4. COSMIC DISTANCE LADDER I: PARALLAX

EQUIPMENT

Protractor with attached string
Tape measure
Computer with internet connection

GOALS

In this lab, you will learn:

1. How to use parallax to measure distances to objects on Earth

2. How to use parallax and Earth's diameter to measure distances to objects within our solar system

3. How to use parallax measurements of objects within our solar system to measure the astronomical unit (AU)

4. How to use parallax and the AU to measure distances to nearby stars

1. BACKGROUND

A. THE COSMIC DISTANCE LADDER

Distance is one of the most difficult things to measure in astronomy. You cannot see distance: You never know if you are looking at a low-luminosity star nearby (A) or a high-luminosity star far away (B):
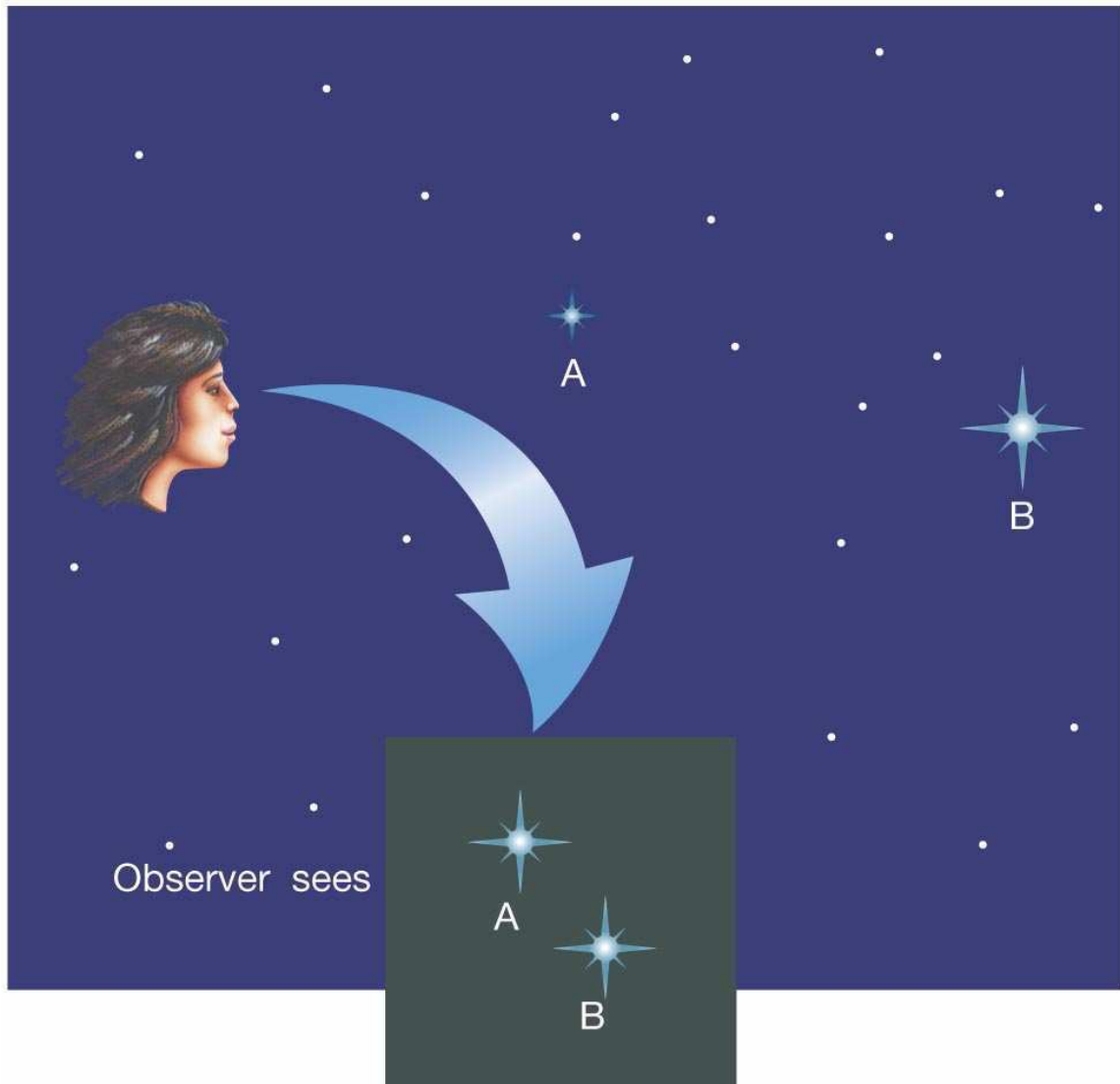
In both cases, the star can appear to be equally bright.

To deal with this, astronomers have developed a hierarchy of techniques for measuring greater and greater distances:
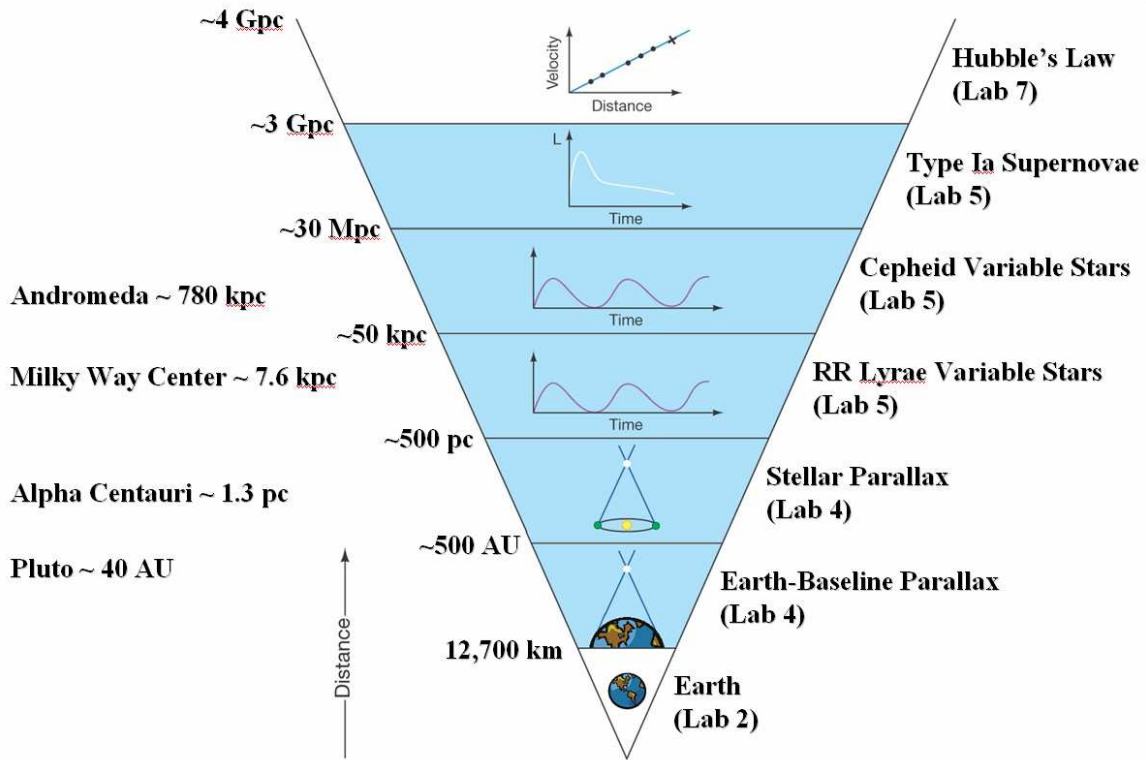
In Lab 2, you measured Earth's diameter in kilometers. This is the base of the cosmic distance ladder.

