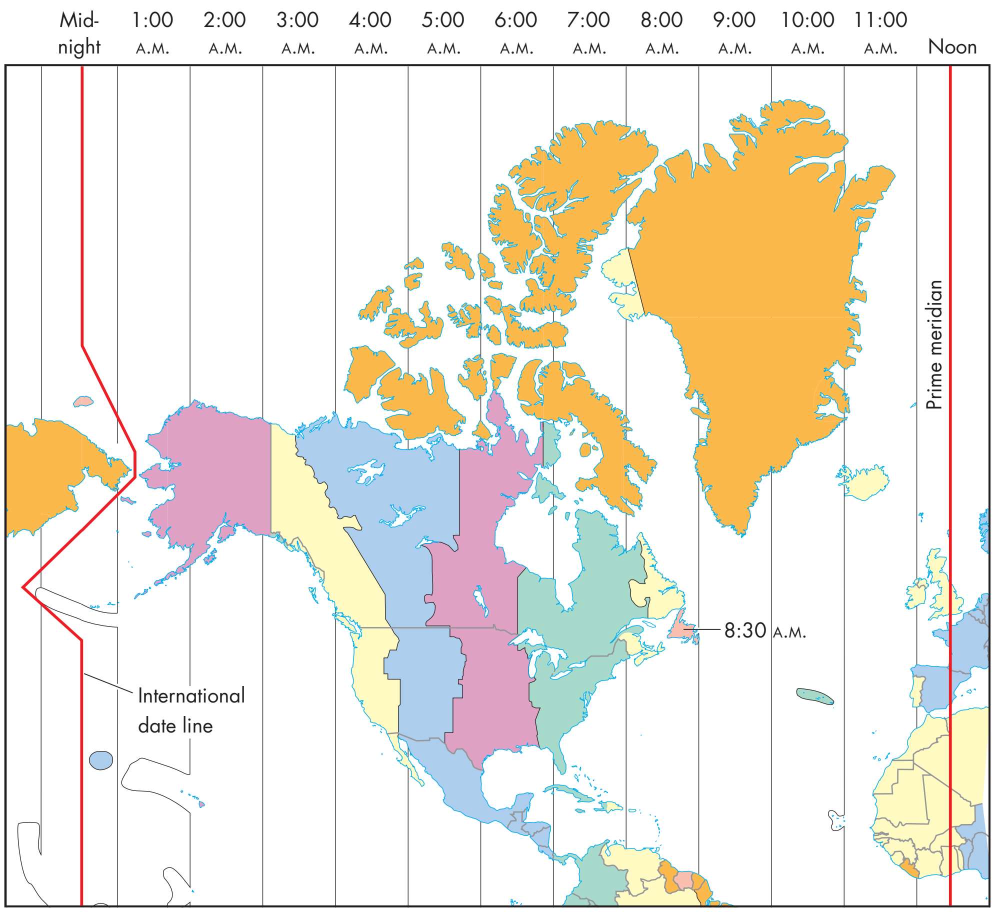


FIGURE 2.18
Time Zones in North America
The time zones are roughly 15° wide and centered at longitudes of 60° W, 75° W, and so on. Political boundaries, however, often cause the outlines of time zones to be irregular.



the day is longer or shorter than average. Suppose you had a clock that kept time according to the average length of the solar day. That is, the clock measured 24 hours as the average length of time it took the Sun to return to the meridian. Such a clock keeps **mean solar time,** or average solar time. (There are such clocks. You probably are wearing one on your wrist because we run our civilization on mean solar time.) On the other hand, a clock that kept time according to the actual position of the Sun in the sky would keep **apparent solar time.** It would show the hour angle of the Sun plus 12 hours, since the solar day starts at midnight.

A sundial keeps apparent solar time. A mechanical clock that kept apparent solar time would have to run at a variable rate during the year. The difference between mean and apparent solar time can be as great as 16 minutes.

