# How Far Away Are Stars? Part 1

**Objective:** So how far away are they anyway, and how do you know?

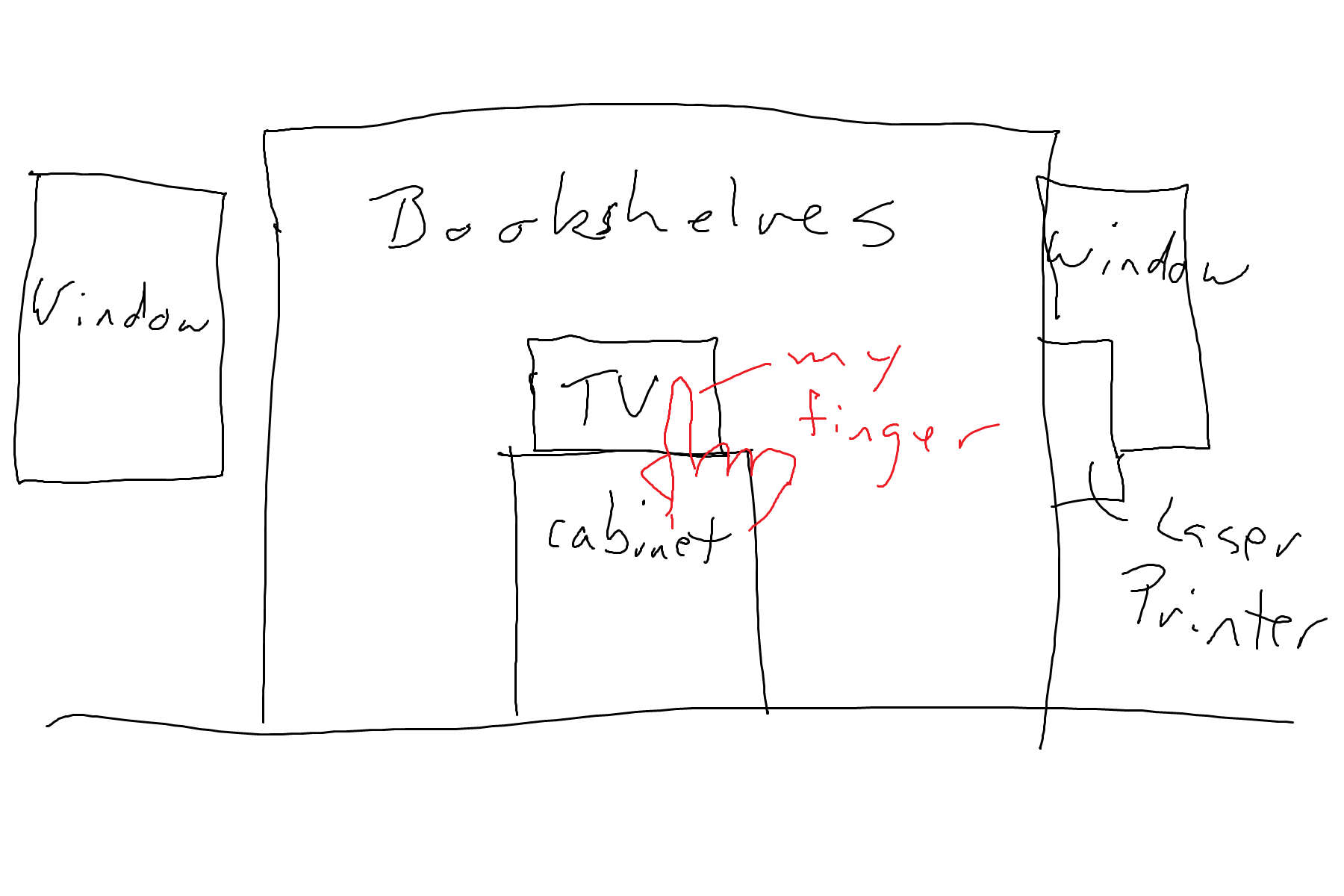
**Requirements:** Stellarium planetarium simulator

**Strategy:** Explore how the distance to an object affects our perceptions of it, then apply that knowledg to the Moon and Stars.

## A. Messing Around With The Phenomena

There are a number of ways to determine the distance to a star. We’ll look at several later on as we come to them. They vary a lot with regard to accuracy, uncertainty, and applicability, so you have to choose the one that is appropriate to the circumstances. Let’s start with what is historically the first truly accurate method.

