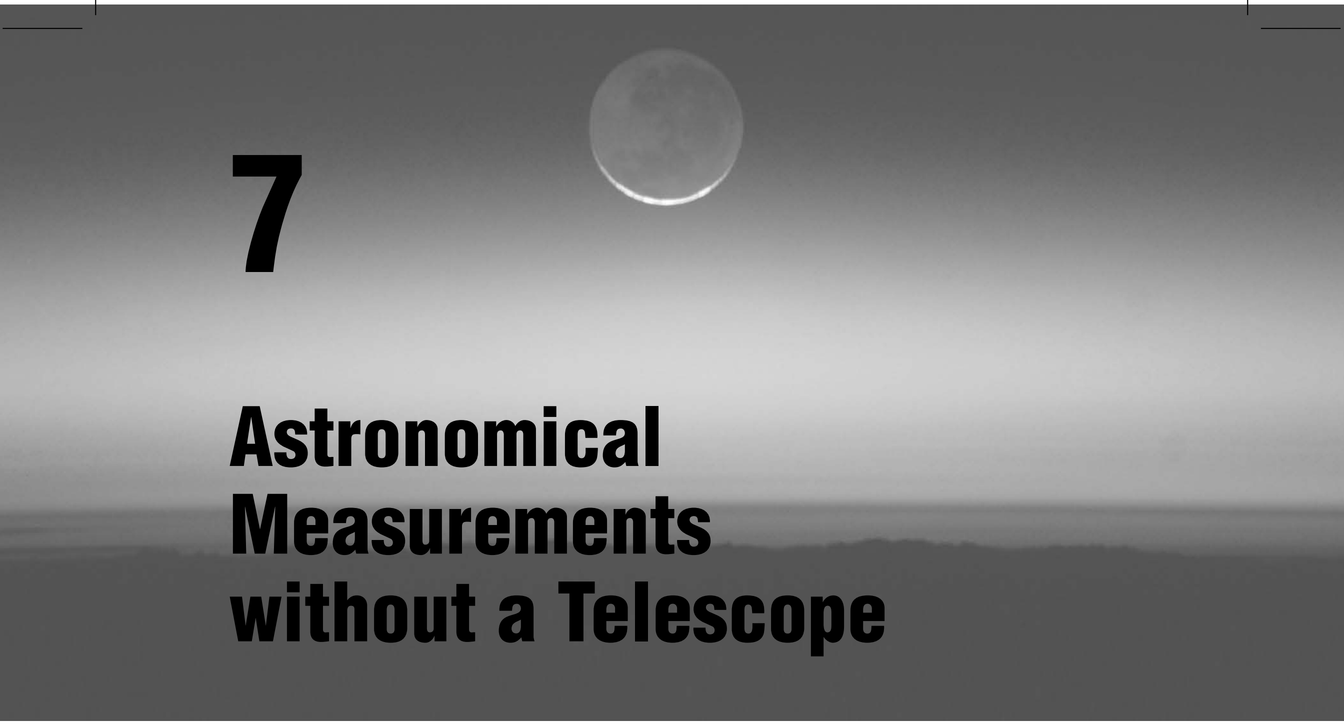

7

Astronomical Measurements without a Telescope

In this chapter we describe some astronomical experiments that can be carried out with very simple equipment. Details of our own work can be found in two articles published in the *American Journal of Physics*.[1,2]

Aristarchus (ca. 287–212 BC) devised a clever method for determining the distance to the Moon using the geometry of a lunar eclipse. Such an eclipse happens when the full Moon occasionally enters the Earth's shadow. This does not happen every month because the plane of the Moon's orbit around the Earth is inclined by five degrees to the plane of the Earth's orbit around the Sun. Aristarchus determined that the distance to the Moon is between sixty and seventy Earth radii. One fact necessary for the method of Aristarchus is the mean angular size of the Moon. This is about 0.5 degree.

Claudius Ptolemy (ca. 100–170 AD) summarized Greek astronomy in his famous book, the *Almagest.* In it he states that the angular size of the Moon ranges from 31.3 to 35.3 arc minutes, where sixty arc minutes equals one degree, by definition. However, Ptolemy was primarily interested in describing the *direction* toward the Moon. His model of the motion of the Moon implied that it ranged in distance from 33.55 Earth radii to 61.17 Earth radii, nearly a factor of two in distance. Thus, its angular size should also range by a factor of two, rather than ±6 percent. And it was Ptolemy's model of the *motion* of the Moon that was used until it was supplanted in the sixteenth century.