A further complication with timekeeping is that the moment when the Sun crosses the meridian depends on a person's longitude. This means that if everyone kept time according to when the Sun crossed his or her meridian, the only people whose watches would agree would be those located due north or south of each other. To keep the correct time, it would be necessary to reset your watch continually as you moved east or west. This became a problem when railroads made rapid travel possible. The problem was overcome by the introduction of time zones, which are regions on the Earth, roughly 15° wide in longitude, in which everyone keeps the same **standard time** (Figure 2.18). For most of the people in a time zone, the Sun doesn't actually cross the meridian when their watches read noon. However, because the difference is usually a half hour or less, most people don't even notice where the Sun is at noon. They are quite happy to sacrifice the accuracy with which their watches can tell the Sun's position for the convenience of having the same time across the time zone.

The **tropical year** is the length of time it takes the Sun to return to the vernal equinox. This is the unit of time associated with the annual cycle of the seasons. The length of the tropical year (usually referred to simply as the year) was found by the ancient Egyptians to be roughly 365 days. The Egyptians used a calendar in which the year was divided into 12 months of 30 days each with an extra 5 days added to bring the total to 365. However, they recognized that the actual length of the year was somewhat greater than 365 days. The way they discovered that the year is longer than 365 days was that, over centuries, annual events such as the Nile flood occurred later and later in the calendar. The average rate at which annual events slipped through the calendar was about ¼ day per year. The Egyptians realized that after about 1500 years, the year of the seasons would slip all the way through the calendar and the Nile flood would return to the date where it occurred 1500 years before.

Since the time of the Egyptians, the accuracy with which we know the length of the year has improved. We now know that it is 365.242199 days or 365 days, 5 hours, 48 minutes, and 46 seconds long. We could use calendars in which each year had the correct number of days, hours, minutes, and seconds. The price we would have to pay would be to start years at various times of day rather than at midnight. Suppose that a particular year began at midnight. It would end (and January 1 of the next year would begin) 365.242199 days later, at a little before six in the morning. For the rest of that year, the date would change just before six in the morning rather than at midnight. The following year and each of its days would begin slightly before noon. Rather than accept that kind of confusion, we instead use a calendar in which no given year is really the right length of time, but in which the average of many years is correct. Some years are too short, others are too long. We do this by adding extra days to **leap years,** which occur about every 4 years. Actually, an extra day every 4 years would result in a calendar in which the average year was 365.25 days, which is a little longer than the tropical year. To shorten the average year slightly, century years are not leap years unless they can be evenly divided by 400. Thus, 1900 was not a leap year, but 2000 was. This eliminates 3 days every 400 years. Using this pattern of leap years, the average length of the calendar year is almost exactly equal to what it needs to be to keep annual events occurring at the same time of year. This procedure is the basis for the Gregorian calendar used in most of the western world.

2.3 THE PHASES OF THE MOON

The monthly pattern of the Moon's phases is among the most dramatic regular cycles in the sky. When sunlight falls on the Moon, it illuminates only half of the Moon's surface (the day side of the Moon). Some of this sunlight is reflected to the Earth, making the illuminated part of the Moon look bright. The rest of the Moon is turned away from the Sun and receives no sunlight. The absence of reflected sunlight makes this part of the Moon appear dark. The phase of the Moon depends on how much of the side turned toward us is illuminated by the Sun.

You can do a simple experiment to investigate the phases of the Moon. In an otherwise darkened room, set up a lamp. Seat yourself on a stool perhaps 10 feet from the lamp. Then, as shown in Figure 2.19, have a friend move around you holding a ball while you watch how the bright part of the ball changes in shape. Your friend should start so that the ball is nearly on the opposite side of you from the lamp. In this position, the bright hemisphere of the ball is almost entirely visible to you. The ball is at **full phase.** As your friend circles toward the lamp, less of the bright hemisphere of the ball can be seen. The phase is now **gibbous.** When your friend has moved a quarter of the way around you, only half of the bright hemisphere

