Surveying the Stars

It is an enormous step to go from the planets to the stars. For example, our Voyager 1 probe, which was launched in 1977, has now traveled farther from Earth than any other spacecraft. As of 2021, Voyager 1 is 152 AU from the Sun.[1] The nearest star, however, is hundreds of thousands of AU from Earth. Even so, we can, in principle, survey distances to the stars using the same technique that a civil engineer employs to survey the distance to an inaccessible mountain or tree—the method of *triangulation*.

Triangulation in Space

A practical example of triangulation is your own depth perception. As you are pleased to discover every morning when you look in the mirror, your two eyes are located some distance apart. You therefore view the world from two different vantage points, and it is this dual perspective that allows you to get a general sense of how far away objects are.

To see what we mean, take a pen and hold it a few inches in front of your face. Look at it first with one eye (closing the other) and then switch eyes. Note how the pen seems to shift relative to objects across the room. Now hold the pen at arm's length: the shift is less. If you play with moving the pen for a while, you will notice that the farther away you hold it, the less it seems to shift. Your brain automatically performs such comparisons and gives you a pretty good sense of how far away things in your immediate neighborhood are.

If your arms were made of rubber, you could stretch the pen far enough away from your eyes that the shift would become imperceptible. This is because our depth perception fails for objects more than a few tens of meters away. In order to see the shift of an object a city block or more from you, your eyes would need to be spread apart a lot farther. Let's see how surveyors take advantage of the same idea. Suppose you are trying to measure the distance to a tree across a deep river (Figure 19.4). You set up two observing stations some distance apart. That distance (line AB in Figure 19.4) is called the baseline. Now the direction to the tree (C in the figure) in relation to the baseline is observed from each station. Note that C appears in different directions from the two stations. This apparent change in direction of the remote object due to a change in vantage point of the observer is called parallax.

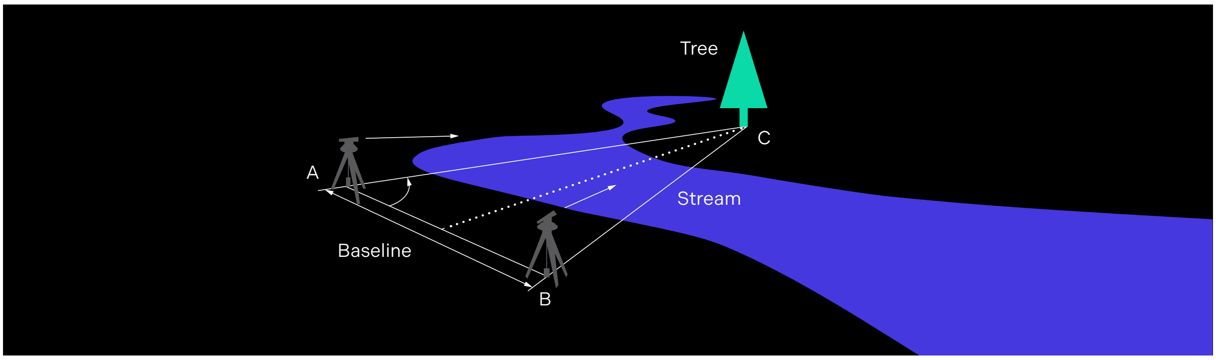


Figure 19.4 Triangulation. Triangulation allows us to measure distances to inaccessible objects. By getting the angle to a tree from two different vantage points, we can calculate the properties of the triangle they make and thus the distance to the tree.

1 To have some basis for comparison, the dwarf planet Pluto orbits at an average distance of 40 AU from the Sun, and the dwarf planet Eris is currently roughly 96 AU from the Sun.

The parallax is also the angle that lines AC and BC make—in mathematical terms, the angle subtended by the baseline. A knowledge of the angles at A and B and the length of the baseline, AB, allows the triangle ABC to be solved for any of its dimensions—say, the distance AC or BC. The solution could be reached by constructing a scale drawing or by using trigonometry to make a numerical calculation. If the tree were farther away, the whole triangle would be longer and skinnier, and the parallax angle would be smaller. Thus, we have the general rule that the smaller the parallax, the more distant the object we are measuring must be.