I got to thinking, "Using the kind of equipment that Ptolemy had at his disposal [i.e., no telescopes], is it possible to measure the cyclical variations of the Moon's angular size?" Very few such measurements have come down to us from antiquity or the Middle Ages. Two observers who addressed this issue were Levi ben Gerson (1288–1344) and Ibn al-Shatir (1304–1375/6). Like Ptolemy, they claimed that the Moon's angular size varies by a few arc minutes.

I fashioned a Moon-sighting device from the bottom of a box of pancake mix, a second piece of cardboard, and a metal yardstick (see Figure 7.1). After observations over seven cycles of the Moon's phases, I had enough data to demonstrate that regular variations of the Moon's angular size *can* be measured with the naked eye.[1] Since then I have taken more data. Over a span of 1145 days (nearly thirty-nine cycles of the Moon's phases) I obtained a hundred measurements.[3] Our mean value of the Moon's angular diameter was 31.1 arc minutes, essentially equal to the accepted modern value. The data yield a mean perigee to perigee period of 27.5042 ± 0.0334 days. The modern, officially correct, value is 27.55455 days. (When a body that orbits the Earth is as close as it gets, it is said to be at perigee.) The agreement is quite satisfactory.

In Figure 7.2 we show our data phased with the derived period. Clearly, there is considerable scatter. Any individual data point is uncertain, on average, by ± 0.9 to 1.0 arc minutes, but we were able to demonstrate how much the

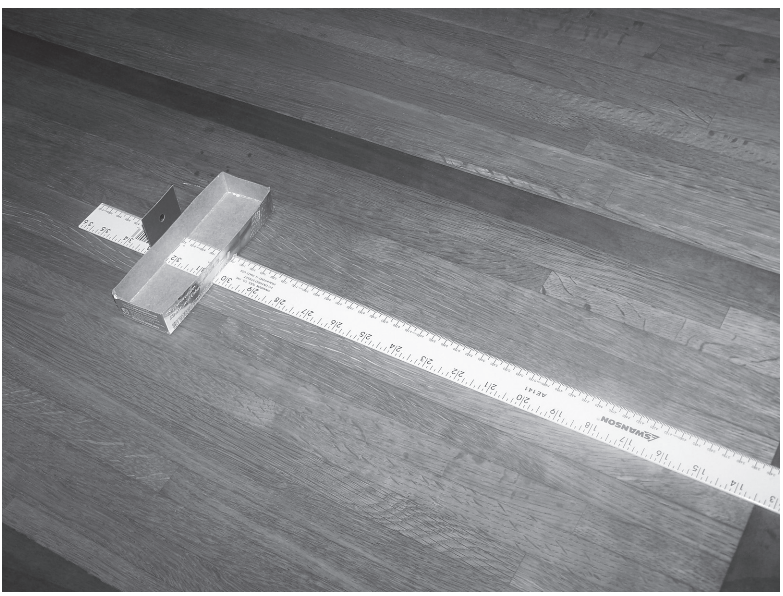

Figure 7.1 Device for measuring the angular size of the Moon.
Source: Kevin Krisciunas.

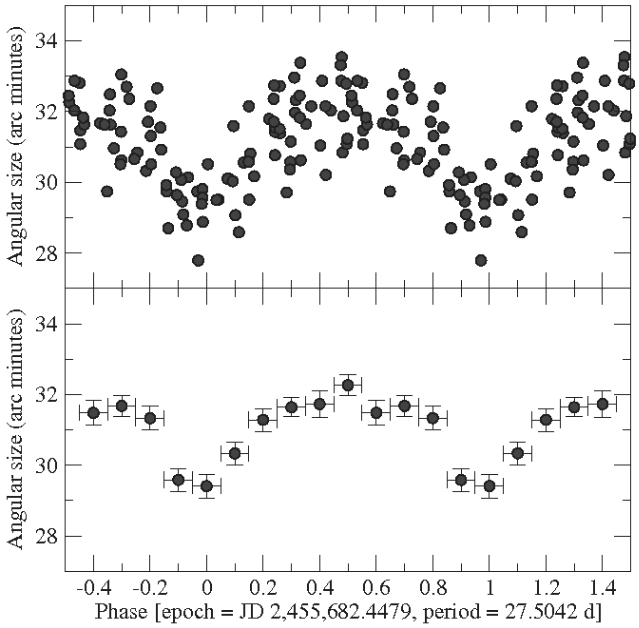

Figure 7.2 Phased observations of the angular size of the Moon. The upper diagram shows the individual data points obtained from April 21, 2009, through June 9, 2012. The lower diagram shows the averages for binned data.
Source: Kevin Krisciunas.