1.) So let’s start with a very simple experiment. Hold your finger up about 6 to 8 inches from your face and close your right eye. Make a sketch of the objects in the background and where your finger appears to be in front of them. I did this in my living room and got something like this.

Now, without moving your finger, close your left eye, open your right eye, and make a similar sketch of where your finger appears to be.

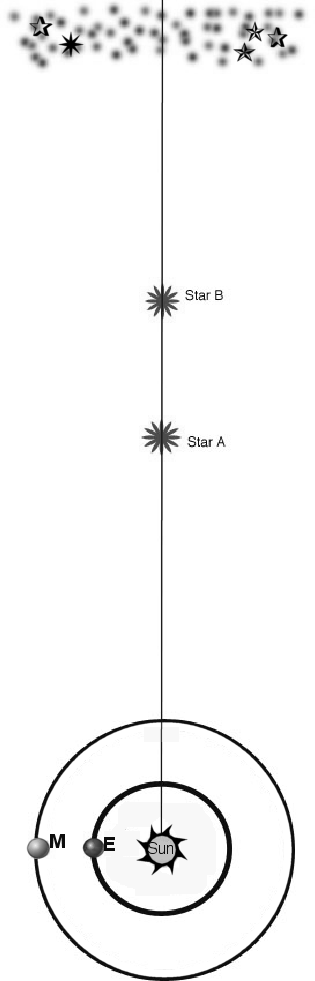
What you have just seen is called a parallax shift (from the Greek parallaxis, “a change”), and it is one of the pieces of information your brain uses to figure out how far away things are in your environment.

2.) Repeat experiment A, this time holding your finger at arm’s length. How is the parallax shift related to distance?

3.) Holding your finger at arm’s length, look at it with your right eye and make a sketch similar to the ones in part A. Then, have someone sit next to you and, without moving your finger, make a similar sketch. What happened to the parallax shift compared to part A? The distance between your observation points is called the *baseline.*

**Discuss your results with your instructor at this point**

## B. Apply the Phenomenon to the Moon and Stars

Of course, your finger did not really move. It just looked like it did because you changed your viewpoint. The only thing you can determine with your eye (or with a telescope) is what direction the light came from. When you changed eyes, you were looking in a different direction so you saw the light from that direction. The parallax, then, is a direction difference, and a direction difference is measured by an angle.

1.) What about the background objects? Wouldn’t there be a parallax for them as well? Under what circumstances could you justify using them for reference objects when observing your finger? What could you do to choose better reference objects? If it isn’t raining, go outside and look for parallax shifts in objects at greater and greater distances to help with this question.

This picture shows two stars at different distances from the Earth. The circle labeled E represents the Earth’s orbit and its location on that orbit on a particular day, let’s say January 1. There are two stars at different distances from the Earth, and some very distant background stars. One easy way to do steps 2 and 3 is to copy and paste the diagram into Word and use Word’s drawing tool to make your lines.

2.) Draw a line from the Earth to the background stars going through star A. Next, find where the Earth will be 6 months later, on June 1. Draw a second line from the Earth (6 months later) to the background stars going through star A. Mark the angle between the above two lines at Star A. This is the parallax angle. Make a sketch similar to part A except this time using the background stars as reference objects and the apparent position of Star A playing the role of your finger.

3.) Repeat step 2 for star B using a different color for the lines if you can, or using a second sketch. How does the parallax angle and sketch for star B compare to that of star A? Is this consistent with your eyeball experiment above?

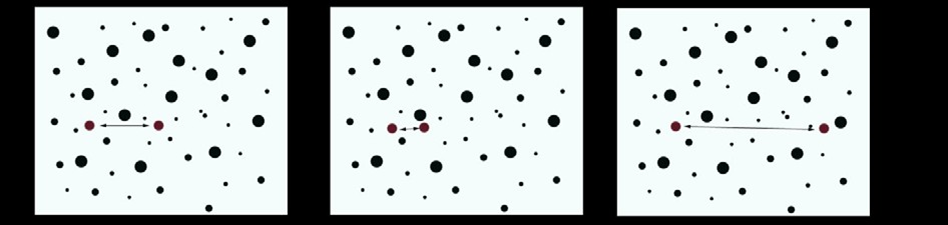
4.) The circle labeled M is Mars, repeat the steps for star A as you would see it if Elon Musk sends you to Mars, thereby making your baseline bigger. The time between the two points now has to be half a Martian year. How does the Martian parallax angle and sketch compare to the Earthly one?

