

3. THE GALILEAN REVOLUTION: EARTH'S PLACE IN THE SOLAR SYSTEM

EQUIPMENT

Computer with internet connection

GOALS

In this lab, you will learn:

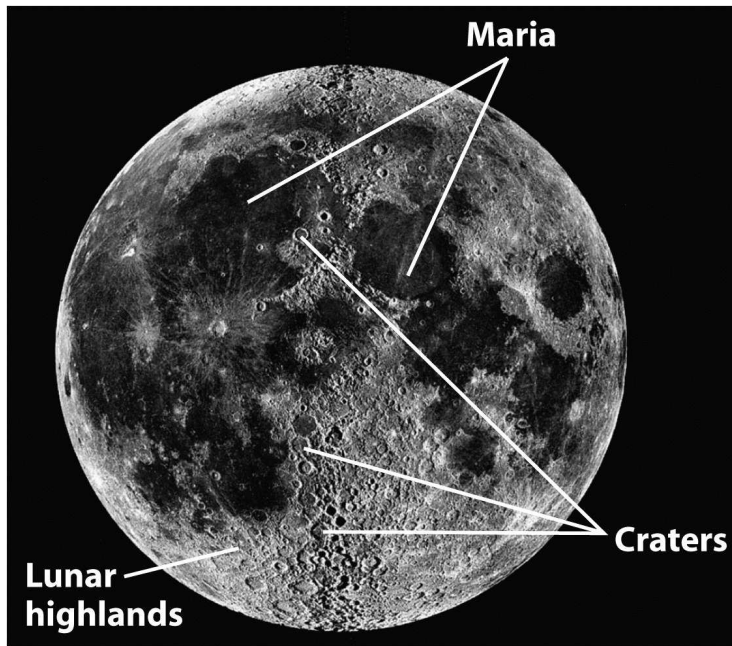
1. How to measure a moon's orbit around a planet
2. How to use this information to measure the mass of the planet
3. How to measure the phase and angular diameter of Venus
4. How to use this information to distinguish between the geocentric and heliocentric models of the universe

BACKGROUND

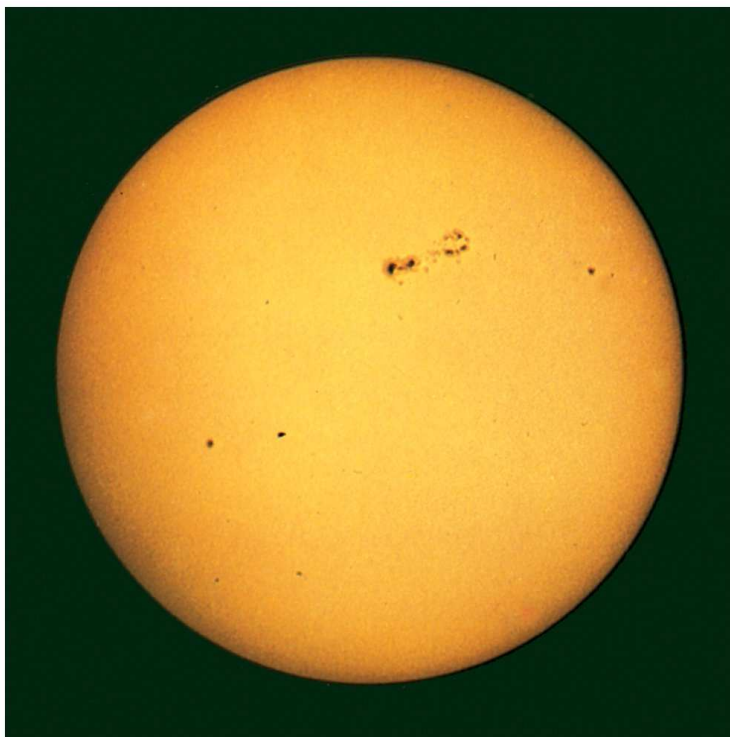
A. THE GALILEAN REVOLUTION

Galileo did not invent the telescope, but he was the first to point it to the heavens. Beginning in 1609, this led to four revolutionary discoveries:

1. He discovered craters and mountains on the moon:

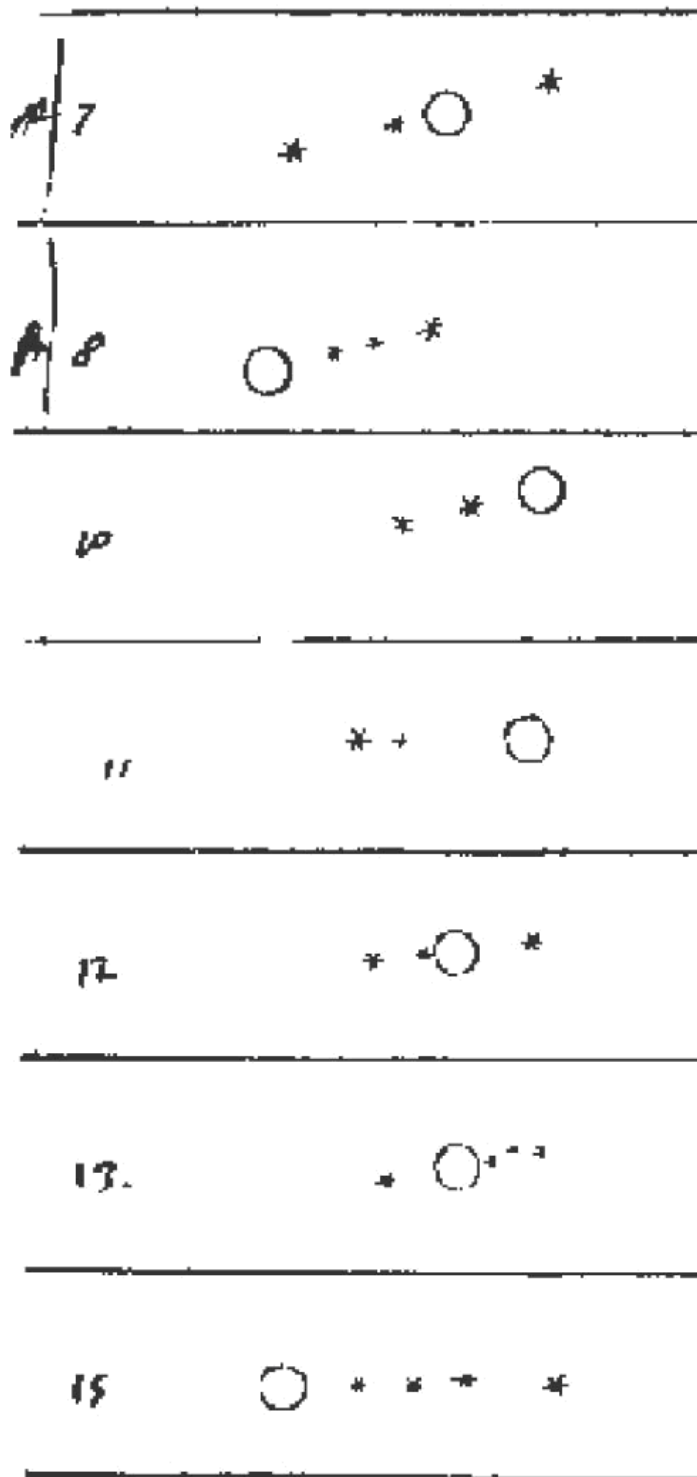


2. He discovered spots on the sun:



Both of these were revolutionary in that the Catholic church had long ago adopted the Aristotelian idea that the moon and sun were “perfect” objects – spherical, perfectly smooth, and in the case of the sun, unblemished.

3. He discovered four moons orbiting Jupiter:



This was revolutionary in that it contradicted the geocentric model of the universe – the idea that Earth is at the center of the universe and everything orbits it. The geocentric model had also been long ago adopted as truth by the Catholic church.

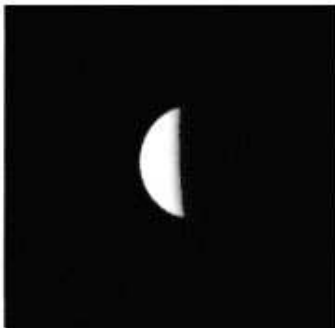
4. He discovered the phases of Venus:



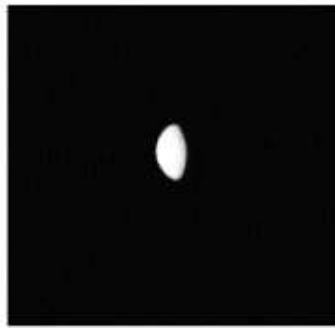
$\alpha = 58''$



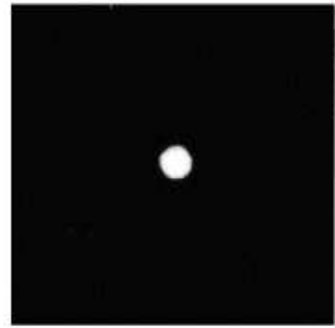
$\alpha = 42''$



$\alpha = 24''$



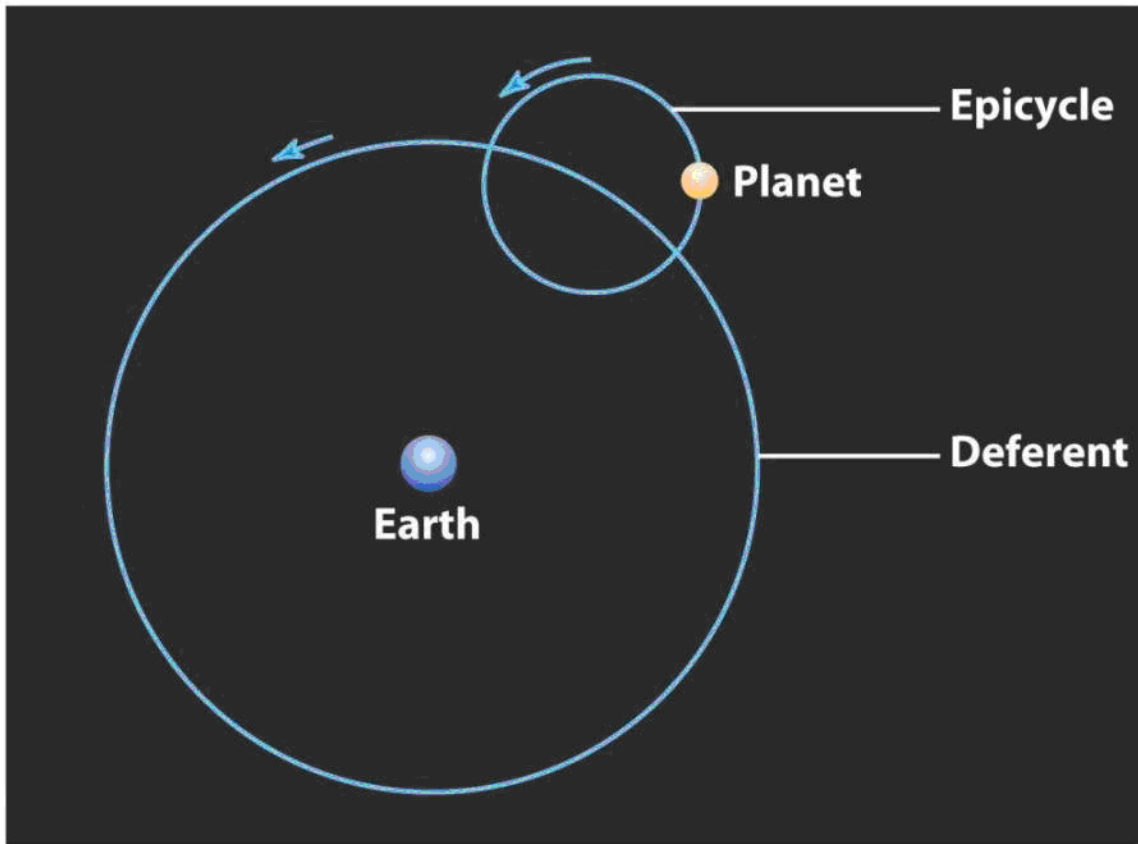
$\alpha = 15''$



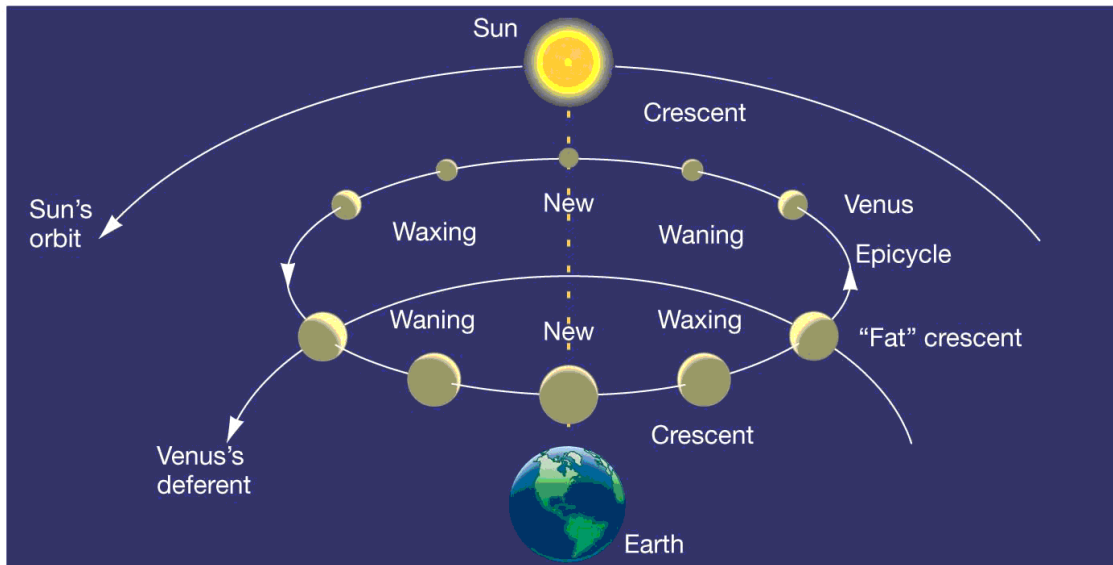
$\alpha = 10''$

Although lesser known than the discovery of Jupiter's moons, the discovery of Venus's phases is more significant, in that it not only contradicted the geocentric model of the universe, it confirmed a prediction of the heliocentric model of the universe – the idea that the sun, not Earth, is at the center.