In practice, the kinds of baselines surveyors use for measuring distances on Earth are completely useless when we try to gauge distances in space. The farther away an astronomical object lies, the longer the baseline has to be to give us a reasonable chance of making a measurement. Unfortunately, nearly all astronomical objects are very far away. To measure their distances requires a very large baseline and highly precise angular measurements. The Moon is the only object near enough that its distance can be found fairly accurately with measurements made without a telescope. Ptolemy determined the distance to the Moon correctly to within a few percent. He used the turning Earth itself as a baseline, measuring the position of the Moon relative to the stars at two different times of night.

With the aid of telescopes, later astronomers were able to measure the distances to the nearer planets and asteroids using Earth's diameter as a baseline. This is how the AU was first established. To reach for the stars, however, requires a much longer baseline for triangulation and extremely sensitive measurements. Such a baseline is provided by Earth's annual trip around the Sun.

Distances to Stars

As Earth travels from one side of its orbit to the other, it graciously provides us with a baseline of 2 AU, or about 300 million kilometers. Although this is a much bigger baseline than the diameter of Earth, the stars are so far away that the resulting parallax shift is still not visible to the naked eye—not even for the closest stars.

In the chapter on Observing the Sky: The Birth of Astronomy, we discussed how this dilemma perplexed the ancient Greeks, some of whom had actually suggested that the Sun might be the center of the solar system, with Earth in motion around it. Aristotle and others argued, however, that Earth could not be revolving about the Sun. If it were, they said, we would surely observe the parallax of the nearer stars against the background of more distant objects as we viewed the sky from different parts of Earth's orbit (Figure 19.6). Tycho Brahe (1546–1601) advanced the same faulty argument nearly 2000 years later, when his careful measurements of stellar positions with the unaided eye revealed no such shift.

These early observers did not realize how truly distant the stars were and how small the change in their positions therefore was, even with the entire orbit of Earth as a baseline. The problem was that they did not have tools to measure parallax shifts too small to be seen with the human eye. By the eighteenth century, when there was no longer serious doubt about Earth's revolution, it became clear that the stars must be extremely distant. Astronomers equipped with telescopes began to devise instruments capable of measuring the tiny shifts of nearby stars relative to the background of more distant (and thus unshifting) celestial objects.

This was a significant technical challenge, since, even for the nearest stars, parallax angles are usually only a fraction of a second of arc. Recall that one second of arc (arcsec) is an angle of only 1/3600 of a degree. A coin the size of a US quarter would appear to have a diameter of 1 arcsecond if you were viewing it from a distance of about 5 kilometers (3 miles). Think about how small an angle that is. No wonder it took astronomers a long time before they could measure such tiny shifts.

The first successful detections of stellar parallax were in the year 1838, when Friedrich Bessel in Germany (Figure 19.5), Thomas Henderson, a Scottish astronomer working at the Cape of Good Hope, and Friedrich Struve in Russia independently measured the parallaxes of the stars 61 Cygni, Alpha Centauri, and Vega, respectively. Even the closest star, Alpha Centauri, showed a total displacement of only about 1.5 arcseconds during the course of a year.

