2.1

Early Ideas of the Heavens: Classical Astronomy

The ancient Greek astronomers of classical times were some of the first to try to explain the workings of the heavens in a careful, systematic manner, using observations and models. Given the limitations of naked-eye observation, these astronomers were extraordinarily successful, and their use of logic, mathematics, and geometry as tools of inquiry created a method for studying the world around us that we continue to use even today. This method is in many ways as important as the discoveries themselves.

The Shape of the Earth

The ancient Greeks knew that the Earth is round. As long ago as about 500 B.C., the mathematician Pythagoras (about 560–480 B.C.) was teaching that the Earth is spherical, but the reason for his belief was as much mystical as rational. He, like many of the ancient philosophers, believed that the sphere was the perfect shape and that the gods would therefore have utilized that perfect form in the creation of the Earth.

By the fourth century B.C., however, Aristotle (384–322 B.C.) was presenting arguments for the Earth's spherical shape that were based on simple naked-eye observations that anyone could make. Such reliance on careful, firsthand observation was the first step toward acquiring scientifically valid knowledge of the contents and workings of the Universe. For instance, Aristotle noted that if you look at an eclipse of the Moon when the Earth's shadow falls upon the Moon, the shadow can be clearly seen as curved, as figure 2.1A shows. He wrote in his treatise "On the Heavens":

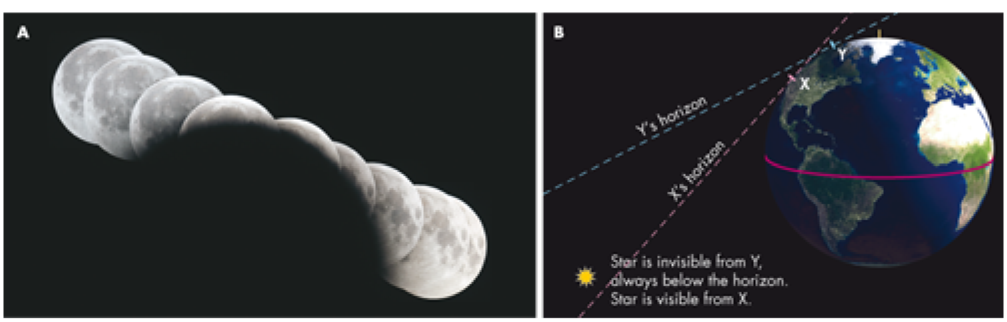

FIGURE 2.1
(A) A sequence of photographs during a partial lunar eclipse. The edge of the Earth's shadow on the Moon is always a portion of a circle, showing that the Earth must be round. (B) As a traveler moves from north to south on the Earth, different stars become visible. Some stars that were previously hidden become visible above the southern horizon. This variation would not occur on a flat Earth.

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The shapes that the Moon itself each month shows are of every kind—straight, gibbous, and concave—but in eclipses the outline is always curved: and, since it is the interposition of the Earth that makes the eclipse, the form of this line will be caused by the form of the Earth's surface, which is therefore spherical.

Another of Aristotle's arguments that the Earth is spherical was based on the observation that a traveler who moves south will see stars that were previously hidden below the southern horizon, as illustrated in figure 2.1B. For example, the bright star Canopus is easily seen in Miami but is invisible in Boston. This could not happen on a flat Earth.

It was also observed that as ships sailed away from port, the lower parts of the ships would disappear below the horizon while the sails remained visible. Today you can see this phenomenon if you travel away from a city across the ocean: the bottoms of buildings disappear below the horizon, while the tops remain visible (fig. 2.2). If the surface of the ocean were flat, the bottom of a building (or a ship) would remain visible at any distance. Therefore the surface of the ocean must be curved.

FIGURE 2.2
A sequence of photos taken from a boat traveling away from Boston. Note that the tops of the tallest buildings remain visible as the bottom parts and shorter buildings disappear over the curved ocean surface.

Distances and Sizes of the Sun and Moon

About a century after Aristotle, Aristarchus of Samos (an island in the Mediterranean) used geometric methods to estimate the relative sizes of the Earth, Moon, and Sun, and the relative distances to the Moon and Sun. His values for these numbers were not very accurate, but they were the best estimates for almost 2000 years, and gave at least the correct sense of the order of sizes and distances of these bodies compared to the Earth.

