The principle of geometrical parallax

One of the hardest things to do in astronomy is to determine how far away things are. Does the star Vega in Lyra appear exceptionally bright because it’s an intrinsically bright star, or simply because it’s unusually close by? What about Betelgeuse in Orion? If we didn’t know the distances to these stars, we wouldn’t know that Betelgeuse is a red giant star, with a much greater intrinsic brightness than Vega (and much larger diameter). Nor would we know that many stars visible in the night sky are much like the Sun, but just much, much farther away so they appear much fainter.

So how do astronomers determine distances to stars and other objects? Actually, there are many different ways, some more accurate than others. One of the most straightforward ways is the method of parallax. This method only works for relatively nearby stars (a small fraction of all the stars in the Milky Way, and none of the stars in any other galaxies), but it is the starting point of all other distance measurements. It is sometimes referred to as the first “rung” in the astronomical distance “ladder” that extends all the way out to close to the edge of the observable Universe.

Parallax is a geometrical phenomenon that is actually common in everyday life. We’re so used to its effect that we hardly notice it happening. When you walk around, nearby objects appear to move relative to more distant ones. You can even see the phenomenon without moving at all by holding up a finger in front of your face, and then observing it first with one eye closed, then the other. Your finger appears to move relative to objects in the distance. How much it appears to move depends on how far away from your face it is. The closer it is, the more it appears to move.

This apparent shift of a nearby object relative to more distant ones is called parallax, and is exactly the method used by astronomers to determine distances to nearby stars. The separation between your eyes is enough to make your finger appear to move, since it is very nearby. To make stars appear to move, we need a much larger baseline. Even two positions on Earth separated by thousands of kilometers wouldn’t be enough to see a shift of even the nearest stars. But we can get a bigger baseline by taking advantage of Earth’s motion around the Sun, which takes it to positions 300 million km apart in 6 months!

Diagram of parallax method:
Image 2 (taken three months later)
**Exercise 1:** Determining the distances to stars using the parallax method

In this exercise, you will determine the distances to stars that appear in a pair of images taken 3 months apart. Some stars are in different positions in the two images. You will also determine the minimum distance to those stars for which there is no measurable parallax.

The previous two pages of the lab are two images of the same patch of sky taken 3 months apart. You can assume that the patch of sky is near the plane of the ecliptic. (Note that these images are actually artificial constructions to make it possible to measure many stellar parallaxes in one image. In practice, stars that are close enough to us to have measurable parallaxes wouldn’t be so close together on the sky.) The images are “negatives,” so that stars appear black on a white (or gray) background. The size of a star in the images is determined not by the star’s physical dimensions, but by its brightness. The brighter stars appear bigger than faint ones.

**Step 1:** Compare the two star images carefully, looking for stars that appear in different locations in the two images. You may find it helpful to take the images out of your lab book, lay image #1 on top of image #2, and hold them up to a light. Be careful to align the two images well (most stars will line up perfectly). You can also try using a ruler to check if separations or alignments between stars have changed.

**Step 2:** Mark each star that has moved noticeably with an arrow on image #1. Draw the arrows in BELOW the stars, so they point “up” at the stars. Label each star with a number, letter or name.

**Step 3:** For each star that moves, estimate its center by eye as best you can on image #1, and make a small dot there. (For bright stars these dots will be a little hard to see.) Then lay image #1 on top of image #2, and look for where each star moved to in image #2. Make a small dot on image #1 at the location where the star is centered in image #2. You should now have two dots on image #1 associated with each star that moves.

**Step 4:** Use a metric ruler to measure how far each star shifted in the three month period between image #1 and image #2. Make the measurement in millimeters (mm), and record it in Table 1.

**Step 5:** Convert your measurements in millimeters to an angular size using the following conversion:

\[
1 \text{ mm} = 0.1 \text{ arcsecond}
\]

The resulting shift in units of arcseconds is the known as the “parallax” of the star. Record the parallax values in Table 1.
TABLE 1: Stars with Measurable Parallaxes

<table>
<thead>
<tr>
<th>star name</th>
<th>amount of shift (mm)</th>
<th>parallax (arcseconds)</th>
<th>distance (parsecs)</th>
<th>distance (ly)</th>
</tr>
</thead>
</table>

**Step 6:** Compute the distances to each of the stars that moved noticeably. Use the parallax formula:

\[ d = \frac{1}{p} \]

where \( d \) is the distance in parsecs (pc) and \( p \) is the parallax angle measured in arcseconds. For example, a star with a parallax of 0.5 arcsec has a distance of \( \frac{1}{0.5} = 2.0 \text{ pc} \). Record your results in Table 1.

**Step 7:** Compute the distances to each of the stars in lightyears (ly), and record your results in Table 1. Use the conversion:

\[ 1 \text{ pc} = 3.26 \text{ ly} \]

**Step 8:** Estimate the smallest apparent shift you hypothetically could have measured. That is, how far in mm would a star need to have shifted for you to have been able to notice the shift? What does this smallest measurable shift correspond to in arcseconds? Then compute the distance to a star that has this value of the parallax, following steps 5 and 6 above.

Smallest measurable shift:

Smallest measurable parallax:

Distance to star for which a parallax could just barely be measured:
**Questions on Exercise 2:**

**Q1:** Look at your result from Step 5 above. What, if anything, can be said about the distances of stars that didn’t seem to move from image #1 to image #2? [e.g. “they must be closer than ....” or “they must be farther away than ....” (Fill in the blanks with a number.)]

**Q2:** Suppose you observed the same field of stars 3 months after image #2 was taken. Describe in words how you would expect the positions of stars to appear. Include a sketch if that would help explain what you would see.

**Q3:** Suppose you observed the field once more 9 months after image #2 was taken. Describe in words how you would expect the apparent positions of stars to compare to those observed in image #1 and/or image #2. (Double-check your answer with the diagram in the introduction.)

**Q4:** Put aside the images you’ve been working on for a moment. Imagine that all the stars in the Galaxy have the same intrinsic brightness, like light bulbs all of the same wattage. Stars would then appear brighter or fainter depending on whether they were relatively close or relatively far away from the Earth. If this were the case, which stars would appear brighter as seen from Earth: those with large parallaxes, or those with small parallaxes? Explain.

**Q5:** Now consider the results of your analysis of the two images. Are the results consistent with the hypothesis that all stars in the Galaxy have the same intrinsic brightness? Why or why not? If not, give at least one specific example from this exercise that proves your point.