5.) How does the parallax angle depend on the distance to the star? How does it depend on the distance between your two viewpoints (this is called the baseline)?

6.) The diagram includes “very distant background stars.” In terms of parallax angles, what would be a good definition of “very distant?” What would this mean about the baseline compared to the background star distance?

Well, this is what you could do in principle. In practice, measuring the direction your telescope points relative to a diameter of the Earth’s orbit is fraught with problems. Among other things, the rotation axis of the Earth is tilted so the direction across the orbit is different on different days. So in practice, we look at where the star is compared to the “very distant background stars” instead. Using your diagram for Earth, find where star A and star B appear to be relative to the background stars. How would you tell which if further away from that observation?

7.) Here are photographs taken of three stars. Each one is two photos taken 6 months apart and superimposed.



**A**

**B**

**C**

For the stars that show a parallax shift relative to the background stars, rank them in order of distance from closest to furthest. Why do most of the stars not show a parallax shift? Explain your logic.

**Discuss your results with your instructor at this point**

## C. Measuring the Phenomenon

First, we will do the distance to the Moon. Your eyes aren’t far enough apart to see a parallax. We need them to be further apart. And we can do this by having two people make simultaneous measurements from opposite sides of the Earth. So let’s make this work. Fire up Stellarium and we’ll measure the parallax angle for the Moon with observations made from the North and South poles.

### Getting Stellarium Ready

There are two menus in the lower left corner of the screen that pop up when you move your mouse there, one on the side and one on the bottom. First thing we need to do is configure an angle measuring tool. This is on the left side menu. Click the wrench and star icon on the left side for configuration and go to the last tab, plugins. The second thing on the list is called Angle Measure. Select it. At the bottom of the screen, click load on startup and the configure button. Then restart Stellarium.

Stellarium shows you what you’d really see from right here, right now. That includes blue sky and trees, which are in our way so we can turn them off. Move your mouse to the left bottom side of the screen and a control menu will pop up. When you move your mouse over a button, its name will pop up. In the third group of icons from the left, there is a “ground (a hill with trees)” and an “atmosphere (a cloud with Sun).” Click each to turn that one off. Cool, huh? Now you have a transparent Earth and no blue sky.

Another thing you will find on the left side menu is a magnifying glass with a star. Click it and search for the Moon. There it is! There is also rather a lot of information you don’t really need and it can get in your way. On the left side menu, bring up the configuration window again and this time go to the Information tab. You will see “All Information” selected. Change it to short or none.

We’re going to use the Earth as a baseline by observing simultaneously from both the North and South poles. Stellarium is currently updating the view as time passes. To simulate two people observing simultaneously, we need to freeze simulated time while we make our observations. On the bottom menu, you’ll find some video controls on the far right hand side. Change from play to pause. Of course, in the real world, you can’t do this but you can send two expeditions, with clocks.

Now you can go to the North Pole. The top item on the left menu (a compass rose) is a location tool. In the latitude box, type N 90. Longitude doesn’t matter as all longitude lines meet at the North Pole. In the Name/City box, you can type North Pole and set the region to nothing (“-”). That will add it to your list so in the future you can just search by name. You might have to find the Moon again. If so, hit the space bar to lock onto it after you’ve found it.

### Parallax Measurement for the Moon

By default, you should already be in angle measuring mode, but check to make sure. On the bottom screen menu, you should see an angle looking thing. It is the thing with the box around it in this image.



1.) Refer back to the picture in question B7. This is how parallax is actually measured. You take two photos, superimpose them, and then measure the angle between the two positions. To simulate taking two photos, we can use Stellarium’s ability to mark a position. Turn the angle measure tool off (else it will interfere with setting a marker) and shift-click on the Moon as seen from the North Pole. You’ve just set a marker of its position as seen from the North Pole, and you should see a green cross labeled “Marker 1.” You can undo markers if you need to by shift-right click.

Now we need to go to the South Pole. Bring up the location menu again and this time set the latitude to S 90. You can also add this position to your list with the region Antarctica or you can just use the South Pole Telescope, which is located where you would expect it to be. You should see the Moon shifted away from your marker. Click on the Moon and hit spacebar to lock onto it again. It didn’t move very far so it would help to use a telescope for our observations. You can simulate this by zooming in with a mouse wheel or two finger scroll.