Aristarchus estimated the relative distances of the Moon and the Sun through a clever bit of reasoning. He realized that when the Moon appears exactly half lit (first or third quarter), as shown in figure 2.3, the Sun must be shining down on the Moon at an angle exactly 90° to our line of sight. However, if the Sun were only a few times farther away than the Moon, as sketched in figure 2.3, we would observe an angle between the Sun and the Moon much less than 90° at these phases. What Aristarchus found is that the half-lit Moon is only slightly less than 90° from the Sun, so the Sun must be much farther away than the Moon. He estimated 20 times farther away. Today we know the Sun is much farther away than that, about 400 times the Moon's distance. The problem is not with the method but with the difficulty in making measurements that are accurate enough with just the unaided eye. The important thing was that Aristarchus showed that the Sun is much more distant than had been previously suspected.

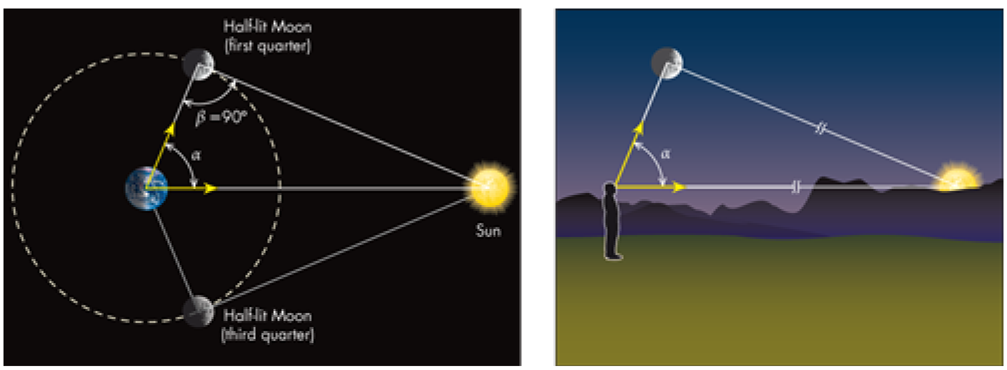

FIGURE 2.3
Aristarchus estimated the relative distance of the Sun and Moon by observing the angle between the Sun and the Moon ($\boldsymbol{\alpha}$ in the diagram) when the Moon is exactly half lit. Angle $\boldsymbol{\beta}$ must be 90° for the Moon to be half lit. By observing the angle $\boldsymbol{\alpha}$, he could then set the scale of the triangle and thus the relative lengths of the sides. (Sizes and distances are not to scale.)

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If we know the relative distances of the Sun and Moon, we can also determine their relative sizes. Recall that the Moon just barely covers the Sun during a total solar eclipse (chapter 1), so the two orbs appear to be about the same size in the sky. Astronomers call this apparent size of an object its **angular size**, as is illustrated in figure 2.4. The Sun and the Moon both have an angular size of about ½°. (Note that our perception of angular sizes is not always reliable, as discussed in Extending Our Reach: "The Moon Illusion," so it is important to measure them with appropriate instruments.) If the Sun were 20 times farther from us than the Moon, for example, to have the same angular size, it would have to be 20 times bigger than the Moon (fig. 2.4).

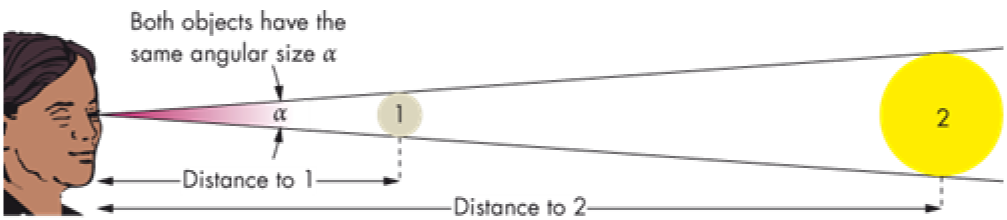

FIGURE 2.4
The angle that an object covers from an observer's point of view is called its angular size. Note that a larger object at a larger distance may have the same angular size as a nearer, smaller object.