2 AU = 300 mio km

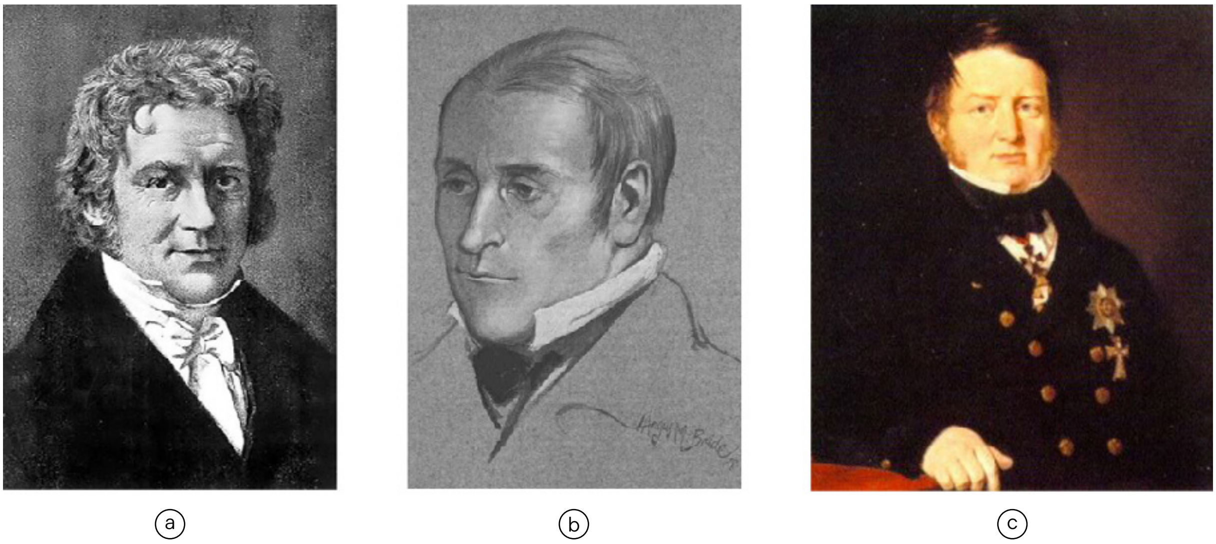


Figure 19.5 Friedrich Wilhelm Bessel (1784–1846), Thomas J. Henderson (1798–1844), and Friedrich Struve (1793–1864). a — Bessel made the first authenticated measurement of the distance to a star (61 Cygni) in 1838, a feat that had eluded many dedicated astronomers for almost a century. But two others, b — Scottish astronomer Thomas J. Henderson and c — Friedrich Struve, in Russia, were close on his heels.

Figure 19.6 shows how such measurements work. Seen from opposite sides of Earth's orbit, a nearby star shifts position when compared to a pattern of more distant stars. Astronomers actually define parallax to be one-half the angle that a star shifts when seen from opposite sides of Earth's orbit (the angle labeled P in Figure 19.6). The reason for this definition is just that they prefer to deal with a baseline of 1 AU instead of 2 AU.

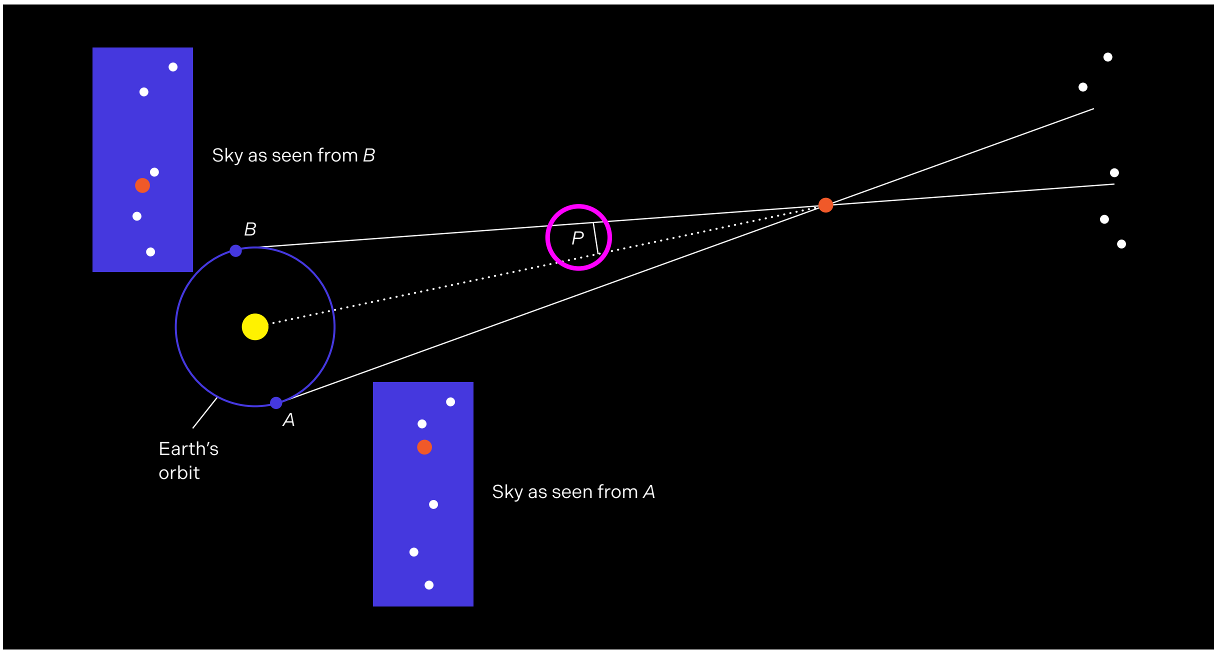


Figure 19.6 Parallax. As Earth revolves around the Sun, the direction in which we see a nearby star varies with respect to distant stars. We define the parallax of the nearby star to be one half of the total change in direction, and we usually measure it in arcseconds.