Moon's angular size (and hence distance) varies. We found a value of the eccentricity of the Moon's orbit of 0.039 ± 0.004, which is a bit smaller than the official modern value of 0.0549. Due to the extra effect of the Sun's gravitational force on the Moon, the Moon's distance actually varies from +5.8 percent to −7.3 percent from the mean value.[4]

Another device from olden times is the *gnomon*, like the one pictured in Figure 7.3. It is basically just a vertical stick that casts a shadow of the Sun on the ground. To determine the elevation angle of the Sun, it is better to use a little sphere at the end of the stick. One marks the center of the elliptical shadow of the ball. One can use just a vertical pointed stick or a pointy statue, like the Luxor obelisk in the Place de la Concorde in downtown Paris, but then one must remember to account for the angular radius of the Sun.

I used this gnomon to measure the latitude of College Station, Texas, obtaining a value of 30 degrees 48.7 ± 3.5 arc minutes, which is 11.5 arc minutes north of the true value of 30 degrees 37.2 arc minutes from Google Earth. I also obtained a value of the *obliquity of the ecliptic* of 23 degrees 04.7 ± 3.5 arc minutes, which is a bit lower than the true value of 23 degrees

Figure 7.3 Device for measuring the elevation angle of the Sun above the horizon.
Source: Kevin Krisciunas.

26.2 arc minutes. The obliquity of the ecliptic is the tilt of the Earth's axis of rotation to the plane of its orbit, as shown in Figure 7.4. It is this tilt that causes our seasons. When the northern hemisphere is tilted toward the Sun by 23.4 degrees, it is the beginning of summer in the north. When the northern hemisphere is tilted away from the Sun by 23.4 degrees, it is the beginning of winter in the north.

Having determined my latitude and longitude in South Bend, Indiana, and College Station, Texas, I was able to determine a value of the circumference of the Earth, some 24,557 miles. The resulting radius of the Earth is 6290 km, which is 1.4 percent less than the official equatorial radius of the Earth of 6378 km.

Lahaye (2012) has elaborated a method of determining the eccentricity of the Earth's orbit using a gnomon.[5] This involves the *time* at which the Sun is highest in the sky, thus producing the minimum gnomon shadow length. This is not the same time on your watch, day after day. The *mean* solar time ranges from fourteen minutes ahead of *apparent* solar time to sixteen minutes behind it.[6] This is a result of the tilt of the Earth's axis of rotation and the eccentricity of the Earth's orbit. A full proof of this involves trigonometry and considerations of the geometry of an ellipse, which we need not repeat here.

Lahaye obtained measurements of the maximum elevation angle of the Sun at his location and the time of apparent noon. He did this four or five times