Aristarchus further realized that he could estimate the Moon's size by comparing it to the size of the Earth's shadow during a lunar eclipse, as illustrated in figure 2.5. He carried out his measurement by timing how long the Moon took to cross Earth's shadow, and estimated that the Moon's diameter is about 0.35 times the Earth's. This is a slight overestimate, because at the distance of the Moon the Earth's shadow is actually a little smaller than the Earth itself. We now know that the correct ratio of the bodies' diameters is about 0.27, so the Moon's diameter is about 1/4 that of the Earth.

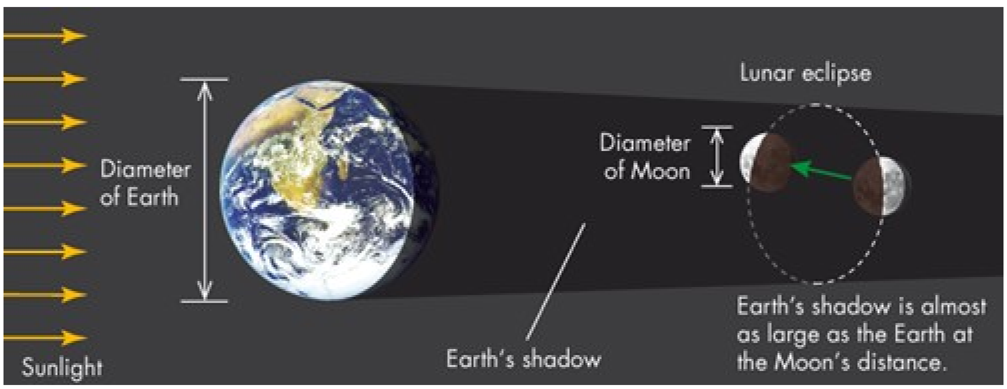

FIGURE 2.5
Aristarchus used the size of the Earth's shadow on the Moon during a lunar eclipse to estimate the relative size of the Earth and Moon.

It is also possible to estimate the size of the Earth's shadow during a lunar eclipse by looking at the curvature of the Earth's shadow on the Moon. Look again at the opening "What is this?" picture at the start of the chapter.

These observations equipped Aristarchus with enough information to estimate the size of the Sun relative to the Earth. By his measurements, the Moon was 0.35 times as big as the Earth, but the Sun was 20 times bigger than the Moon. This meant that the Sun was about 7 (= 20 × 0.35) times larger than the Earth. Today we know the Sun is even bigger, more than 100 times Earth's diameter, but Aristarchus was the first to show that the Sun is the largest body in the Solar System. It was perhaps his recognition of the vast size of the Sun that led Aristarchus to the idea that the Earth orbits the Sun. Aristarchus was right, of course, but his idea was too revolutionary, and another 2000 years passed before scientists became convinced of its correctness.

EXTENDING *our reach*
THE MOON ILLUSION

The Moon sometimes appears to be huge when you see it rising. In fact, if you measure the Moon's angular diameter carefully, you will find it to be smaller when it is near the horizon than when it is overhead, regardless of how huge it looks. This misperception, known as the **Moon illusion**, is still not completely understood but is an optical illusion caused, at least in part, by the observer's comparing the Moon with objects seen near it on the horizon, such as distant hills and buildings. You know those objects are big even though their distance makes them appear small. Therefore, you unconsciously magnify both them and the Moon, making the Moon seem larger. You can verify this sense of illusory magnification by looking at the Moon through a narrow tube that blocks out objects near it on the sky line. Seen through such a tube, the Moon appears to be its usual size.

Figure 2.6 shows a similar effect. Because you know that the rails are really parallel, your brain ignores the apparent convergence of the railroad tracks and mentally spreads the rails apart. That is, your brain provides the same kind of enlargement to the circle near the rails' convergence point as it does to the rails, causing you to perceive the middle circle as larger than the lower one, even though they are the same size.