Units of Stellar Distance

With a baseline of one AU, how far away would a star have to be to have a parallax of 1 arcsecond? The answer turns out to be 206,265 AU, or 3.26 light-years. This is equal to 3.1 × 1013 kilometers (in other words, 31 trillion kilometers). We give this unit a special name, the parsec (pc)—derived from "the distance at which we have a parallax of one second." The distance (D) of a star in parsecs is just the reciprocal of its parallax (p) in arcseconds; that is:

$$D = \frac{1}{p}$$

Thus, a star with a parallax of 0.1 arcsecond would be found at a distance of 10 parsecs, and one with a parallax of 0.05 arcsecond would be 20 parsecs away.

D = 1 / 0.05 = 20 pc

Back in the days when most of our distances came from parallax measurements, a parsec was a useful unit of distance, but it is not as intuitive as the light-year. One advantage of the light-year as a unit is that it emphasizes the fact that, as we look out into space, we are also looking back into time. The light that we see from a star 100 light-years away left that star 100 years ago. What we study is not the star as it is now, but rather as it was in the past. The light that reaches our telescopes today from distant galaxies left them before Earth even existed.

In this text, we will use light-years as our unit of distance, but many astronomers still use parsecs when they write technical papers or talk with each other at meetings. To convert between the two distance units, just bear in mind: 1 parsec = 3.26 light-year, and 1 light-year = 0.31 parsec.

Example 1

How Far Is a Light-Year?

A light-year is the distance light travels in 1 year. Given that light travels at a speed of 300,000 km/s, how many kilometers are there in a light-year?

Solution

We learned earlier that speed = distance/time. We can rearrange this equation so that distance = velocity × time. Now, we need to determine the number of seconds in a year.

There are approximately 365 days in 1 year. To determine the number of seconds, we must estimate the number of seconds in 1 day.

We can change units as follows (notice how the units of time cancel out):

1day × 24 hr/day × 60 min/hr × 60 s/min = 86,400 s/day

Next, to get the number of seconds per year:

365 days/year × 86,400 s/day = 31,536,000 s/year

Now we can multiply the speed of light by the number of seconds per year to get the distance traveled by light in 1 year:

distance = velocity × time = 300,000 km/s × 31,536,000 s = 9.46 × 1012 km

That's almost 10,000,000,000,000 km that light covers in a year. To help you imagine how long this distance is, we'll mention that a string 1 light-year long could fit around the circumference of Earth 236 million times.

Check Your Learning

The number above is really large. What happens if we put it in terms that might be a little more understandable, like the diameter of Earth? Earth's diameter is about 12,700 km.

Answer:

$$1 \text{ light-year} = 9.46 \times 10^{12} \text{ km}$$

$$= 9.46 \times 10^{12} \text{ km} \times \frac{1 \text{ Earth diameter}}{12{,}700 \text{ km}}$$

$$= 7.45 \times 10^{8} \text{ Earth diameters}$$

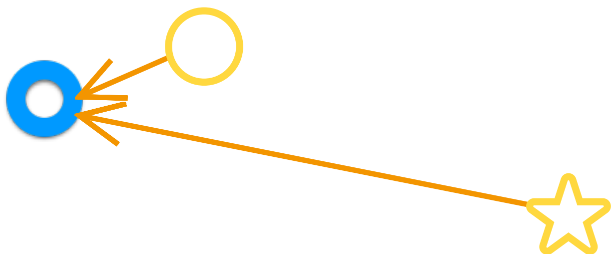
That means that 1 light-year is about 745 million times the diameter of Earth.