You measure angles by turning on the angle tool and clicking and dragging between the center of the Moon and the place where you left a marker. You’ll see a line appear between the two positions that gives you an angle in degrees-minutes-seconds format. We know there is going to be observational uncertainty, so everyone in your group should measure the angle themselves.

This is your parallax angle.

2.) The math for figuring out distance will be WAY easier if we use decimal degrees instead of degrees-minutes-seconds. There are 60 seconds in a minute and 60 minutes in a degree. So divide the seconds by 60 and add to the minutes. Take the result, divide it by 60 and add to the degrees. Now you have decimal degrees, and also a bit of an idea why the metric system is better than the traditional one. Find the average and uncertainty in your group’s measurement of the Moon’s parallax angle.

**Discuss your results with your instructor at this point**

### Parallax Measurement for a Star

Even with modern technology, the North and South Poles are nowhere near far enough apart to see a parallax shift for any star. The biggest distance it is practical to achieve is the diameter of the Earth’s orbit around the Sun. You make a measurement, wait six months, and make another[[1]](#footnote-1). But for stars, there is a major complication that doesn’t exist for the Moon.

Imagine you are standing still with rain falling straight down on you. You have to hold your umbrella directly over your head to stay dry. But if you are moving through the rain, you have to tilt your umbrella to stay dry. That’s because you are moving into raindrops that would not have hit you were you standing still. To you, the rain appears to be coming in at an angle due to your movement.

Now replace you with the Earth, the umbrella with your telescope, and the rain with star light. Since the Earth is moving around the Sun, the star light appears to be coming in at an angle because the Earth is moving into it. This is called aberration. The true position of the star is not the position you see. Even worse, when the Earth goes from one side of its orbit to the other, it is moving in the opposite direction so the offset is in the opposite direction. This animation might help you visualize it:

<https://youtu.be/_UzfBgOwDWo?t=16>

You can see this in Stellarium. Search for Proxima Centauri and zoom WAY in until you can see it. Deselect it by clicking on it. From the left side menu, bring up the date and time controls (the clock icon). Step forward one month at a time and you should see it move in a big oval. Try the same thing with Regulus and it moves back and forth on a straight line. Try it with Polaris and it will go around in a circle. Clearly, aberration is very complicated.

The problem for us is that the aberration angle is about 10 times larger than any parallax angle, totally swamps the parallax, and has nothing to do with distance to the star. To measure parallax, we will need to subtract out the aberration. That is a pretty complicated trigonometric problem since it depends both on the Earth’s orbit as well as where the star is in the sky. So we will assume it has been done for us already by our graduate student and just turn it off like we did the Earth and the Atmosphere.

From the left side menu, bring up the Configuration window and go to the Tools tab. You should see a check box for aberration (the fourth item in the right hand column) that you can uncheck. Be sure to give your graduate student a pat on the head.

3.) Why is aberration just not a problem for making observations of the Moon?

The closest star to Earth, and the only one we have a hope of getting any sort of plausible value for out of Stellarium, is Proxima Centauri. Search for that one. That will take you to a little yellow rotating circle around Proxima Centauri but you won’t be able to see the star itself. That is because it is a very cool, dim star and, as close as it is, it still isn’t bright enough to see. So we need to magnify it as if we were looking though a telescope.

You do this by either two-finger dragging on a touchpad, or spinning the wheel on a mouse. Zoom in until you can see it easily.

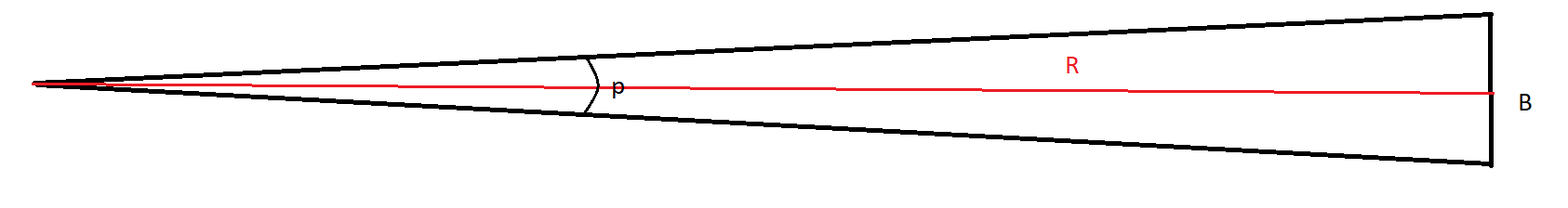
4- 5.) Now repeat steps 1 and 2 except in step 1 where you go to the South Pole, instead stay where you are and advance the calendar 6 months. You can do this using the Date/Time controls again.