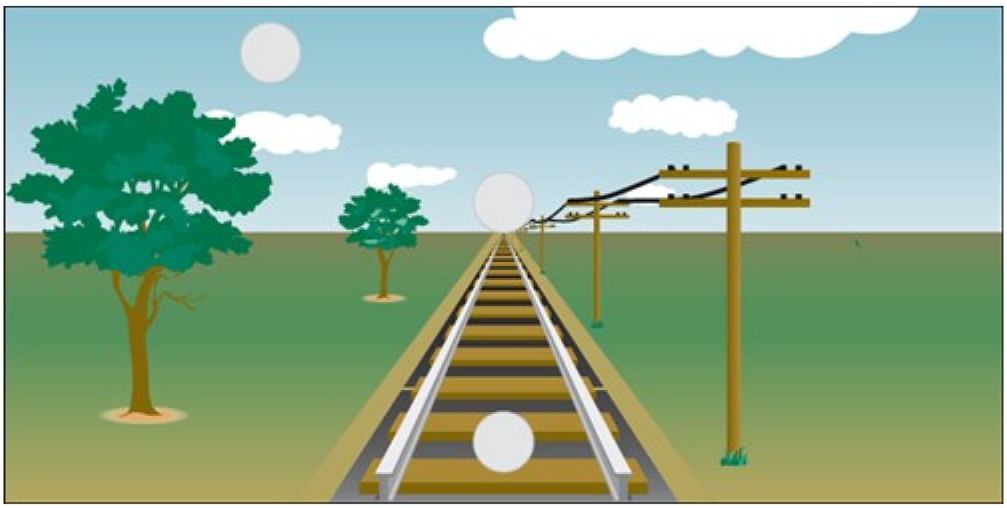

FIGURE 2.6
Circles beside converging rails illustrate how your perception may be fooled. The bottom circle looks smaller than the circle on the horizon but is in fact the same size. Similarly, the circle high in the sky looks smaller than the circle on the horizon.

Arguments for an Earth-Centered Universe

In ancient Greek times there was a good reason for not believing that the Earth moves around the Sun. If it did, argued the critics of Aristarchus, the positions of stars should change during the course of the year. Looking at figure 2.7, you can see two examples of why they expected to see effects of the Earth's motion.

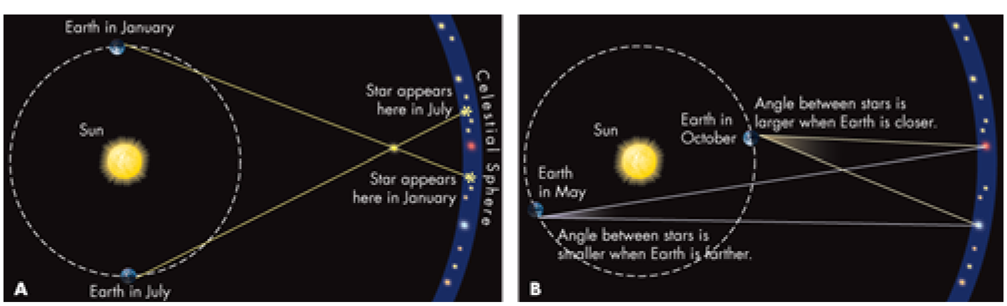

FIGURE 2.7

Most ancient astronomers argued against the idea of the Earth revolving around the Sun because: (A) if some stars are nearer than other stars, we would see their positions appearing to shift relative to their neighbors (stellar parallax) as the Earth moved around the Sun; and (B) even if all the stars lay at the same distance (on the celestial sphere), as Earth orbited we would sometimes be closer to the stars and sometimes farther, so the angular size of constellations would change. Neither effect was seen because stars are so tremendously distant.
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If some stars are nearer than others, they would shift against background stars due to Earth's changing perspective (fig. 2.7A). This apparent shift in position of a foreground star relative to the background is called the star's **parallax**. Even if all stars lay at the same distance on the celestial sphere, as the Earth moved closer and farther from stars forming a constellation on one part of the celestial sphere, the angular size of constellation would appear to change (fig. 2.7B).