In Aristotle's (and later Ptolemy's) geocentric model of the universe, Venus rides on a circle called an epicycle and the center of Venus's epicycle rides on a circle called a deferent around Earth:

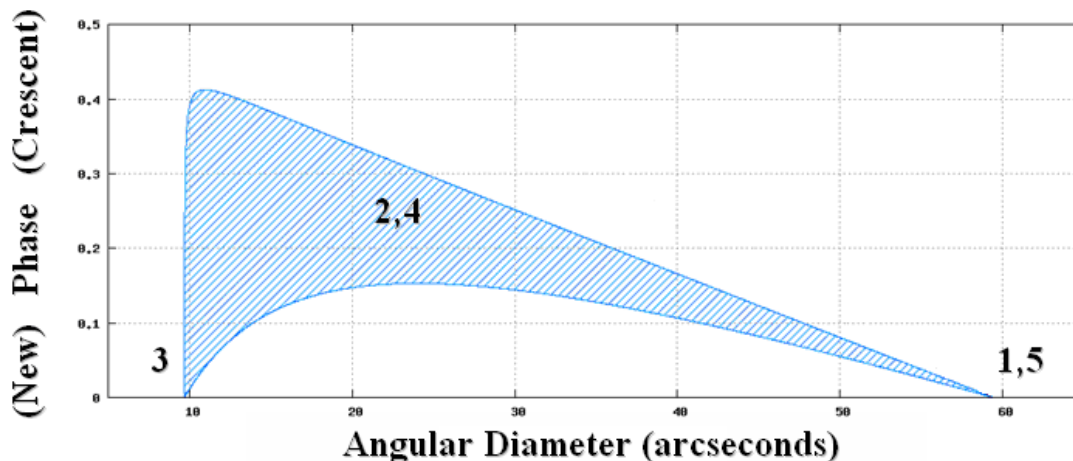


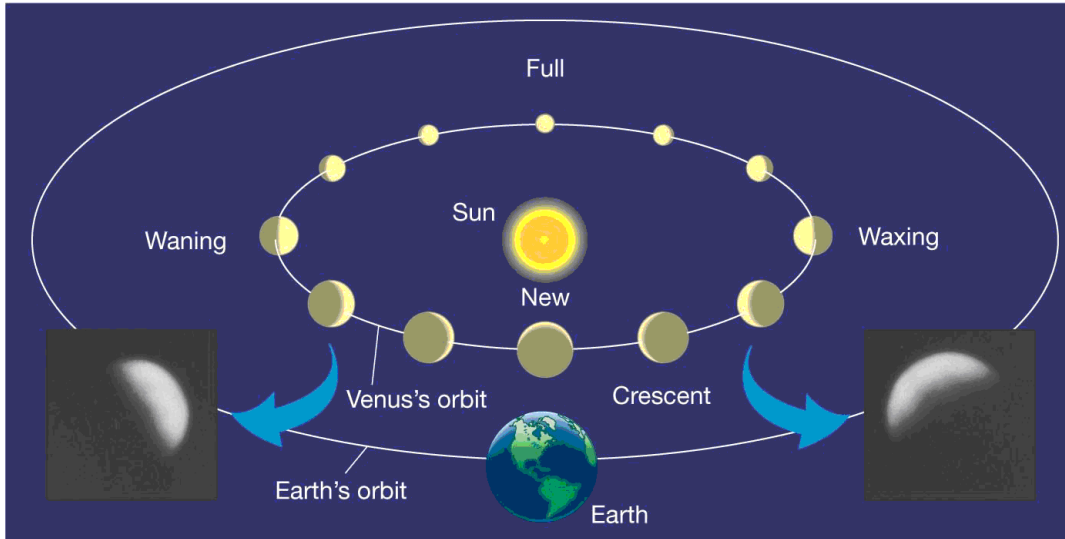
The center of Venus's epicycle is always on a line between Earth and the sun. Consequently, Venus never wanders too far from the sun in the sky, which is what is observed:



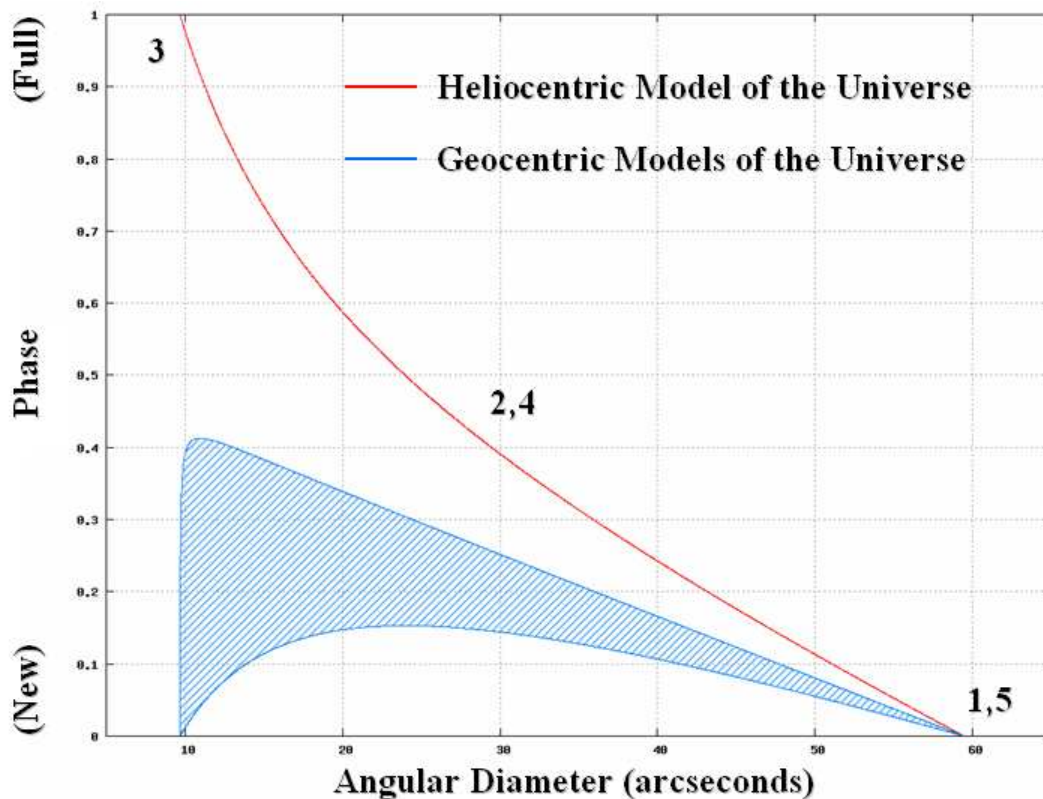
The geocentric model of the universe makes specific predications about Venus's phases: (1) Venus's phase is new or very close to new when it is closest to Earth and consequently appears largest; (2) It transitions to crescent as it recedes from Earth and consequently appears smaller; (3) It transitions to new or very close to new again when it is farthest from Earth and consequently appears smallest; (4) It transitions to crescent again when it is approaching Earth and consequently appears larger; and (5) It transitions to new or very close to new again when it is closest to Earth and consequently appears largest.

These phase and angular diameter transitions correspond to a curve in the following plot. The curve is thick because different versions of the geocentric model of the universe make slightly different predictions:





The heliocentric model of the universe makes very different predications about Venus's phases: (1) Venus's phase is new or very close to new when it is closest to Earth and consequently appears largest; (2) It transitions to crescent and then quarter and then gibbous as it recedes from Earth and consequently appears smaller; (3) It transitions to full or very close to full when it is farthest from Earth and consequently appears smallest; (4) It transitions to gibbous and then quarter and then crescent again when it is approaching Earth and consequently appears larger; and (5) It transitions to new or very close to new again when it is closest to Earth and consequently appears largest:



Here's a video of Venus in the geocentric model of the universe:

<http://www.youtube.com/watch?v=OlnlbZHP-jk>

It plays fast. Play it enough times to see all of the phase and angular diameter transitions.

Here's a video of Venus in the heliocentric model of the universe:

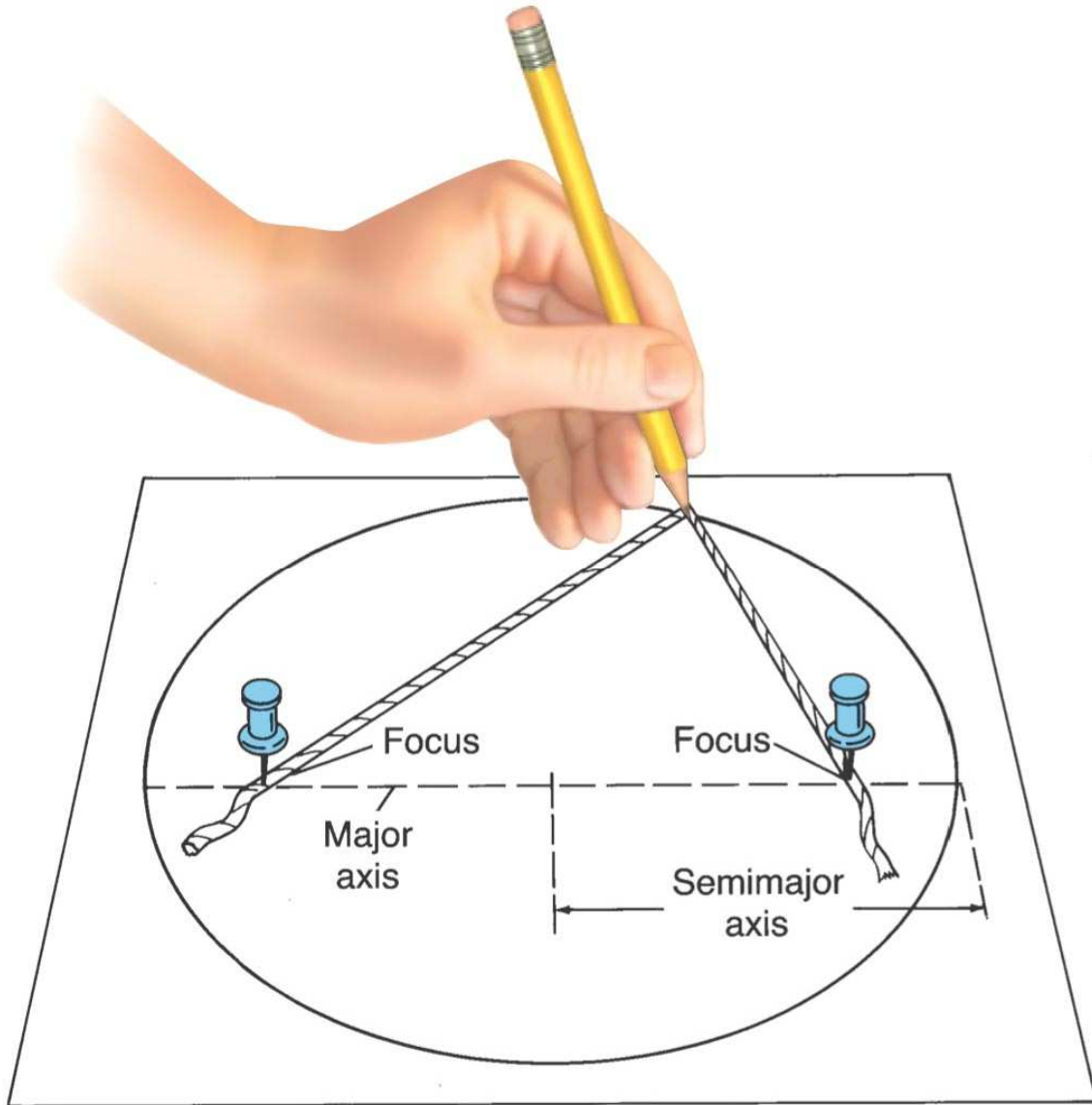
http://www.youtube.com/watch?v=0Z_v7Tag4fg

Again, play it enough times to see all of the phase and angular diameter transitions.

If part C of the procedure, you will measure Venus's phase and angular diameter at different times and then use this information to distinguish between the geocentric and heliocentric models of the universe.

B. ORBITS

Kepler showed that planets orbiting the sun and moons orbiting planets do not travel on circles, but on ellipses, with the central body at one of the two foci:



The long axis of an ellipse is called the **major axis**. Half of the major axis is called the **semi-major axis**, which is usually denoted **a**.

Kepler also showed that the time that it takes for a planet to orbit the sun or for a moon to orbit a planet – the **orbital period**, which is usually denoted **P** – is related to the semi-major axis in the following way:

$$\mathbf{P^2 = constant \times a^3}$$

where the value of the constant depends on the central body: All planets orbiting the sun have the same constant. All moons orbiting Jupiter share a different constant. The moon orbiting Earth has yet another constant.

Newton showed that the value of the constant depends on the mass of the central body:

$$\mathbf{P^2 = (4\pi^2 / M) \times a^3}$$

(This assumes that the mass of the central body is significantly greater than the mass of the orbiting body.)

Now, consider the case of Earth orbiting the sun. Then $P = 1$ year, $M = 1$ solar mass, and $a = 1$ AU (astronomical unit = 1 sun-Earth distance). Hence:

$$\mathbf{(1 \text{ year})^2 = (4\pi^2 / 1 \text{ solar mass}) \times (1 \text{ AU})^3}$$

Dividing this equation into the previous equation yields:

$$\mathbf{(P / 1 \text{ year})^2 = (1 \text{ solar mass} / M) \times (a / 1 \text{ AU})^3}$$

Solving for the mass of the central body yields:

$$\mathbf{M = [(a / 1 \text{ AU})^3 / (P / 1 \text{ year})^2] \text{ solar masses.}}$$

Hence, by measuring the semi-major axis of a moon's orbit around a planet in AU and its orbital period in years, you can measure the mass of the planet in solar masses. In parts A and B of the procedure, you will measure the orbit of a moon around one of the four Jovian planets and then use this information to measure the mass of that planet.