In this lab, you will use Earth's diameter in kilometers and a technique called **parallax** to measure distances to two solar-system objects: an asteroid and the planet Venus.

You will then use your measurement of the distance to Venus to determine how many kilometers are in one astronomical unit (AU). One AU is the average distance between Earth and the sun.

Finally, you will use your measurement of the AU in kilometers and parallax to measure the distance to the closest star system to the sun: Alpha Centauri.

With current technology, parallax can only be used to measure distances out to about 500 parsecs, which is about 1.5×10^{16} kilometers. This might seem like a great distance, but it is only about 7% of the way to the center of our Milky Way galaxy. In Labs 5 and 7, you will learn techniques that can be used to measure distances across the entire Milky Way galaxy and to other galaxies, both nearby and far away.

B. PARALLAX

Hold a pencil vertically in front of and close to your nose. Focus on distant objects or a background wall. Close one eye and then open it while closing the other. Notice how much your pencil appears to shift with respect to the distant objects. This is called **parallax: the apparent shift of a foreground object with respect to background objects due only to a change in the observer's position.**

Now, hold your pencil at arms length and repeat this exercise. Is the angular shift smaller or larger?

The closer the foreground object, the larger the angular shift. The farther away the foreground object, the smaller the angular shift:


4
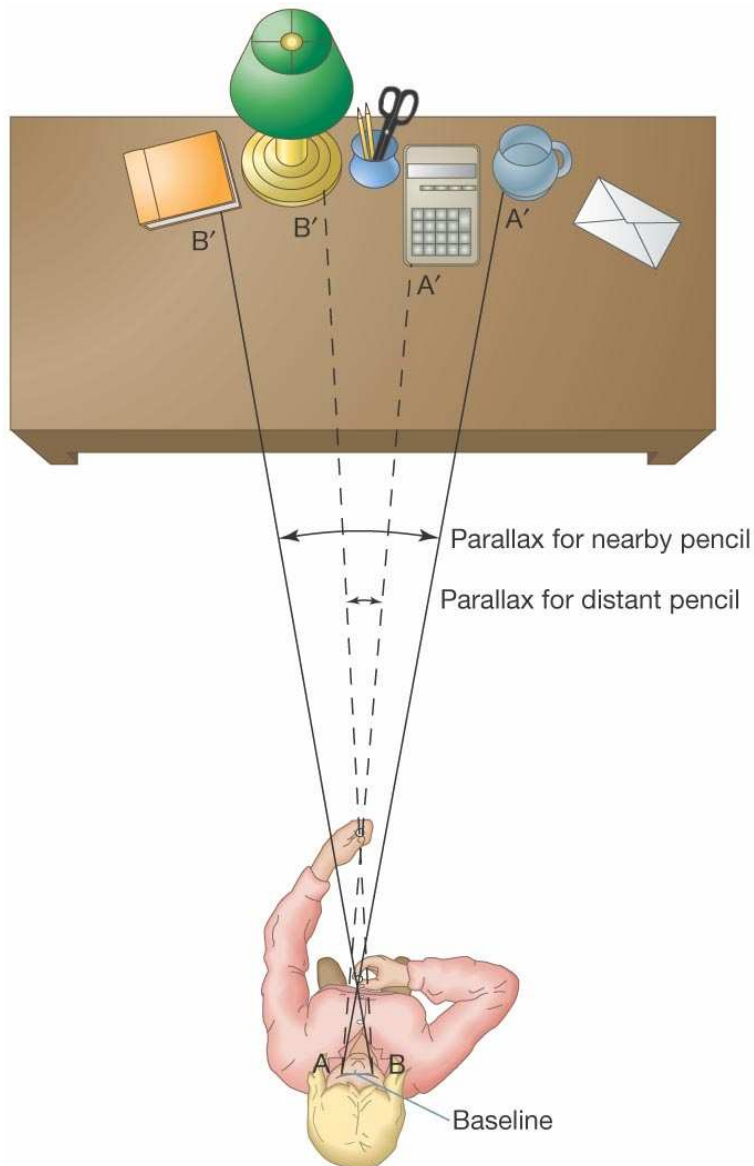
The distance between the two observing positions is called the **baseline**. In the above exercise, the baseline is the distance between your eyes.

Astronomically, two baselines are commonly used:

1. Earth-Baseline Parallax: The two observing positions are different positions on Earth, in which case the baseline is a fraction of Earth's diameter (which you measured in Lab 2):

(a)

B'   A'

Object in space

Parallax

A   B

Earth

(b)