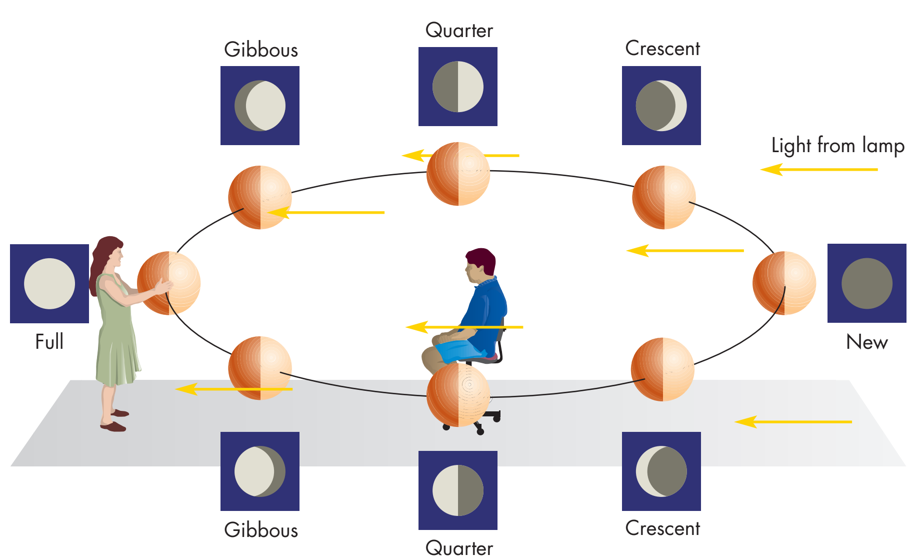


FIGURE 2.19
The Phases of the Moon
As a ball illuminated from the right is moved around an observer, the observer sees the ball go through its cycle of phases. The inset drawings show how the ball looks to the observer at each position.

INTERACTIVE *Lunar phases*

FIGURE 2.20
A Prehistoric Astronomical Record
The scratches on this bone may follow the phases of the Moon.

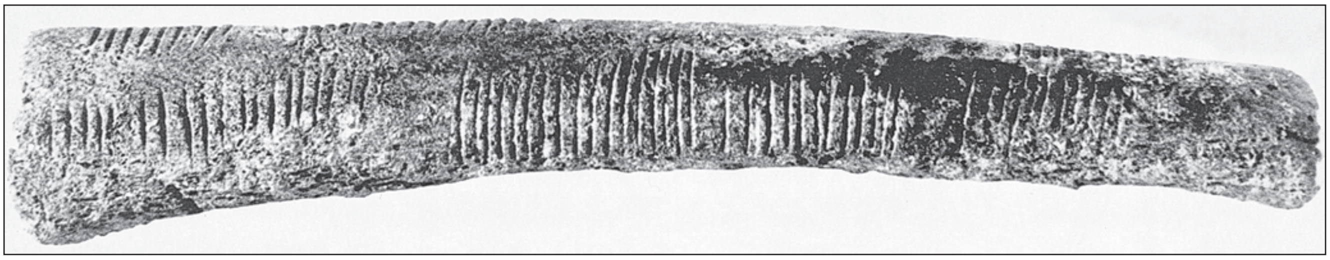
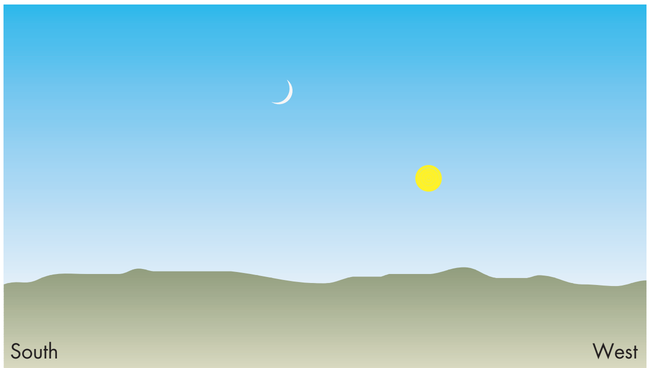
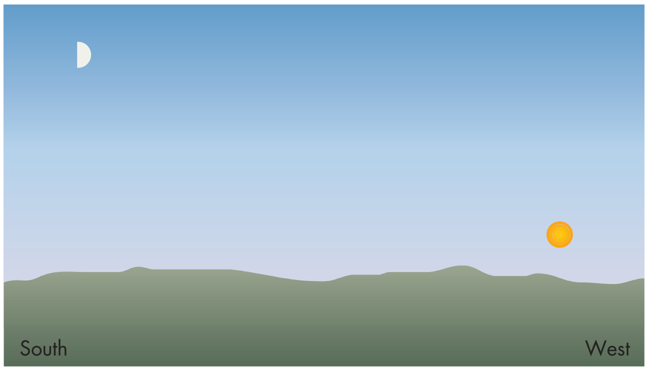


FIGURE 2.21
The Sun and the Moon at Waxing Crescent Phase
The waxing crescent Moon is a little east of the Sun and sets shortly after sunset.