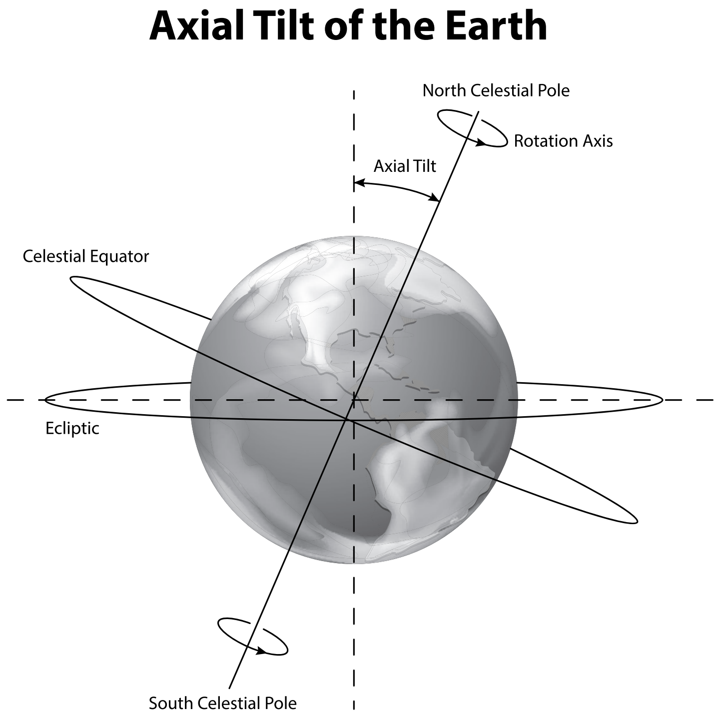

Figure 7.4 The Earth in space. The horizontal plane represents the plane of the Earth's orbit around the Sun. The axis of rotation of the Earth is not perpendicular to that plane. It is tilted 23.4 degrees, as shown. The axis of rotation points toward the South Celestial Pole (SCP) in the southern hemisphere, and toward the North Celestial Pole (NCP) in the northern hemisphere. *Image © BlueRingMedia, 2013. Used under license from Shutterstock, Inc.*

each month throughout the year. He obtained a value of the obliquity of the ecliptic of 23.5 ± 0.1 degrees. For the eccentricity of the Earth's orbit he obtained 0.017 ± 0.001; the modern accepted value is 0.0167. From six gnomon experiments carried out on the campus of Texas A&M University and our value of the obliquity of the ecliptic, we obtained 0.014 ± 0.003 for the eccentricity of the Earth's orbit.

Throughout history astronomers have been preoccupied with the distance scale of the universe. This involves calibration of many rungs on what is called the *cosmological distance ladder*. This begins with surveying planet Earth—determining how big it is. We can then move on to determine the distance to the Moon in terms of the radius of the Earth. Using simultaneous observations of Mars or an asteroid from two locations on the Earth, we can then calibrate the scale of the solar system. This third rung of the distance ladder requires the use of telescopes. Prior to the end of the seventeenth century we only knew the *relative* sizes of the orbits of the planets, according to Kepler's Third Law of planetary motion. We discuss the first three rungs of the distance ladder in our 2012 article.[2]

To determine the distances to the nearest stars other than the Sun requires positional measurements considerably more accurate than one second of arc (1/3600 of a degree). We use the diameter of the Earth's orbit as our baseline for surveying the cosmos. This method of determining distance is called *trigonometric parallax*. The nearby stars move back and forth with respect to the distant background of stars owing to the motion of the Earth around the Sun. The first parallax measures were not obtained until the 1830s, nearly three centuries after Copernicus suggested that the Earth was just another planet orbiting the Sun.

The calibration of the scale of our Galaxy and the rest of the universe is carried out with *astronomical standard candles*, objects whose intrinsic brightness we know by one method or another. Two key types are pulsating stars called Cepheids, whose periods of pulsation are related to the mean brightness, and Type Ia supernovae, which are exploding white dwarf stars visible halfway across the universe with 4-m class telescopes. At maximum brightness such a supernova is roughly four billion times more luminous than the Sun.[7]

Endnotes

1. Krisciunas, Kevin "Determining the eccentricity of the Moon's orbit without a telescope," *American J. of Physics*, 78, pp. 828–833 (August 2010).
2. Krisciunas, K., E. DeBenedictis, J. Steeger, A. Bischoff-Kim, G. Tabak & K. Pasricha, "The first three rungs of the cosmological distance ladder," *American J. of Physics*, 80, no. 5, pp. 429–438 (May 2012).
3. The individual data points and further discussion can be obtained at http://people.physics.tamu.edu/krisciunas/moon_ang.html (accessed November 13, 2013).
4. *Allen's Astrophysical Quantities*, 4th ed., Arthur N. Cox, ed., New York, Berlin, Heidelberg: Springer-Verlag, 2000, p. 308.
5. Lahaye, Thierry, "Measuring the eccentricity of the Earth's orbit with a nail and a piece of plywood," http://arxiv.org/abs/1207.0982 (2012).
6. http://en.wikipedia.org/wiki/Equation_of_time (accessed March 9, 2013).
7. Krisciunas, Kevin "The usefulness of Type Ia supernovae for cosmology—a personal review," *J. of the Amer. Assoc. of Variable Star Observers*, 40, pp. 334–347 (May 2012). Also available via: http://arxiv.org/abs/1205.6835