As seen from A   As seen from B

5
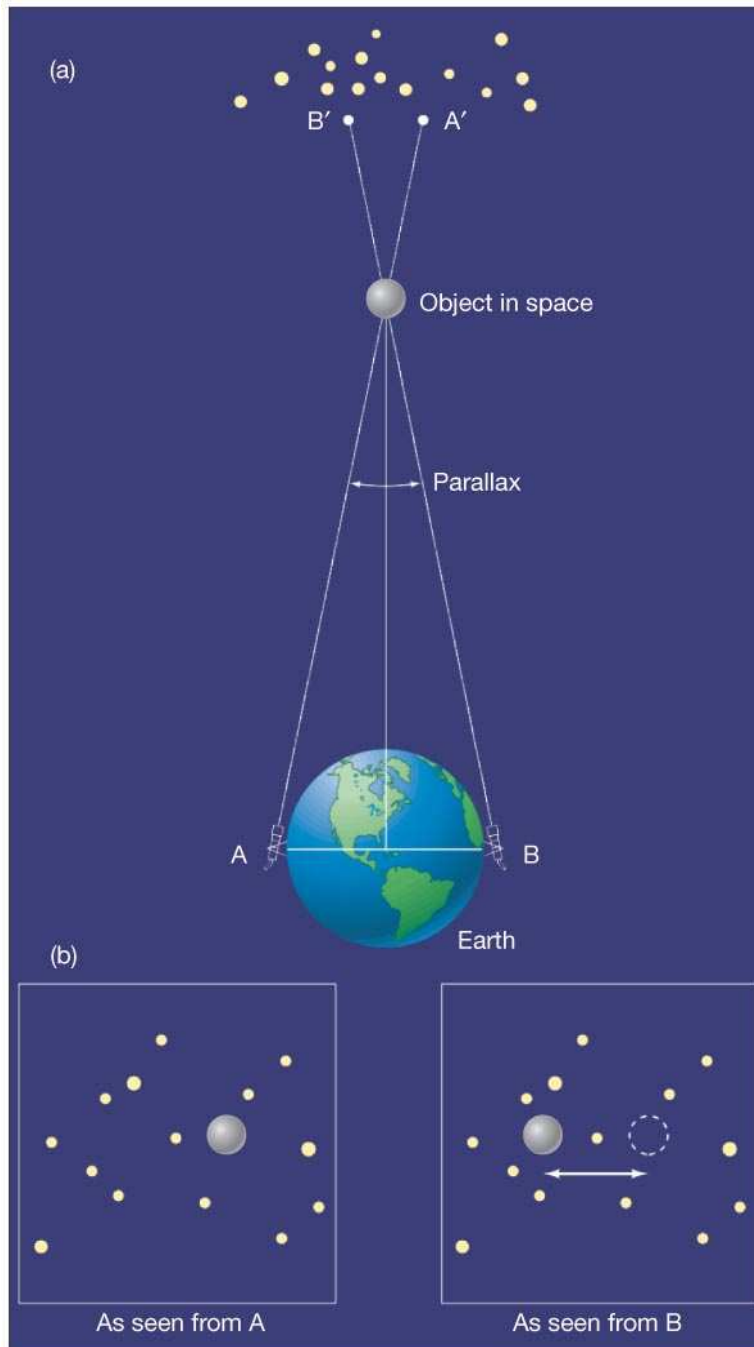
2. Stellar Parallax: The two observing positions are on opposite sides of Earth's orbit around the sun, in which case the baseline is two AU (which you will measure in section D of the procedure of this lab):
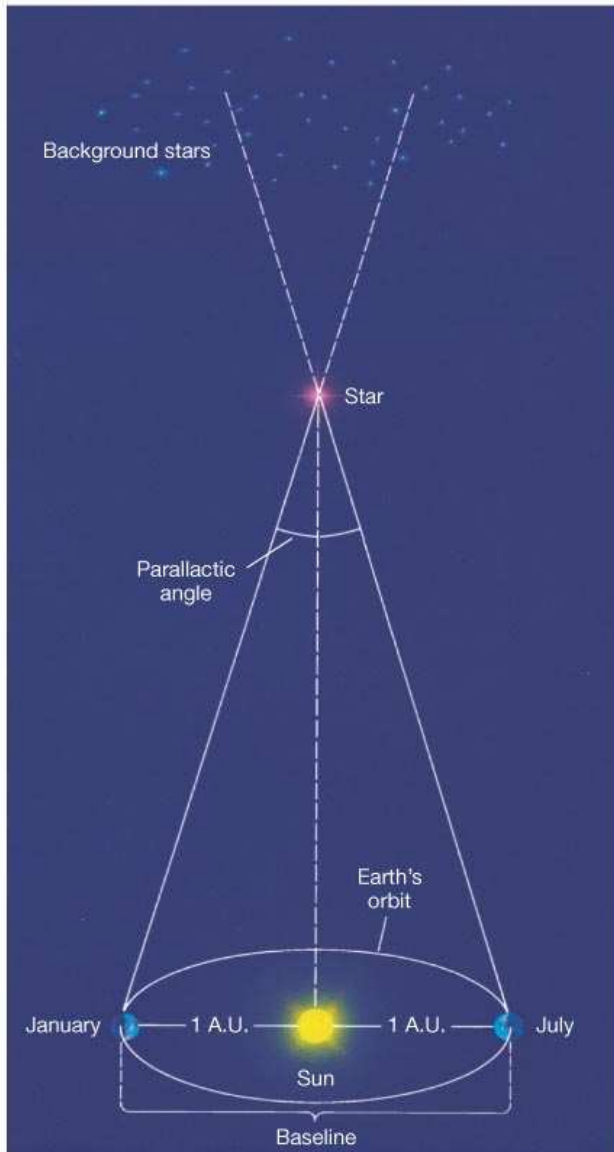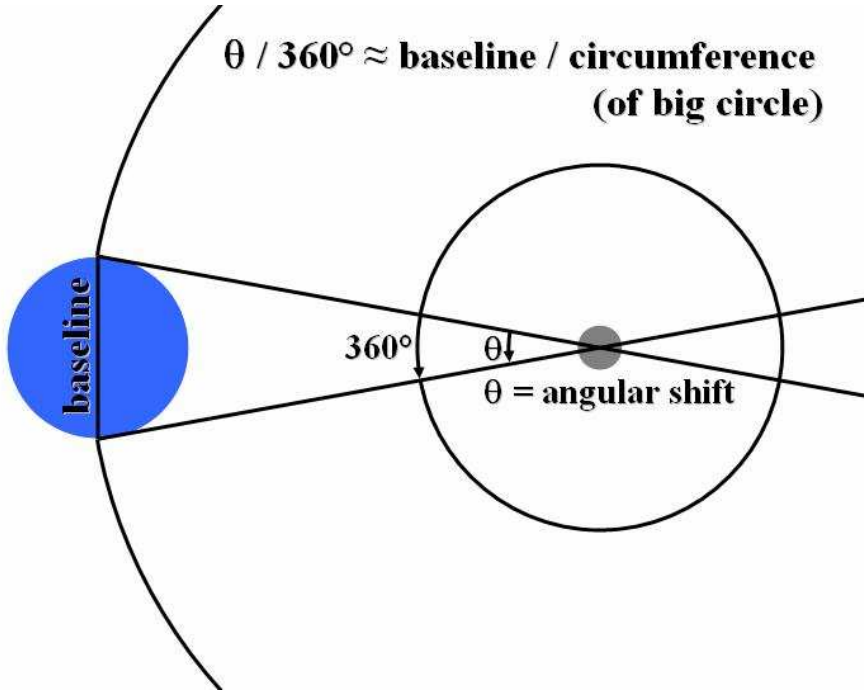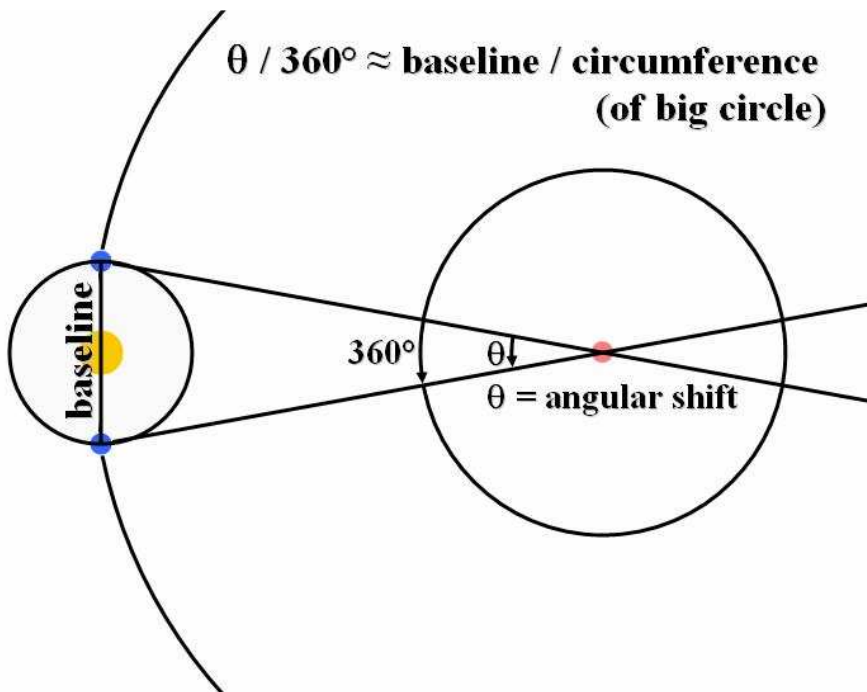

As seen in January   As seen in July

In either case, the relationship between the baseline between the two observing positions, the angular shift of the foreground object due to parallax, and the distance to the foreground object is the same:

1. **Earth-Baseline Parallax:**

θ / 360° ≈ baseline / circumference (of big circle)

360° $\theta\downarrow$
θ = angular shift

baseline

2. **Stellar Parallax:**

θ / 360° ≈ baseline / circumference (of big circle)

360° $\theta\downarrow$
θ = angular shift

baseline

The baseline as a fraction of the circumference of the big circle is the same as the angular shift as a fraction of 360°:

baseline / circumference = θ / 360°

Since circumference = 2π times radius and the radius of the big circle is the distance to the foreground object:

baseline / ($2\pi \times$ distance) = θ / 360°

Solving for the distance to the foreground object yields:

distance = (baseline / 2π) × (360° / θ)

Note: Remember to convert θ to degrees before using this equation!