The Nearest Stars

No known star (other than the Sun) is within 1 light-year or even 1 parsec of Earth. The stellar neighbors nearest the Sun are three stars in the constellation of Centaurus. To the unaided eye, the brightest of these three stars is Alpha Centauri, which is only 30° from the south celestial pole and hence not visible from the mainland United States. Alpha Centauri itself is a binary star—two stars in mutual revolution—too close together to be distinguished without a telescope. These two stars are 4.4 light-years from us. Nearby is a third faint star, known as Proxima Centauri. Proxima, with a distance of 4.3 light-years, is slightly closer to us than the other two stars. If Proxima Centauri is part of a triple star system with the binary Alpha Centauri, as seems likely, then its orbital period may be longer than 500,000 years.

Proxima Centauri is an example of the most common type of star, and our most common type of stellar neighbor (as we saw in Stars: A Celestial Census.) Low-mass red M dwarfs make up about 70% of all stars and dominate the census of stars within 10 parsecs (33 light-years) of the Sun. For example, a recent survey of the solar neighborhood counted 357 stars and brown dwarfs within 10 parsecs, and 248 of these are red dwarfs. Yet, if you wanted to see an M dwarf with your naked eye, you would be out of luck. These stars only produce a fraction of the Sun's light, and nearly all of them require a telescope to be detected.

The nearest star visible without a telescope from most of the United States is the brightest appearing of all the stars, Sirius, which has a distance of a little more than 8 light-years. It too is a binary system, composed of a faint white dwarf orbiting a bluish-white, main-sequence star. It is an interesting coincidence of numbers that light reaches us from the Sun in about 8 minutes and from the next brightest star in the sky in about 8 years.



Example 2

Calculating the Diameter of the Sun

For nearby stars, we can measure the apparent shift in their positions as Earth orbits the Sun. We wrote earlier that an object must be 206,265 AU distant to have a parallax of one second of arc. This must seem like a very strange number, but you can figure out why this is the right value. We will start by estimating the diameter of the Sun and then apply the same idea to a star with a parallax of 1 arcsecond. Make a sketch that has a round circle to represent the Sun, place Earth some distance away, and put an observer on it. Draw two lines from the point where the observer is standing, one to each side of the Sun. Sketch a circle centered at Earth with its circumference passing through the center of the Sun. Now think about proportions. The Sun spans about half a degree on the sky. A full circle has 360°. The circumference of the circle centered on Earth and passing through the Sun is given by:

$$\text{circumference} = 2\pi \times 93{,}000{,}000 \text{ miles}$$

Then, the following two ratios are equal::

$$\frac{0.5°}{360°} = \frac{\text{diameter of Sun}}{2\pi \times 93{,}000{,}000}$$

Calculate the diameter of the Sun. How does your answer compare to the actual diameter?

Solution

To solve for the diameter of the Sun, we can evaluate the expression above.

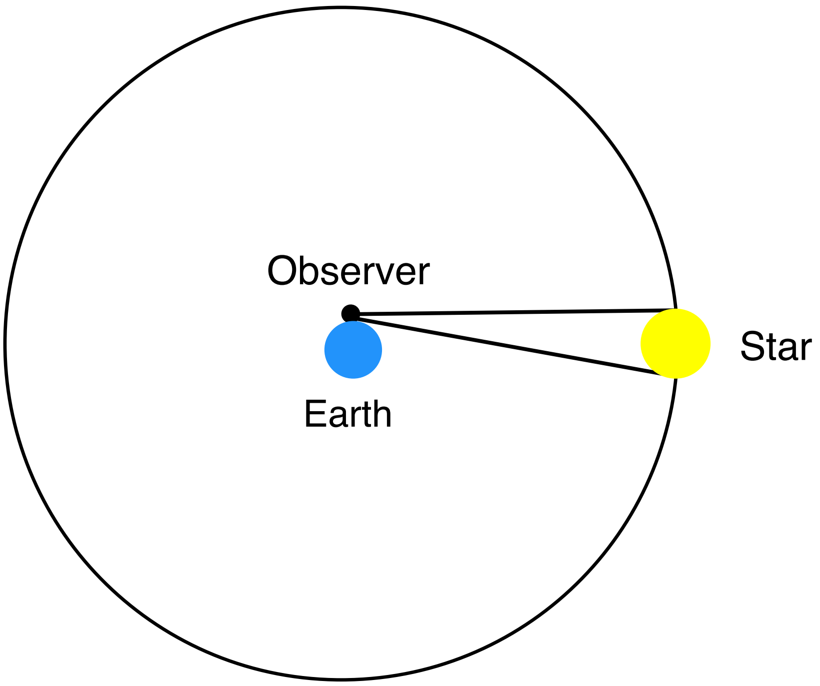
$$\text{diameter of Sun} = \frac{0.5°}{360°} \times 2\pi \times 93{,}000{,}000 \text{ miles} = 811{,}577 \text{ miles}$$

This is very close to the true value of about 848,000 miles.