**Discuss your results with your instructor at this point**

## D. From Parallax, Distance

First of all, we are using Stellarium for a purpose for which it was never intended so the best we can expect is to get the order of magnitude about right.

I promised not much trig, but we do need to use one function. The triangles you drew at the beginning of part B are in reality very, very long and very, very skinny. We can use that to make the math easy. It is an isosceles triangle so if we divide it in half, we get two right triangles.



B is the distance between your viewpoints, called the *baseline*. The parallax angle you just measured is p. If B is the entire baseline, then the base of either of the right triangles is ½ B. Similarly, the opposing angle is ½ p. R is the distance to the star. The definition of the tangent function is “length of the side opposite the angle divided by length of the side adjacent to the angle”. Here, that is:

tan( ½ p) =( ½ B)/R

Now there is a magic relation for very tiny angles, which these are because, you know, long skinny triangles. If an angle is measured in radians and if it is really small, tan(angle) is approximately equal to the angle, and the smaller the angle is, the better the approximation. Try it on your calculator and see. So, to a very good approximation, you can get rid of the trig function.

The ½’s cancel and that gives us

p = B/R or R = B/p for p measured in radians.

1.) Use the red equation to compute the distance to the Moon and the uncertainty in that distance from your measurements. What value should the baseline be? If your calculator does not convert degrees to radians, you can ask Dr. Google “how many radians is <some number of degrees>” or just multiply by π/180 since there are π radians (and 180 degrees) in a half circle. Look up the actual distance. Did you get in the ballpark? What did you use for a baseline?

2.) Radians are inconveniently huge units for the tiny angles associated with stars. Astronomers usually measure them in arcseconds (there are 3600 of these in one degree, if you remember from earlier in this activity). In one radian, then, there are (180 x 3600)/π = 206,265 arcseconds. So astronomers also introduce a new distance unit called the parsec – the distance at which the parallax angle is 1 arcsecond. Finally, the astronomical unit (AU) is the radius of the Earth’s orbit. As it happens, there are 206,265 AUs in a parsec (can you see why?) so that weird number goes away. I’ll leave the math to you, but you get the exact same formula back again but with quantities measured in different units:

R = B/p for R in parsecs, B in AUs, and p in arcseconds

Since the baseline is the diameter of the Earth’s orbit, and that is by definition exactly 2 AU, this gets even simpler:

R = 2/p for R in parsecs and p in arcseconds

So find the distance to Proxima Centauri and the uncertainty in that distance from your measurements. Be sure you have everything in the right units. Look up the actual figure. You’re probably quite a ways off because remember the angles were super tiny so even a little uncertainty is a big deal. But are you at least in the ballpark?

Congratulations! You’ve now earned your math badge for this course! And, next time you watch Star Wars, you also get to laugh knowingly at how stupid Han Solo (and by extension George Lucas) is for using parsecs to measure how much time it takes to make the Kessel run.

**Discuss your results with your instructor at this point**

3.) An important part of doing science is thinking about implicit assumptions that might limit the validity of your results. When we measured the distance to Proxima Centauri, we did position observations six months apart. So one obvious assumption is that the star didn’t move while we were waiting. But stars *do* move. They are orbiting the galaxy just like the Sun. The motion of a star across the sky is called its *proper motion.* Look up the range of values that have been measured for proper motion. Do you think it is a significant source of uncertainty when you do a parallax measurement? Did we make a reasonable approximation by assuming that they don’t move?

4.) As it happens, astronomers in the ancient world were not dumb. In fact, Aristotle used parallax to argue that the Earth does not move, that it is stationary at the center of the cosmos. Aristotle knew that if the Earth moved, the stars should show a parallax, so he looked for it and was unable to measure one. There are two possible explanations for this. What are they and why would Aristotle choose one over the other?

**Discuss your results with your instructor at this point**

**When you finish this activity, please complete the peer assessment for your group on D2L**

1. Even so, the angle is still going to be tiny. Even though parallax was understood in ancient times, technology was not up to the task of actually measuring it until Friedrich Bessel did it in 1838. [↑](#footnote-ref-1)