Hence, by (1) knowing the baseline between two observing points, and (2) measuring the angular shift of a foreground object due to parallax, you can (3) measure the distance to the foreground object.

Under ideal circumstances, Earth-baseline parallax can be used to measure distances to objects out to about 500 AU, beyond which the angular shift is too small to be measured accurately given current technology.

However, larger baselines result in larger, and consequently easier to measure, angular shifts: Stellar parallax can be used to measure distances to objects out to about 500 pc, which is about 10^8 AU.

To measure distances to objects beyond 500 pc, astronomers employ standard-candle techniques, which is the subject of Lab 5.

1. PROCEDURE

A. DISTANCES TO OBJECTS ON EARTH

We will begin by using parallax to measure distances to two objects here on Earth.

On-campus students will stand behind the south wall of the Chapman Observing Deck and measure distances to two objects in front of them: (1) a smokestack on the roof of Morehead Laboratory (not Morehead Planetarium or Morehead Observatory), and (2) the campus water tower:
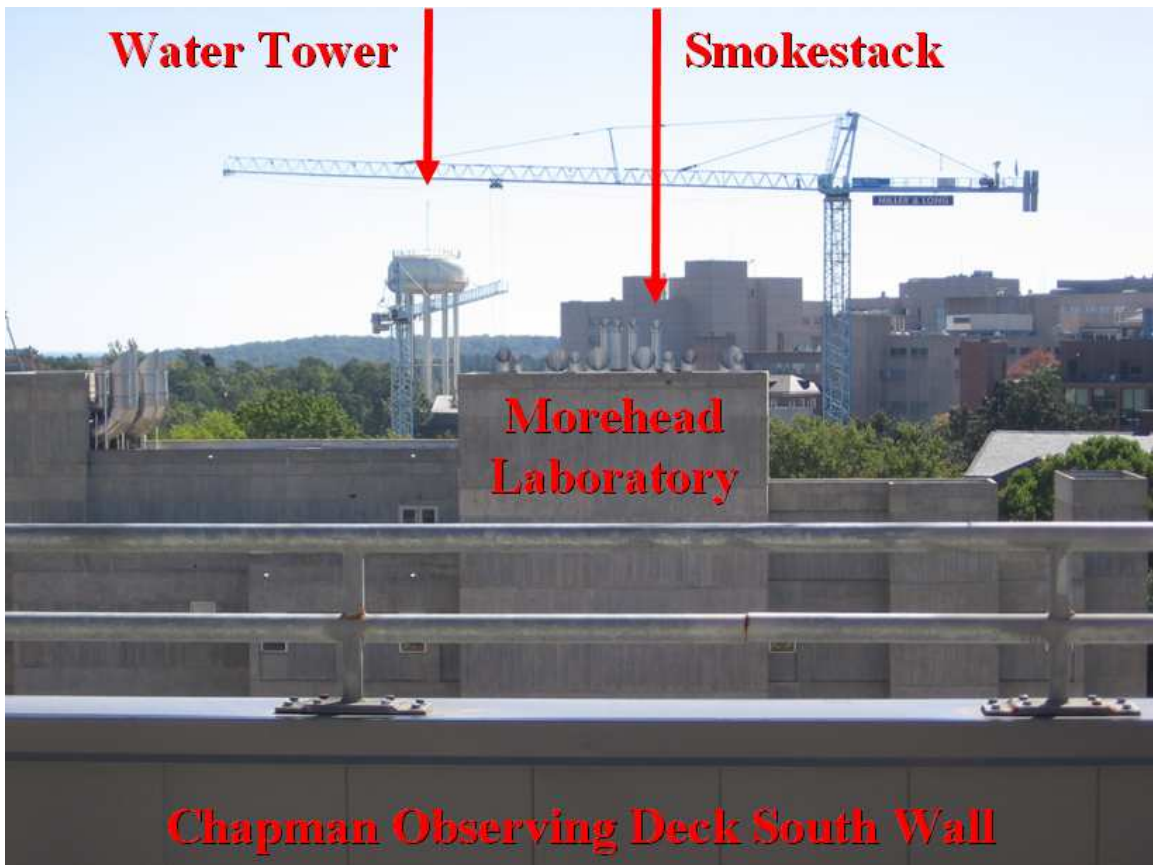
Note: Online students will need to find a wall, or fence, or similar structure behind which they can stand and over which they can identify two objects to measure distances to.

First, stand on the far left side of the wall. Place your protractor flush against the back of the wall and squat down such that your eyes are right behind where the string attaches to the protractor. Move the string such that it points to the smokestack:

Without moving the string, stand up and read the angle off of the protractor to the nearest 0.1 degrees:

first angle: _____

Mark the position of your protractor on the wall (e.g., with a pebble) and move to the far right side of the wall. Repeat your measurement:

second angle: _____

The positive value of the difference between these two angles is the angular shift due to parallax:

angular shift = | first angle – second angle |

angular shift = _____

Next, use the tape measure to measure the baseline between your two observing positions in feet:

baseline = _____

Note: The tape measure will probably not be long enough, in which case measure one part at a time and add the measurements together.

Calculate the distance to the smokestack using parallax:

distance = (baseline / 2π) × (360° / θ)

distance = _____

The true distance to the smokestack is 360 feet. Calculate your percent error:

percent error = _____

Note: To calculate percent errors, online students will need to measure the true distance to each of their objects with the tape measure. Consequently, select objects that are not unreasonably far away (but certainly farther away than the length of your baseline).

Repeat this exercise for the water tower:

first angle: _____

second angle: _____

angular shift = _____

baseline = _____

distance = _____

The true distance to the water tower is 2800 feet. Calculate your percent error:

percent error = _____

In your lab report, discuss sources of error. Which of your measurements was less accurate? Why? At what point is parallax not an accurate technique for measuring distance? What are two ways that you could more accurately measure the distance to an object using parallax?

B. OBSERVE AN ASTEROID WITH SKYNET

First, we are going to try to observe an asteroid with Skynet telescopes in different hemispheres, to measure its distance with parallax.

Since asteroids (and planets) move across the sky quickly, the two telescopes will need to image the asteroid *simultaneously*. That way, any difference in the asteroid's position between the images will be due to parallax, instead of due to the asteroid moving between when the two images were taken.

This is a very challenging observation to make. First of all, different telescopes will take different amounts of time to slew into position. Consequently, we will shoot a rapid-fire sequence of images from both telescopes. Both telescopes might not start their sequences at the same time, but as long a one image in the first telescope's sequence overlaps in time with one image in the second telescope's sequence, we will be good to go.

This observation is also challenging to make because although the PROMPT telescopes belong to UNC-Chapel Hill, most of Skynet's northern hemisphere telescopes do not. Your priority level is not high enough to override them, but for this week only we will give your instructor a priority level that is high enough to do this. Consequently, we will request only one set of observations per section.