Aristarchus's critics were absolutely right in supposing that these shifts in stars' positions should occur. So, when they did not observe any effects caused by the Earth's motion, they concluded that Aristarchus's Sun-centered system must be wrong. But what no one appreciated at the time was how tiny these shifts would be.

The size of the parallax shift grows smaller the farther away a star is, but the ancient Greeks did not imagine that stars could be so enormously far away that their parallaxes would be imperceptible to the human eye. In Aristarchus's time, about 2000 years before the telescope was invented, there was no hope of detecting the parallax of stars. It was not until 1838 that astronomers had telescopes of sufficient accuracy to measure the nearest stars' parallaxes. Thus Aristarchus's idea was rejected for reasons that were logically correct but were based on inaccurate data.

The Size of the Earth

Even though Aristarchus had established a great deal about the *relative* sizes and distances of astronomical bodies, his methods could not say whether the Moon was a thousand or a million miles across. All the sizes were related to Earth's diameter, so if that could be measured, then the other sizes would be known. But how was it possible to find the diameter of the Earth in an age long before there were means of circling the globe? It required another remarkable piece of geometry and deduction to reveal the true physical dimensions of the cosmos.

Eratosthenes (276–195 B.C.), head of the famous Library of Alexandria in Egypt, succeeding in making the first measurement of the Earth's size. He obtained a value for its circumference of about 25,000 miles, remarkably close to its actual value. Eratosthenes's demonstration is one of the most beautiful ever performed. Because it so superbly illustrates how science links observation and logic, the demonstration is worth describing in some detail.

By ancient Greek times, astronomers were very well acquainted with the yearly movement of the Sun and could predict accurately the times of the solstices and equinoxes (chapter 1). The summer solstice marked the day of the year in Alexandria when the Sun would reach its highest point in the sky at noon. However, the Sun was not straight overhead but still cast a shadow at noon. Eratosthenes, a geographer as well as an astronomer, heard that lying to the south, in the Egyptian town of Syene (the present city of Aswan), the Sun would be directly overhead at noon and cast no shadow. Proof of this was the fact that at that time the Sun shone straight down a deep well near there.

Appreciating the power of geometry, Eratosthenes realized he could deduce the circumference of the Earth. He analyzed the problem as follows: Because the Sun is far away from the Earth and much larger, as shown by Aristarchus, its light travels in nearly parallel rays toward the Earth. Thus, two rays of sunlight, one hitting Alexandria and the other shining down the well, are parallel lines, as depicted in figure 2.8, and the ray hitting the well in Syene would be aimed directly toward the center of the Earth.

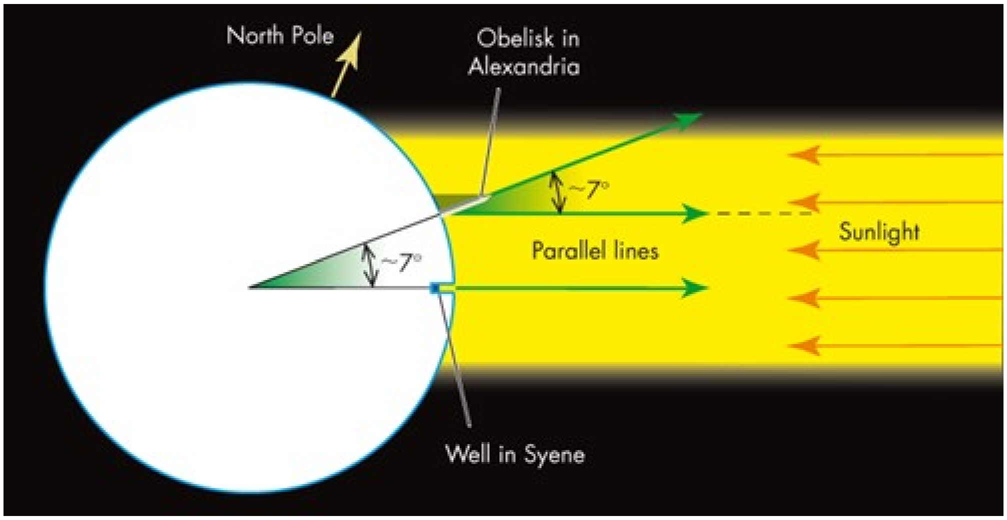

FIGURE 2.8
Eratosthenes's calculation of the circumference of the Earth. The Sun is directly overhead at local noon on the summer solstice at Syene, in southern Egypt. On that same day and time, Eratosthenes found the Sun to be 1/50th of a circle (about 7°) from the vertical in Alexandria, in northern Egypt. Eratosthenes deduced that the angle between two verticals placed in northern and southern Egypt must be 1/50th of the circumference of the Earth.