Check Your Learning

Now apply this idea to calculating the distance to a star that has a parallax of 1 arcsec. Draw a picture similar to the one we suggested above and calculate the distance in AU. (Hint: Remember that the parallax angle is defined by 1 AU, not 2 AU, and that 3600 arcseconds = 1 degree.)

Answer:



Measuring Parallaxes in Space

The measurements of stellar parallax were revolutionized by the launch of the spacecraft Hipparcos in 1989, which measured distances for thousands of stars out to about 300 light-years with an accuracy of 10 to 20% (see Figure 19.8 and the feature on Parallax and Space Astronomy). However, even 300 light-years are less than 1% the size of our Galaxy's main disk.

In December 2013, the successor to Hipparcos, named Gaia, was launched by the European Space Agency. Gaia is measuring the position and distances to almost one billion stars with an accuracy of a few millionths of an arcsecond. Gaia's distance limit will extend well beyond Hipparcos, studying stars out to 30,000 light-years (100 times farther than Hipparcos, covering nearly 1/3 of the galactic disk). Gaia will also be able to measure proper motions[2] for thousands of stars in the halo of the Milky Way—something that can only be done for the brightest stars right now. At the end of Gaia's mission, we will not only have a three-dimensional map of a large fraction of our own Milky Way Galaxy, but we will also have a strong link in the chain of cosmic distances that we are discussing in this chapter. Yet, to extend this chain beyond Gaia's reach and explore distances to nearby galaxies, we need some completely new techniques.

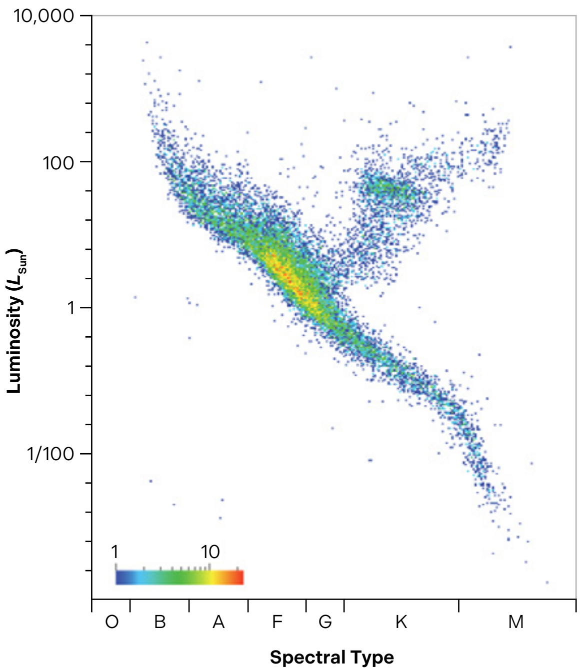


Figure 19.8 H–R Diagram of Stars Measured by Gaia and Hipparcos. This plot includes 16,631 stars for which the parallaxes have an accuracy of 10% or better. The colors indicate the numbers of stars at each point of the diagram, with red corresponding to the largest number and blue to the lowest. Luminosity is plotted along the vertical axis, with luminosity increasing upward. An infrared color is plotted as a proxy for temperature, with temperature decreasing to the right. Most of the data points are distributed along the diagonal running from the top left corner (high luminosity, high temperature) to the bottom right (low temperature, low luminosity). These are main sequence stars. The large clump of data points above the main sequence on the right side of the diagram is composed of red giant stars. (credit: modification of work by the European Space Agency)

2 Proper motion (as discussed in Analyzing Starlight, is the motion of a star across the sky (perpendicular to our line of sight.)

Link to Learning

The European Space Agency (ESA) maintains a **Gaia mission website** where you can learn more about the Gaia mission and to get the latest news on Gaia observations.

To learn more about Hipparcos, explore this **European Space Agency webpage** with an ESA vodcast Charting the Galaxy—from Hipparcos to Gaia.

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