Your instructor will select an asteroid that is observable to both PROMPT and the Skynet telescopes in North America for at least ten minutes each night, this time of year. S/he will then request (1) 15 40-second, open-filter exposures on all available PROMPT telescopes, and (2) 15 40-second, open-filter exposures on all available Skynet telescopes in North America. Finally, for both observations, s/he will set "Don't start before (UTC):" to a time that the asteroid is observable to all of these telescopes:
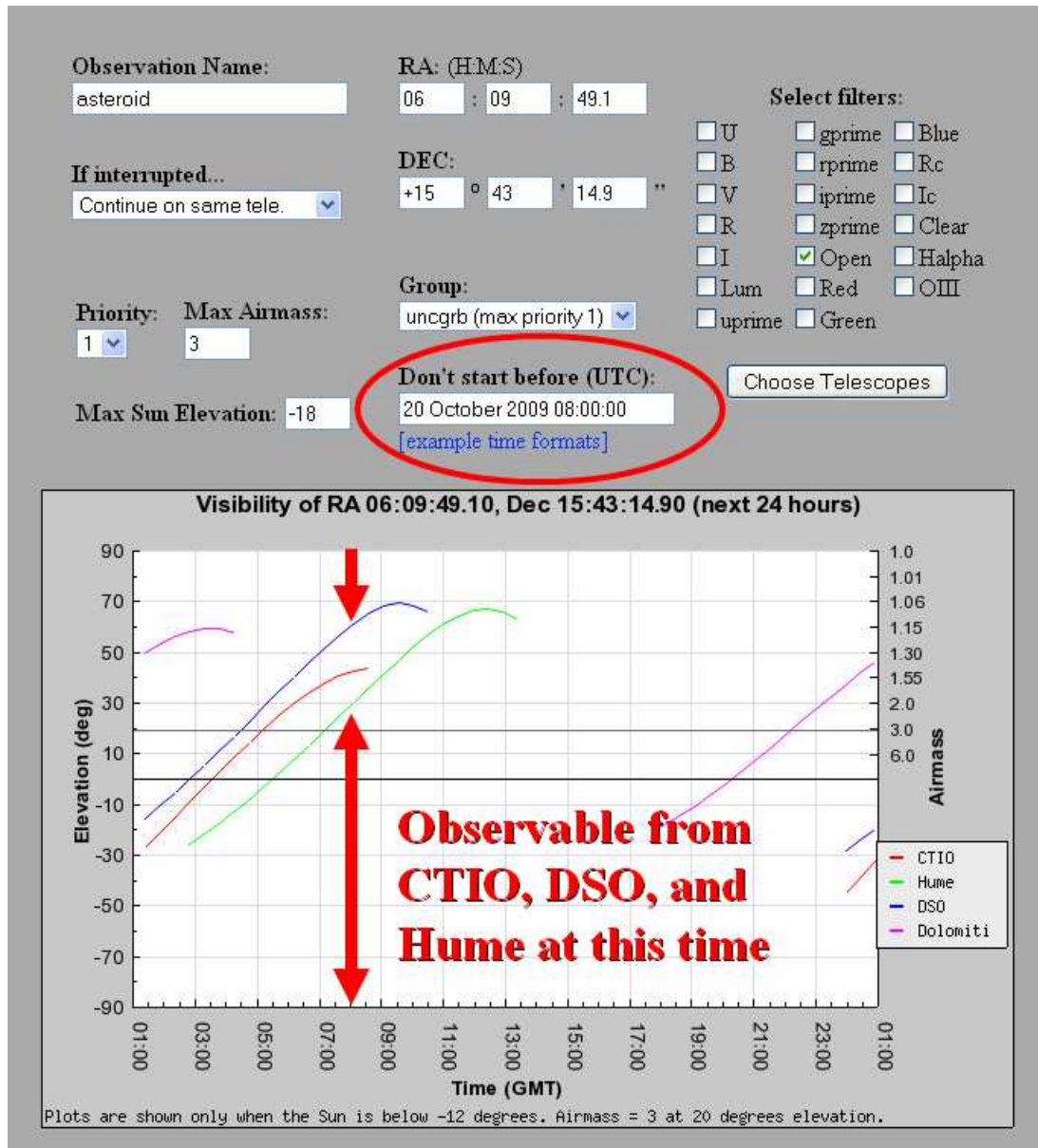
If both observations do not go through on the first night (e.g., if a gamma-ray burst goes off, or if all of the telescopes in one hemisphere or the other are clouded out or offline) you instructor will re-request the observations each night until both go through.

You will be able to access these images once they are completed from your instructor's folder under "Sample Images", "Astro 101 Lab", "Lab 4 – Parallax".

C. DISTANCE TO AN ASTEROID

First, use Afterglow to identify which object is the asteroid:

1. Identify which of the two telescopes produced better images.

2. Select and align all of the images from this telescope. For "Alignment Method", select "One Star Manual". For "Cropping Method", select "Overlap Only". Select "Centroid Sources" and "Stellar Method (PSF)". In your first image, identify a bright, but not saturated, star that is not on the edge of the image. Align to this star in each of the images.

3. Turn your selected and aligned images into a movie. The asteroid will be the moving object, unless you accidentally aligned to the asteroid, in which case everything else in the image will be moving. Download your movie and include it in your lab report.

In the following tutorial, you will learn how to select and align images that were taken by **different** telescopes:

http://skynet.unc.edu/ASTR101L/videos/align2/

In the following tutorial, you will learn (1) how to overlay two images that have already been aligned and (2) how to measure the angular shift of a relatively nearby object in the images due to parallax:

http://skynet.unc.edu/ASTR101L/videos/overlay/

Next, use Afterglow (1) to select, align, and overlay two images of the asteroid that were taken nearly simultaneously by Skynet telescopes in different hemispheres and (2) to measure the angular shift of the asteroid due to parallax:

1.   Your instructor will help you to identify two images that were taken nearly simultaneously.

2. Select and align these images. For "Alignment Method", select "Two Star Manual". For "Cropping Method", select "Overlap Only". Select "Centroid Sources" and "Stellar Method (PSF)". For alignment, use two stars (1) that are bright, but not saturated, (2) that are **not** close to one another in the images, and (3) that are in both images. Do **not** use the asteroid!

3. Overlay your two aligned images and measure the angular shift of the asteroid due to parallax, to the nearest 0.1 arcseconds:

angular shift = _____

The baseline between your two observing positions as a fraction of Earth's diameter is:

Baseline Between CTIO And	Fraction of Earth's Diameter
Dark Sky Observatory, NC	0.554
Hampden-Sydney College Observatory, VA	
Hume Observatory, CA	
Morehead Observatory, NC	0.554
Pisgah Astronomical Research Institute, NC	
Coyote Rim Ranch, CO	

You measured Earth's diameter in Lab 2:

measured diameter from Lab 2: _____

true diameter: _____

Calculate the baseline between the two observing positions using Earth's true diameter:

baseline = fraction of diameter × true diameter

baseline = _____

Calculate the distance to the asteroid using parallax:

distance = (baseline / 2π) × (360° / θ)

Note: Remember to convert θ to degrees before using this equation!

distance = _____

Main-belt asteroids are typically between 1.6×10^8 km and 6.4×10^8 km from Earth. Given this, is your measurement reasonable? In your lab report, discuss sources of error.

D. DISTANCE TO VENUS AND THE SIZE OF THE AU

To measure distances to nearby stars with stellar parallax, where the baseline is 2 AU, we must first measure how many kilometers are in one AU. Historically, this was done by measuring the distance to Venus in kilometers using Earth-baseline parallax when Venus was a known number of AU away.