Looking west in the late afternoon on a day just after new Moon

FIGURE 2.22
The Sun and the Moon at First Quarter Phase
The first quarter Moon crosses the meridian approximately at sunset.

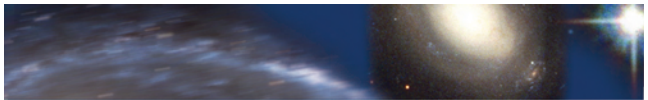


Looking west just before sunset

of the ball can be seen. The ball is at **quarter phase.** By the time your friend has moved nearly between you and the lamp, the phase of the ball has diminished from **crescent** to **new,** at which point almost none of the bright hemisphere can be seen. As your friend continues to circle, the phase changes from new to crescent to quarter to gibbous and back to full again.

Thus we see that the Moon's phases are determined by the position of the Moon relative to the Earth and the Sun. When the Moon is opposite the Sun in the sky so that we are nearly between the Moon and Sun, the Moon's phase is full. When the Moon is nearly between us and the Sun so that the Moon and Sun are close to each other in the sky, the Moon's phase is new. People may have recorded the Moon's phases for more than 30,000 years. Writer-archaeologist Alexander Marshack has examined bone fragments found at prehistoric sites in Europe, Asia, and Africa. Early people engraved lines and other markings on these fragments. One of these fragments is shown in Figure 2.20. Marshack suggested that the pattern of the markings follows the phases of the Moon. He has proposed that Stone Age people made records of the lunar phases. No one knows why early people made such records, but Marshack suggests that the marks may have been "remembering marks," or memory aids for the telling and retelling of stories about the Moon and its phases.

Because the phase of the Moon depends on where it is in the sky relative to the Sun, the Moon's phase is also related to the time of moonrise and moonset. Figure 2.21 shows the Moon and Sun in the sky in late afternoon on a day just after new Moon. The Moon is at **waxing crescent** phase. (Waxing means that its bright part is growing larger.) The horns of the crescent Moon point away from the Sun. The Moon is only about 15° east of the Sun and will set about an hour after sunset. Although the crescent Moon can be seen in daylight, it is most easily seen just after sunset, low in the western sky. Figure 2.22 shows the Moon and Sun at first quarter Moon. The Moon and Sun are about 90° apart. The Moon will set about midnight (6 hours after sunset) and will be conspicuous in the evening sky. When the Moon is full, it is opposite the Sun in the sky. It rises at sunset and is visible all night long. After full Moon, the Moon rises later each night until it rises just before sunrise and is a **waning crescent.** (Waning means that the bright part is shrinking.)



The phases of the Moon occur because we see different portions of the Moon's sunlit hemisphere during a month. The phase of the Moon depends on its location in the sky relative to the Sun.

2.4 THE MOTION OF THE MOON

The motion of the Moon among the stars is similar to that of the Sun. The Moon moves generally eastward relative to the stars, at a rate that varies throughout a month but averages about one lunar diameter per hour, or 13° per day. This means that moonrise and moonset occur nearly an hour later each day. If the Moon is near a bright star, the motion can be detected in an hour or less, as shown in Figure 2.23. The length of time it takes for the Moon to return to the same place among the stars is about 27.3 days, the **sidereal month.** Because the Sun also moves eastward among the stars, it takes more than a sidereal month for the Moon to lap the Sun and return to the same position in the sky relative to the Sun (Figure 2.24). The length of time required for the

FIGURE 2.23
The Motion of the Moon
A, The Moon is seen against a backdrop of stars. **B,** One hour later, the Moon appears to have moved eastward relative to the stars by about its own angular diameter. Both the Moon and the stars appear to move westward during that hour.