Now imagine drawing a straight line from the center of the Earth outward so that it passes vertically through the Earth's surface in Alexandria. The angle between that line and the direction of the Sun's rays in Alexandria is the same as the angle between that line and the line from the center of the Earth up through the well in southern Egypt (fig. 2.8). The reason is that a single line crossing two parallel lines forms the same angle to both (a geometric theorem).

The angle between sunlight and vertical directions in Alexandria can be measured with sticks and a protractor (or its ancient equivalent) and is the angle between the direction to the Sun and the vertical to the ground (fig. 2.8). Eratosthenes found this angle to be about 1/50th of a circle. Therefore the angle formed by a line from Alexandria to the Earth's center and a line from the well to the Earth's center must also be 1/50th of a circle.

To find the circumference of the Earth, all that is needed is to find the distance between Alexandria and the well, which represents 1/50th of the distance around the Earth. Soldiers marching between Alexandria and Syene estimated the distance to be 5000 stadia (where a stadium is about 0.1 mile), so the distance around the entire Earth is 50 × 5000 stadia, or 250,000, stadia. When expressed in miles, this is roughly 25,000 miles, close to the circumference of the Earth as we know it today.

You can use Eratosthenes's technique yourself to measure the size of the Earth by collaborating with someone at a known distance north or south of you, and comparing the difference in angle of the noontime Sun.

Eratosthenes's measurement of the Earth's size was a triumph of logic and the scientific technique, and with it we have the key to the sizes of the Moon and the Sun. Furthermore, because there is a relationship between angular size, physical size, and distance, this measurement provides enough information to determine the Moon's and Sun's immense distances. This is worked out in detail in Astronomy by the Numbers: "The Diameter–Distance Relation of Astronomical Objects."

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ASTRONOMY *by the numbers*
THE DIAMETER–DISTANCE RELATION OF ASTRONOMICAL OBJECTS

We can find an astronomical body's true diameter from its angular diameter if we know its distance, or its distance if we know its diameter. We need either the body's distance or its diameter because angular size changes with both. For example, a building looks big when it is near us and small when it is far away, as shown in figure 2.9. And, of course, a larger building also appears bigger. Furthermore, it is easy to verify that the angular size of a distant object changes inversely with the object's distance. That is, if we double the distance to an object, its angular size is halved.

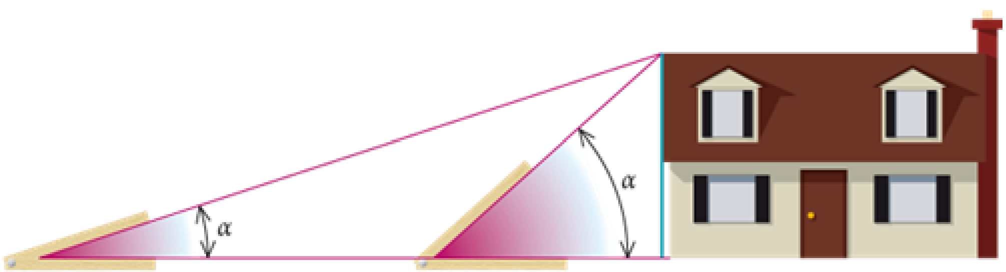

FIGURE 2.9
How angular size varies with distance.

To find an object's true diameter from its angular diameter and distance, imagine we are at the center of a circle passing through the object, as illustrated in figure 2.10. Let ℓ be the diameter of the body and *d* the distance to the body, which is the *radius* of the circle in the figure. Next draw lines from the center to each end of ℓ, letting the angle between the lines be $\boldsymbol{\alpha}$, the object's angular diameter.