For example, Venus is observed to orbit the sun every $P = 0.62$ years.

Kepler's Third Law states that for objects orbiting the sun:
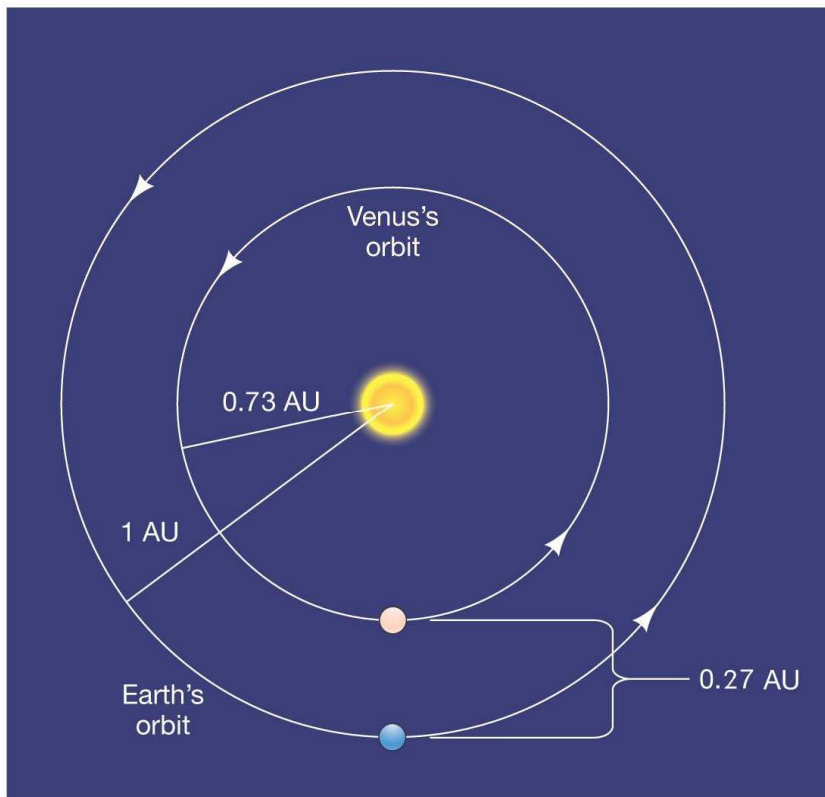
$$(P / 1 \text{ year})^2 = (a / 1 \text{ AU})^3$$

where a is the semi-major axis of Venus's orbit. Solving for a yields:

$$a = (P / 1 \text{ year})^{2/3} \text{ AU}$$

Hence,

$$a = (0.62)^{2/3} = 0.73 \text{ AU}$$

Earth's semi-major axis is 1 AU, by definition. Consequently, when Venus is at closest approach to Earth, it is 1 AU – 0.73 AU = 0.27 AU away:

However, we could not wait until Venus was at closest approach to Earth to image it. Besides, it is very challenging to image Venus at closest approach to Earth because it is very close to the sun in the sky and its phase is very close to new.
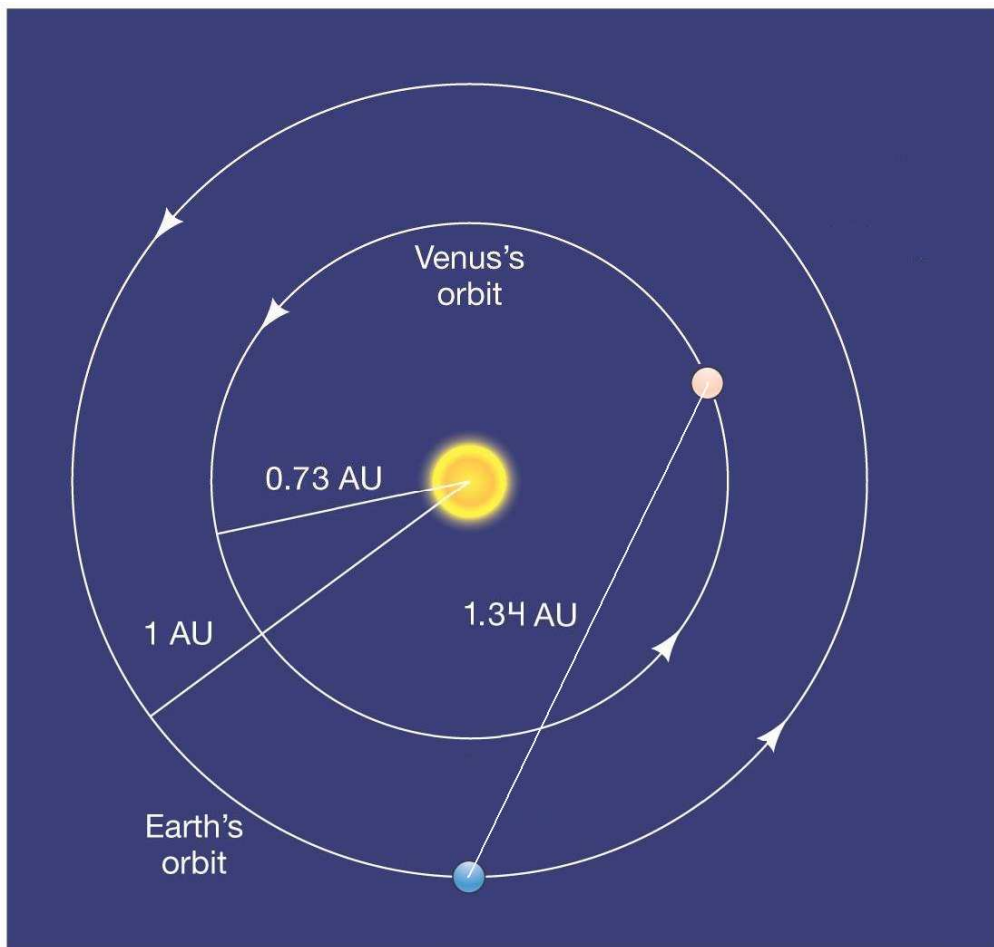
Instead, we imaged Venus when its phase was a waxing gibbous:
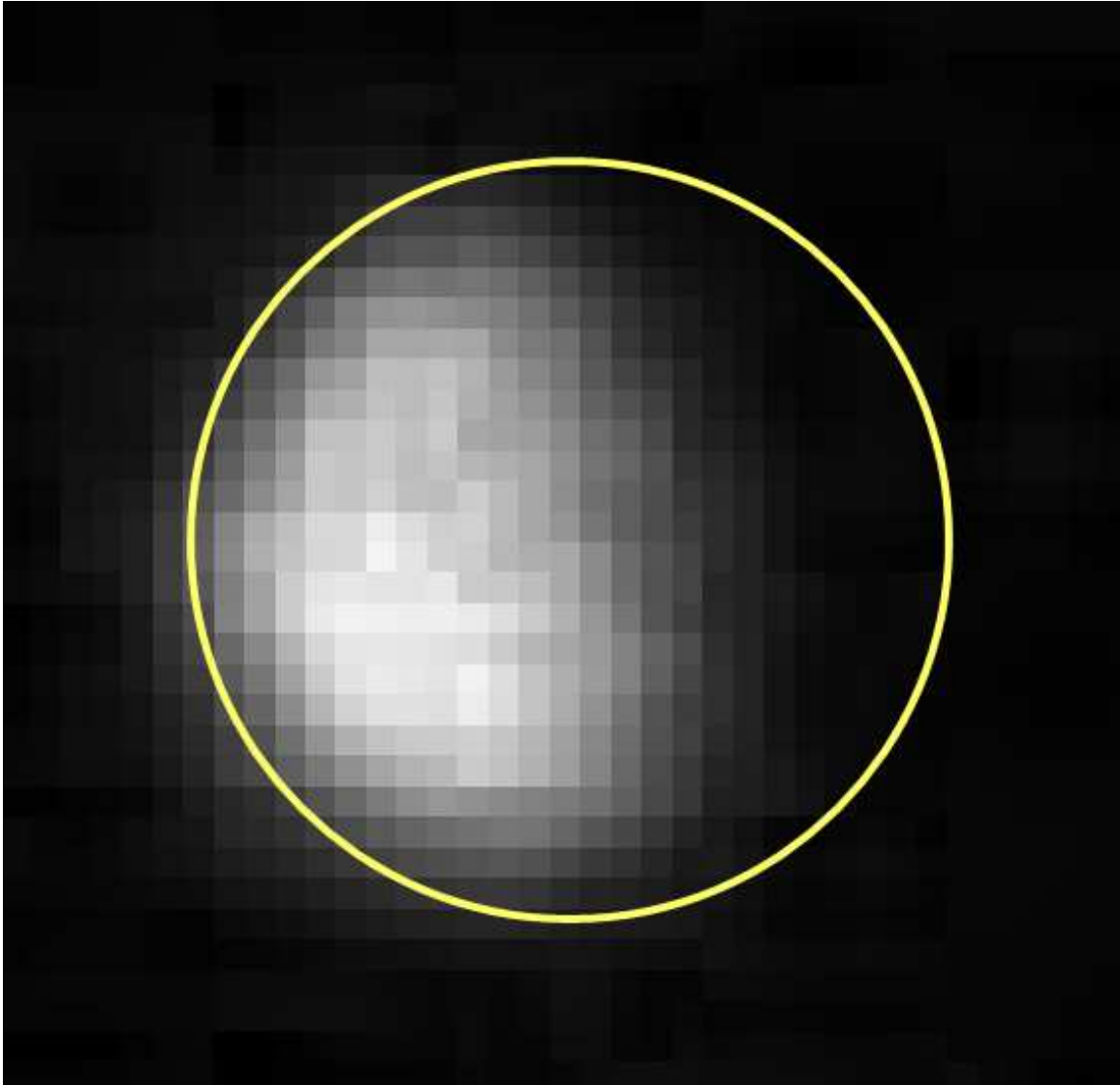
Venus can only be a waxing gibbous of this phase when it is in a particular location in its orbit around the sun relative to Earth:
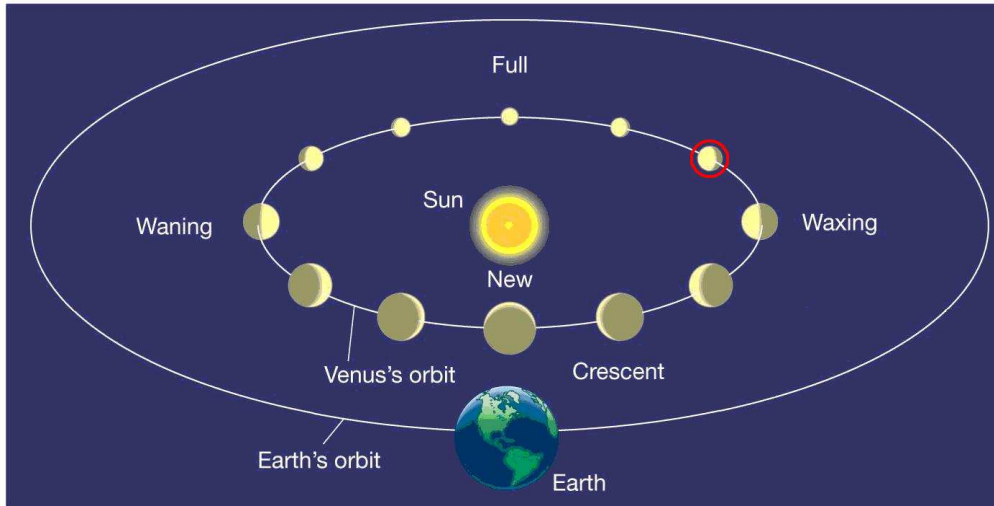
This particular location is 1.34 AU from Earth:

We took simultaneous images of Venus from CTIO in Chile and from Morehead Observatory in North Carolina. Since Venus is so bright, we had to use a special filter that blocks most of the light in the center of the image but very little light elsewhere in the image. This way, we could image for long enough to see stars in the images, which are needed to overlay the two images, without saturating Venus, which is needed to measure its angular shift due to parallax:
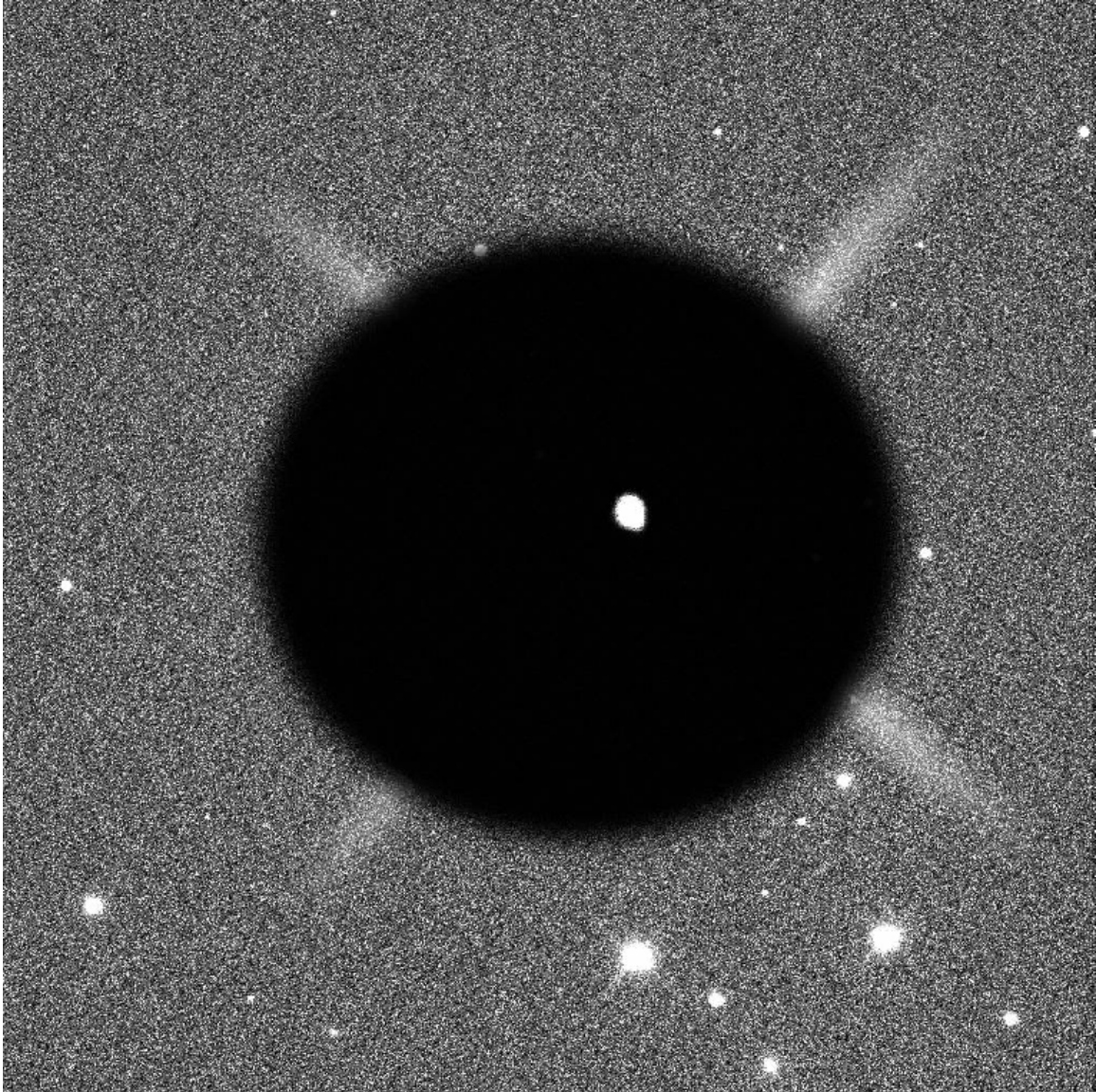
These filters are no longer on the telescopes, so we will use the images that we took previously. You can access them under "Sample Images", "Astro 101 lab", "Lab 4 – Parallax", "Venus".