FIGURE 2.24
The Sidereal and Synodic Months
Because the Sun appears to move eastward with respect to the stars, it takes the Moon longer to return to the same position relative to the Sun (and the same phase) than it does to return to the same position among the stars. **A,** At new Moon, the Sun and Moon are close together in the sky. **B,** After 27.3 days, one sidereal month, the Moon returns to the same place among the stars, but the Sun has moved eastward. The Moon shows a waning crescent phase. **C,** After 29.5 days, one synodic month, the Moon catches up with the Sun and returns to new phase. The sizes of the Sun and Moon are exaggerated in this figure. The arrows indicate the eastward motion of the Sun and Moon among the stars.

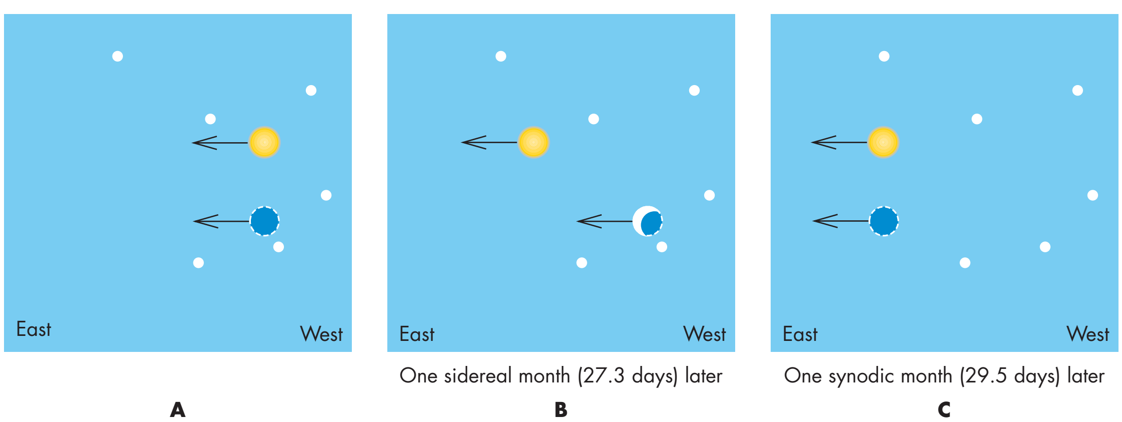
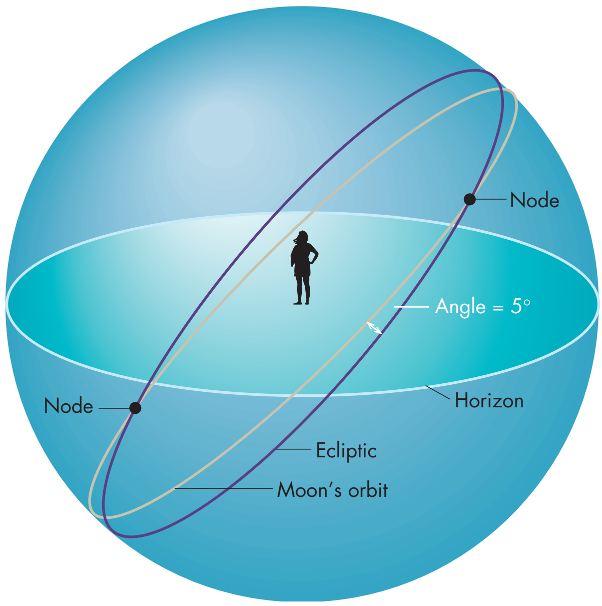


FIGURE 2.25
The Moon's Path
The Moon's path is tilted by about 5° with respect to the ecliptic.



Moon to return to the same position relative to the Sun is called the **synodic month** and is about 29.5 days in length. Because the synodic month describes the relationship between the positions of the Moon and Sun in the sky, it is also related to the time of moonrise and the phases of the Moon.

The Moon's path doesn't quite coincide with the ecliptic. The angle by which the two differ, the inclination of the Moon's **orbit,** is about 5°. Figure 2.25 shows the path of the Moon and the ecliptic. The two great circles intersect at two opposite points, the **nodes** of the Moon's orbit.