PROCEDURE

A. MONITOR A PLANETARY SYSTEM WITH SKYNET

In the following tutorial, you will learn how to monitor an object over an extended period of time:

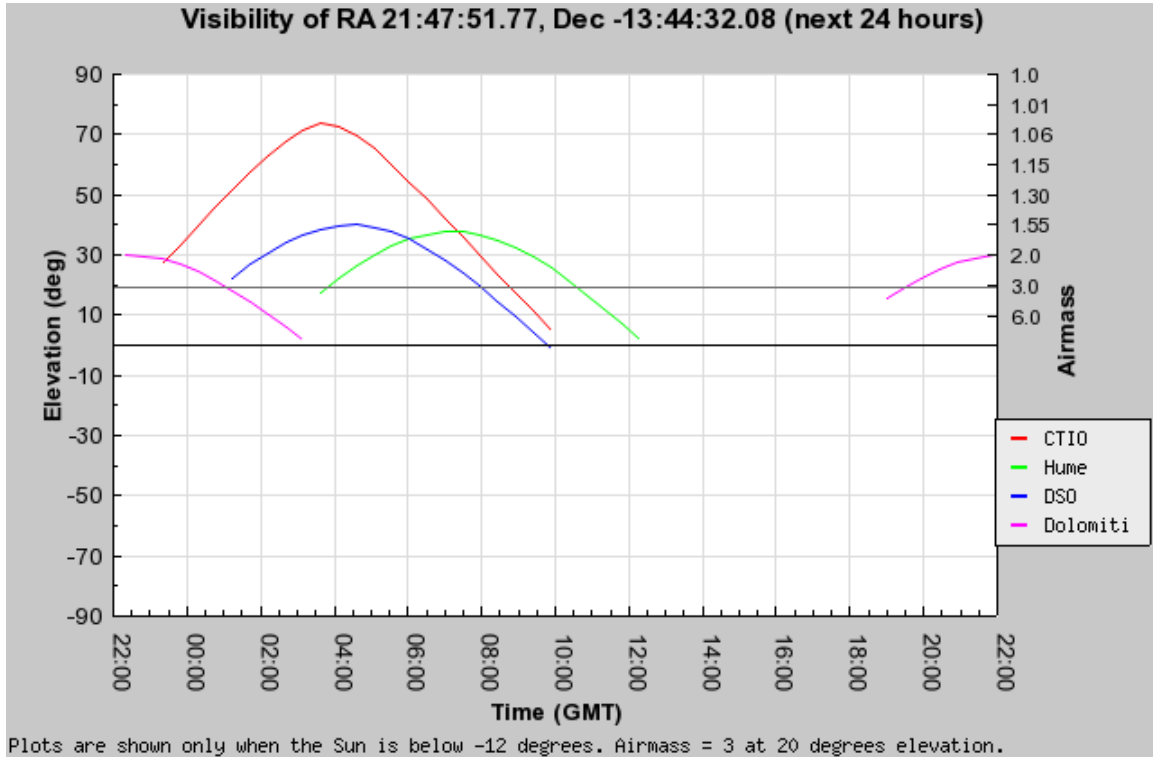
<http://skynet.unc.edu/ASTR101L/videos/monitor/>

Use Skynet to monitor an observable Jovian planetary system every clear night for two weeks. Select Jupiter, Saturn, Uranus, or Neptune. Similar numbers of students should monitor each system.

Remember to change “If interrupted...” to “Continue on next free telescope” just in case the telescope that begins your observations goes offline during the next two weeks.

The screenshot shows the Skynet observation setup interface. The 'Observation Name' field contains 'neptune'. The 'RA: (H.M.S)' field is set to '21 : 47 : 51.8'. The 'DEC' field is set to '-13 ° 44 ' 32.1 ""'. The 'Group' dropdown is set to 'uncch (max priority 2)'. The 'Priority' dropdown is set to '5' and the 'Max Airmass' field is '3'. The 'Max Sun Elevation' field is '-18'. The 'Don't start before (UTC)' field is 'now'. The 'Select filters' section includes checkboxes for U, B, V, R, I, Lum, uprime, gprime, rprime, iprime, zprime, Open (checked), Red, Green, Blue, Rc, Ic, Clear, Halpha, and OIII. A 'Choose Telescopes' button is visible. The 'If interrupted...' dropdown menu is circled in red and set to 'Continue on next free tele.'.

Confirm that the planetary system that you selected is indeed observable from CTIO this time of year:



If it is not, select a different planetary system.

Select as many of PROMPT-1, PROMPT-3, PROMPT-4, and PROMPT-5 as you can, but do not select PROMPT-2 since we take it offline every two weeks.

Select filters and request exposure durations that will allow you to detect as many moons as possible without overly saturating the planet:

System	Filter	Exposure Duration (seconds)*
Jupiter	V	0.03
Saturn	Open	0.03
Uranus	Open	1
Neptune	Open	1

* For PROMPT. Other telescopes might require longer exposures.

Request two exposures (just in case one disappoints) and below this request “Repeat these exposures 14 times with 1 day between groups of exposures”:

Add Exposures
[\[Back\]](#)

Color Band	Num. Exps	Duration (sec)
Open	<input type="text" value="2"/>	<input type="text" value="1"/>

Multiple durations may be specified as a comma-separated list (e.g. 10,20,40)

Repeat these exposures time(s) with days between groups of exposures.