Use Afterglow to overlay these images and measure the angular shift of Venus between the images due to parallax, to the nearest 0.1 arcseconds:

angular shift = _____

Calculate the baseline between the two observing positions using Earth's true diameter:

baseline = fraction of diameter × true diameter

baseline = _____

Calculate the distance to Venus using parallax:

distance = (baseline / 2π) × (360° / θ)

Note: Remember to convert θ to degrees before using this equation!

distance = _____

Now, since:

1.34 AU = distance

1 AU = distance / 1.34

1 AU = _____

The true value is 1.5×10^8 km. Calculate your percent error:

percent error = _____

In your lab report, discuss sources of error.

E. DISTANCE TO ALPHA CENTAURI

Finally, we are going to measure the distance to Alpha Centauri using stellar parallax. Actually, Alpha Centauri consists of two stars – A and B – in close proximity to each other.

Like Venus, Alpha Centauri is sufficiently bright that we had to use one of our special filters to detect other stars without saturating Alpha Centauri:
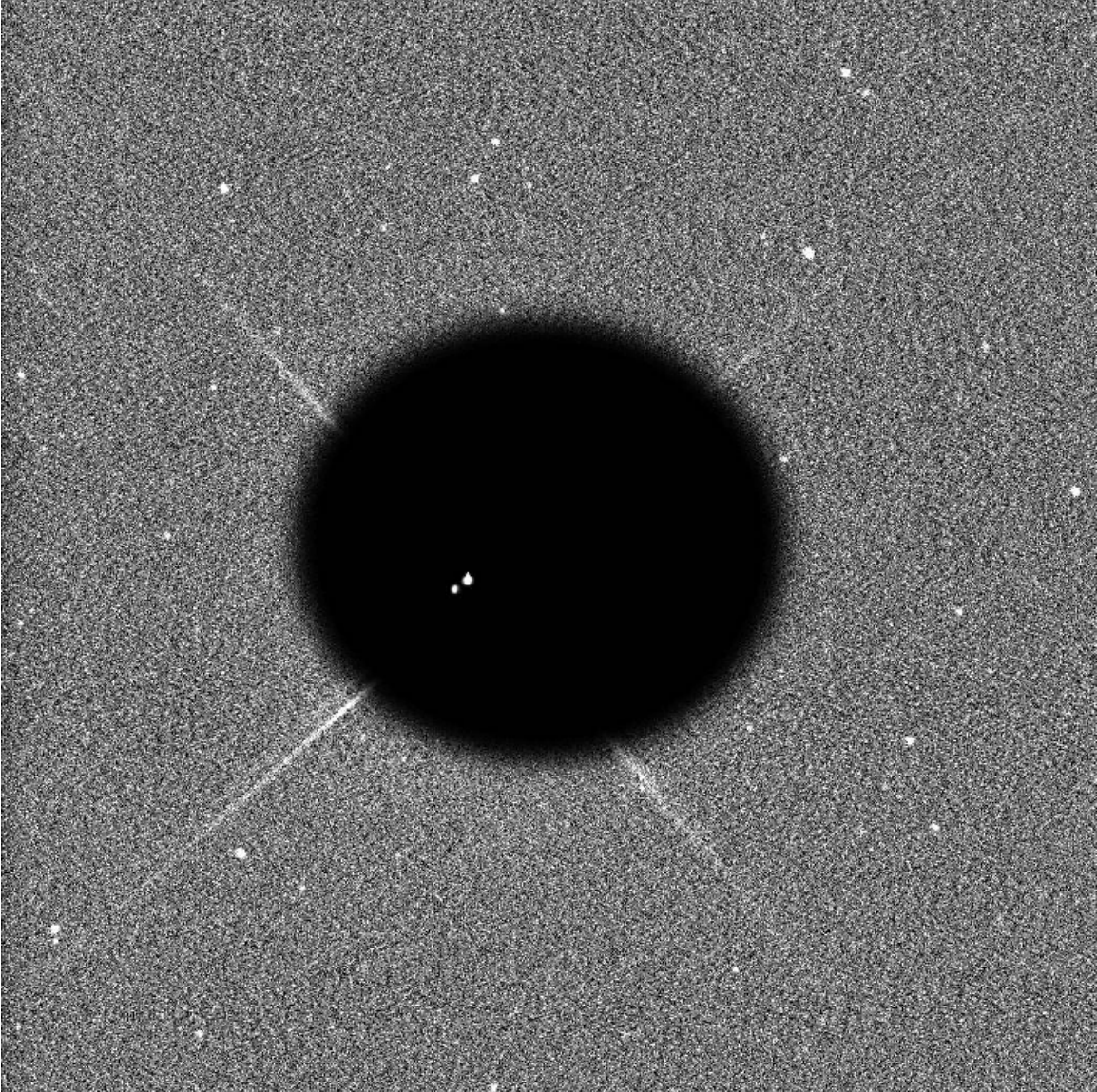
Again, since these filters are no longer on the telescopes we will use images that we took previously. You can access them under "Sample Images", "Astro 101 lab", "Lab 4 – Parallax", "Alpha Centauri".

Use Afterglow to align these images and measure the angular shift of Alpha Centauri between the images due to parallax, to the nearest 0.1 arcseconds:

angular shift = _____

These images were taken six months apart, first when Earth was as far to one side of Alpha Centauri as it can get and again when Earth was as far to the other side of Alpha Centauri as it can get. Consequently, the baseline between the two observing positions is how many AU across?

baseline in AU = _____

First, convert this to kilometers using your measurement of how many kilometers are in an AU:

measured baseline in kilometers = _____

Now convert it to kilometers using the true value:

true baseline in kilometers = _____

Calculate the distance to Alpha Centauri using parallax and the true baseline in kilometers:

distance = (baseline / 2π) $\times$ (360° / θ)

Note: Remember to convert θ to degrees before using this equation!

distance = _____

Google the true value:

true distance = _____

Calculate your percent error:

percent error = _____

In your lab report, discuss sources of error.