The Moon's path doesn't stay fixed but rather slides around the ecliptic like one hoop slipping around another (Figure 2.26). Another way to describe the slippage is to say that the nodes of the Moon's orbit (and the imaginary line through the Earth that connects them) move around the ecliptic. It takes 18.6 years for a node to complete a trip around the ecliptic. The motion of the Moon's nodes has an important consequence for the timing of eclipses, which are described in Chapter 9.

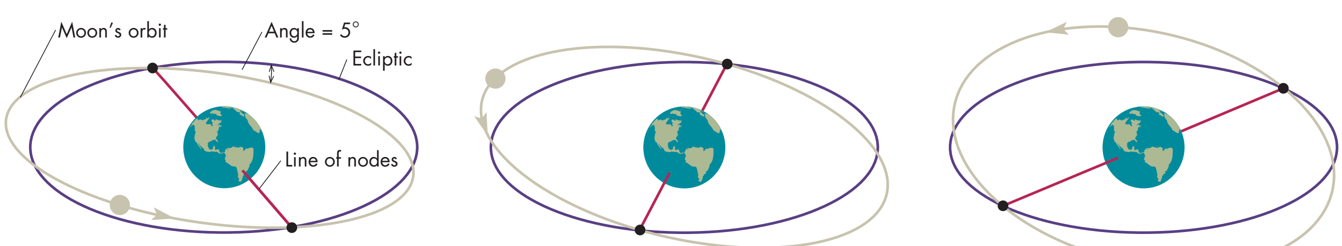
The Moon moves eastward among the stars, returning to the same place with respect to the stars after a sidereal month (27.3 days) and the same place with respect to the Sun after a synodic month (29.5 days). Its path is inclined with respect to the ecliptic by about 5°.

2.5 THE MOTIONS OF THE PLANETS

The westerly diurnal motions of the stars and the eastward motions of the Sun and Moon relative to the stars are reasonably simple to describe. The motions of the planets, however, are much more complicated. The word "planet" is derived from the Greek word for wanderer. It was originally applied to all of the celestial objects that move with respect to the stars. These objects included the Sun and Moon as well as Mercury, Venus, Mars, Jupiter, and Saturn. The remaining planets, Uranus, and Neptune were unknown to the ancients and the similarity between the Earth and the planets was not understood.

FIGURE 2.26
The Movement of the Moon's Nodes
It takes 18.6 years for the Moon's orbit to slide completely around the ecliptic.

ANIMATION *The movement of the Moon's nodes*



Approximately 2 years later

Approximately 2 years later still

FIGURE 2.27

The Retrograde Motion of Mars

The position of Mars relative to the starry background is shown for a 6-month period of time. Initially, Mars moves eastward (prograde) with respect to the stars. Its prograde motion then stops, and Mars moves westward (retrograde) with respect to the stars. Finally, its retrograde motion stops and it resumes its normal prograde motion. Mars undergoes an episode of retrograde motion every 26 months.