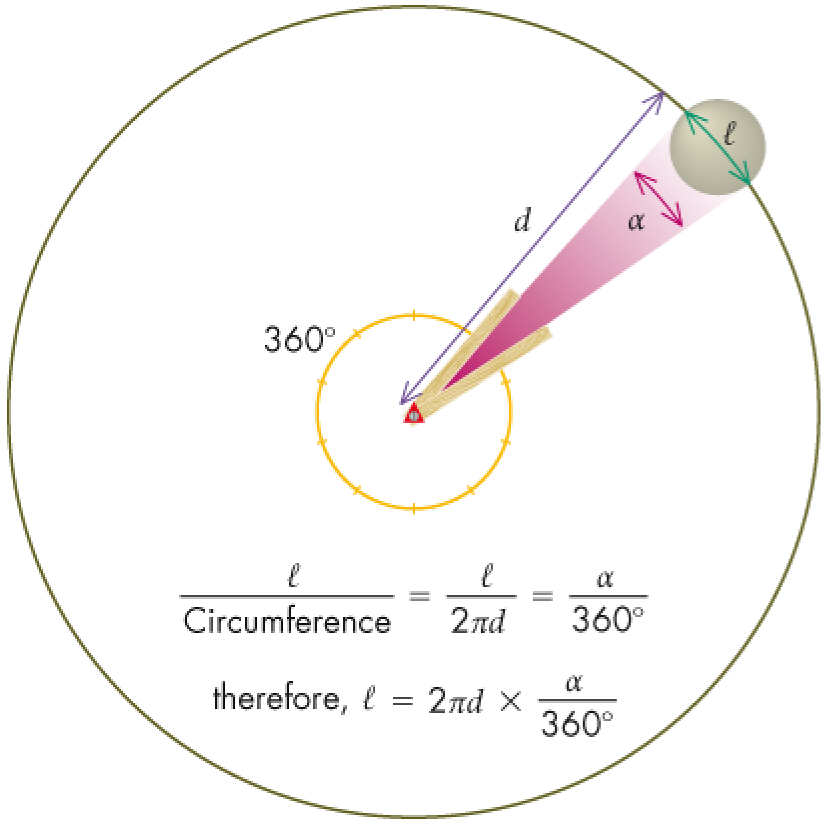

FIGURE 2.10
How to determine linear size from angular size.

We now determine the object's true size, ℓ, by forming the following proportion: ℓ is to the circumference of the circle as α is to the total number of degrees around the circle, which we know is 360°. Thus,

$$\frac{\text{Object's diameter}}{\text{Circumference}} = \frac{\text{Angle between lines}}{360°}$$

$$\frac{\ell}{\text{Circumference}} = \frac{\alpha}{360°}$$

However, we know from geometry that the circle's circumference is $2\pi d$, so

$$\frac{\ell}{2\pi d} = \frac{\alpha}{360°}$$

Multiplying both sides of the equation by ($360°d/\alpha$), we can now solve for d, and find that

$$d = \frac{360°\ell}{2\pi\alpha}$$

Thus, given a body's actual and angular diameters, we can calculate its distance. For example, suppose we apply this method to measure the Moon's distance from the ancient Greek measurements. We stated previously that the Moon's angular diameter is about 1/2°, while its diameter is 0.27 the Earth's, or about 2100 miles. Therefore its distance is about

$$d = \frac{(360°)(2100 \text{ miles})}{2\pi(0.5°)} = \text{about } 240{,}000 \text{ miles}$$

or about 380,000 kilometers.

We can work another example to find a diameter from a distance. We know the angular diameter of the Sun is also about 1/2°, and the Sun's distance is today known to be about 150 million kilometers. The Sun's diameter must therefore be

$$\ell = \frac{2\pi d\alpha}{360°} = \frac{2\pi(150{,}000{,}000 \text{ km})(0.5°)}{360°}$$

$$= \text{about } 1{,}300{,}000 \text{ km}$$

The Sun is more than a million kilometers across!