INTERACTIVE *Retrograde*

ANIMATION *Retrograde motion of Mars*

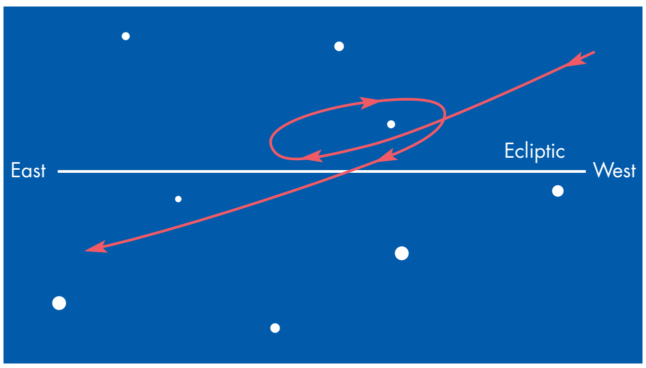
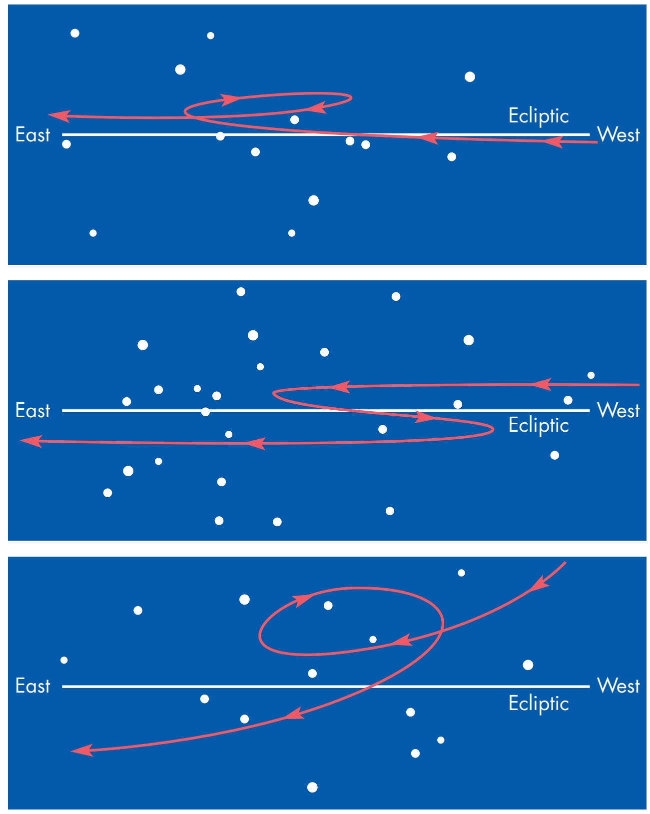


FIGURE 2.28

Three Successive Retrograde Loops for Mars

Mars underwent retrograde motion during the summer of 1984, the summer of 1986, and the fall of 1988. The starfield against which the retrograde loops took place was different for the three episodes of retrograde motion. Also, the loops differed in shape and orientation.



Most of the time, a planet appears to move eastward with respect to the stars. The rate varies greatly from planet to planet. When a planet moves eastward, its motion is said to be **prograde,** or **direct.** At regular intervals, however, a planet appears to reverse its direction of motion and, for a time, moves toward the west with respect to the stars. During this time its motion is said to be **retrograde.** An example of retrograde motion for Mars is shown in Figure 2.27. Retrograde motion occurs for a planet only when it is in a specific arrangement in the sky relative to the Sun. For Mercury and Venus, retrograde motion can take place only when the planet appears to pass near the Sun in the sky. The times when a planet is nearly aligned with the Sun are called **conjunctions.** (For Mercury and Venus, retrograde motion takes place only at every other conjunction.) For the other planets, retrograde motion happens when the planet is opposite the Sun in the sky—that is, when it is at **opposition.**

Episodes of retrograde motion occur at intervals of time known as the **synodic period** of a planet. Synodic periods range from about 4 months for Mercury to about 26 months for Mars. Despite these regularities, the motion of a planet is quite complex. For example, the retrograde loop of a planet differs in appearance from one episode of retrograde motion to the next (as shown in Figure 2.28) and occurs at a different position among the stars. The difficulty in describing the motions of the planets and in accounting for their complex behavior stimulated much of the best astronomical thinking for more than 2000 years. This work, which extended from the era of the ancient Greeks to the time of Isaac Newton, is described in Chapters 3, 4, and 5.

Unlike the Sun and Moon, the planets periodically reverse their usual eastward motion and undergo westward, retrograde motion with respect to the stars. The path of a planet relative to the stars is quite complex.

Chapter Summary

- The daily, or diurnal, westward paths of stars are circles centered on the north celestial pole. The diurnal circles grow smaller for stars that are nearer the north celestial pole. The celestial equator is a line on the celestial sphere that divides it into northern and southern hemispheres. (Section 2.1)
- The equatorial system is used to locate stars on the celestial sphere. This system resembles the terrestrial system of longitude and latitude. In the equatorial system, declination describes the angular distance of a star north or south of the celestial equator. Right ascension describes the east-west location of a star on the celestial sphere. (2.1)
- The Sun appears to move eastward among the stars on a path called the ecliptic, and its motion is repeated annually. The ecliptic is inclined with respect to the celestial equator, so the declination of the Sun varies during the year. (2.2)
- Changes in the declination of the Sun produce an annual pattern of change in its rising and setting points as well as change in its altitude at noon. These changes are responsible for the seasons. (2.2)
- Apparent solar time is reckoned by the position of the Sun in the sky. The variable rate of the Sun's motion on the ecliptic causes changes in the length of the solar day throughout the year. (2.2)
- The phases of the Moon happen because the part of the Moon's illuminated hemisphere that we see varies throughout a synodic month. (2.3)
- The Moon appears to move eastward among the stars, returning to the same place after a sidereal month. (2.4)
- The planets usually appear to move eastward among the stars. However, at regular intervals they appear to move westward during periods of retrograde motion. The motions of the planets among the stars are quite complex. (2.5)

Key Terms

Conceptual Questions

1. Explain why diurnal motion is counterclockwise for a star we observe toward the north but clockwise for a star we observe toward the south.
2. Suppose an observer in the northern hemisphere determines that the diurnal motion of a star keeps it above the horizon for 16 hours. Is the star in the northern or southern hemisphere of the celestial sphere? Does the star rise in the northeast or the southeast? How much time elapses between the time the star rises and the time it crosses the meridian?
3. What is the local hour angle of a star at the moment it crosses the meridian?
4. The equatorial coordinate system is very similar to the terrestrial coordinate system. Which terrestrial coordinate is the counterpart of right ascension? Which terrestrial coordinate is the counterpart of declination?
5. An observer, working at the time of the summer solstice, notes that the Sun circles about the sky at a constant altitude (23.5°). The observations are interrupted by a bear. What color is the bear?
6. What is the orientation of the celestial equator for observers at the Earth's equator?
7. At what latitude is the altitude of the south celestial pole greatest?

8. Suppose an observer finds that Aries is the constellation just above the horizon as the stars fade at sunrise. What constellation would be seen just above the horizon at sunrise 1 month later? How about 1 month later still?
9. Suppose the ecliptic weren't tilted with respect to the celestial equator. How would the azimuth of sunrise vary during a year? How would the length of day and night vary throughout a year?
10. Suppose the ecliptic were tilted by 40° rather than 23.5° with respect to the celestial equator. What effect would this have on the variation of the azimuth of sunrise during a year?
11. Suppose you and your roommate had built a monument with piles of rocks to mark the azimuths of sunrise at the solstices. How could you determine where to place a pile of rocks to mark the azimuth of sunrise at the equinoxes? (Note, there are several correct answers to this question.)
12. Describe why it would be difficult to use sidereal time for civil timekeeping.
13. Why would it be difficult to build a wristwatch that keeps apparent solar time?
14. The Julian calendar, instituted by Julius Caesar in 46 B.C. and replaced by the modern Gregorian calendar beginning in 1582, averaged 365.25 days in length. How did annual events, such as the vernal equinox, move through the calendar while the Julian system was in effect?
15. Suppose the Moon moved westward rather than eastward among the stars. Would the sidereal month be longer or shorter than the synodic month? Explain.

Figure-Based Questions

1. Estimate the right ascension and declination of the star shown in Figure 2.5.
2. Use Figure 2.18 to find the time in Mexico City, Mexico, when it is 5 P.M. in Washington, D.C. Ignore any complications that might be caused by daylight savings time.
3. Suppose an astronaut on the Moon watches the Earth throughout a month. Use Figure 2.19 to answer the following questions about what the astronaut would observe. When we see new Moon, what phase of the Earth does the astronaut see? What phases does the astronaut see when we see the lunar phases of first quarter, waxing gibbous, full, and waning crescent?

Group Activities

1. Divide your group into two subgroups. After a few minutes of preparation, have a short debate about the advantages and disadvantages of mean solar time versus apparent solar time for civil timekeeping. Be sure to take account of practicality, convenience, and universality in your arguments.
2. With a partner, mark the azimuth of the rising or setting Sun (your choice), as shown in Figure 2.13, for at least a week. Find out how many days it takes for you to be absolutely sure that the azimuth of sunrise (or sunset) is changing.

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