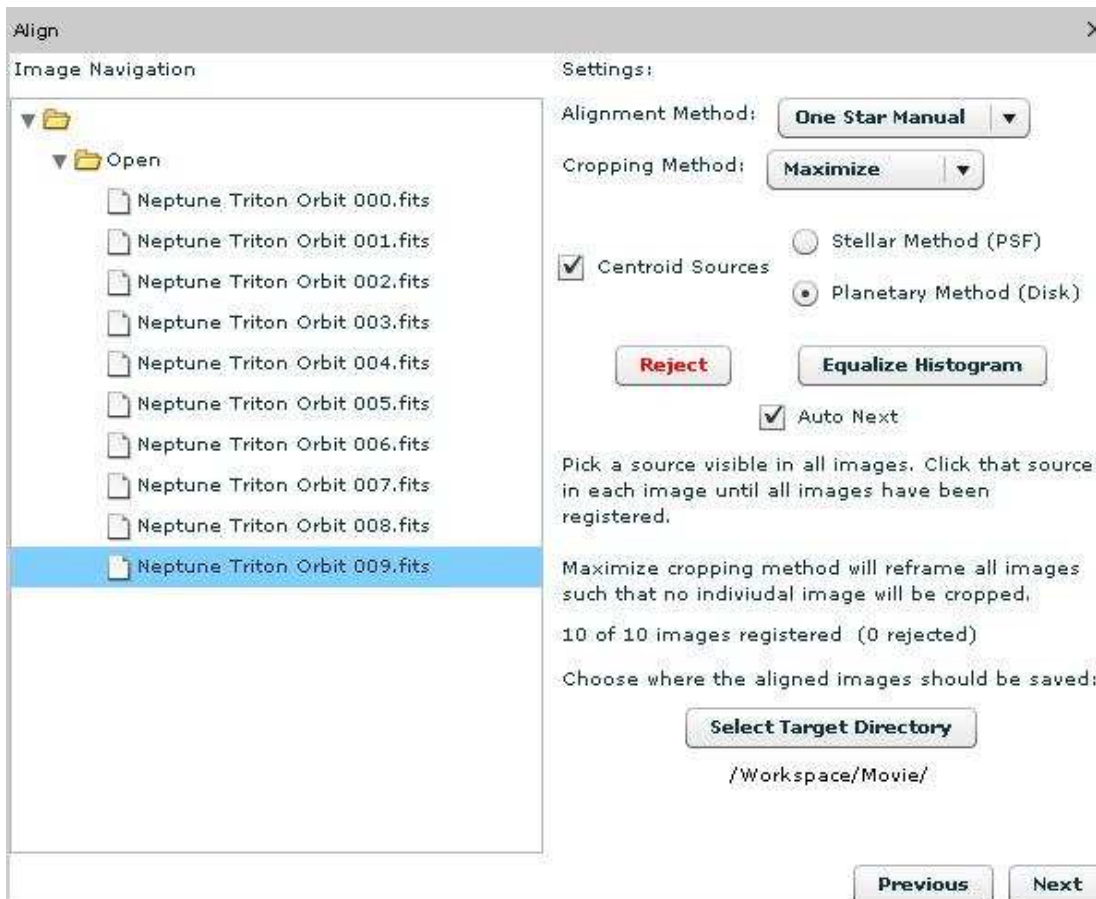
EXERCISE 1: MAKE A MOVIE OF THE MOONS ORBITING THE PLANET

In the following tutorial, you will learn how to select and align images, which must be done before they can be made into a movie:

<http://skynet.unc.edu/ASTR101L/videos/align/>

Select and align your images. Remember:

1. If the planet is in the same general area in each of your images, feel free to change “Cropping Method” to “Overlay Only”. Otherwise, use “Maximize”.
2. Since you will align by clicking on the planet, change “Stellar Method (PSF)” to “Planetary Method (Disk)”.
3. Select, or create and select, a target directory in your “Workspace”, where your selected and aligned images can be saved.
4. For each image, either select and align it by clicking on the planet or reject it by clicking the “Reject” button.



In the following tutorial, you will learn how to turn selected and aligned images into a movie:

<http://skynet.unc.edu/ASTR101L/videos/movie/>

Turn your selected and aligned images into a movie. Remember:

1. If you want to see the moons orbit the planet, stop the movie. Select “ZScale” in the “Histogram” window and “Equalize Histogram” in the “Make Movie” window. Then play.
2. If you want to see the planet rotate, stop the movie. Select “MinMax” in the “Histogram” window and “Equalize Histogram” in the “Make Movie” window. (This is more impressive for Jupiter than it is for Saturn, Uranus, and Neptune).

Repeat #1 to see the moons orbit the planet and click “Download Movie”. Include this movie in your lab report.

B. ORBIT AND MASS DETERMINATION

EXERCISE 2: MEASURE THE ANGULAR AND PHYSICAL DIAMETERS OF THE PLANET

Identify the sharpest looking of your images. Open it in Afterglow and zoom in until the planet fills your window. Select the histogram window and select minmax.

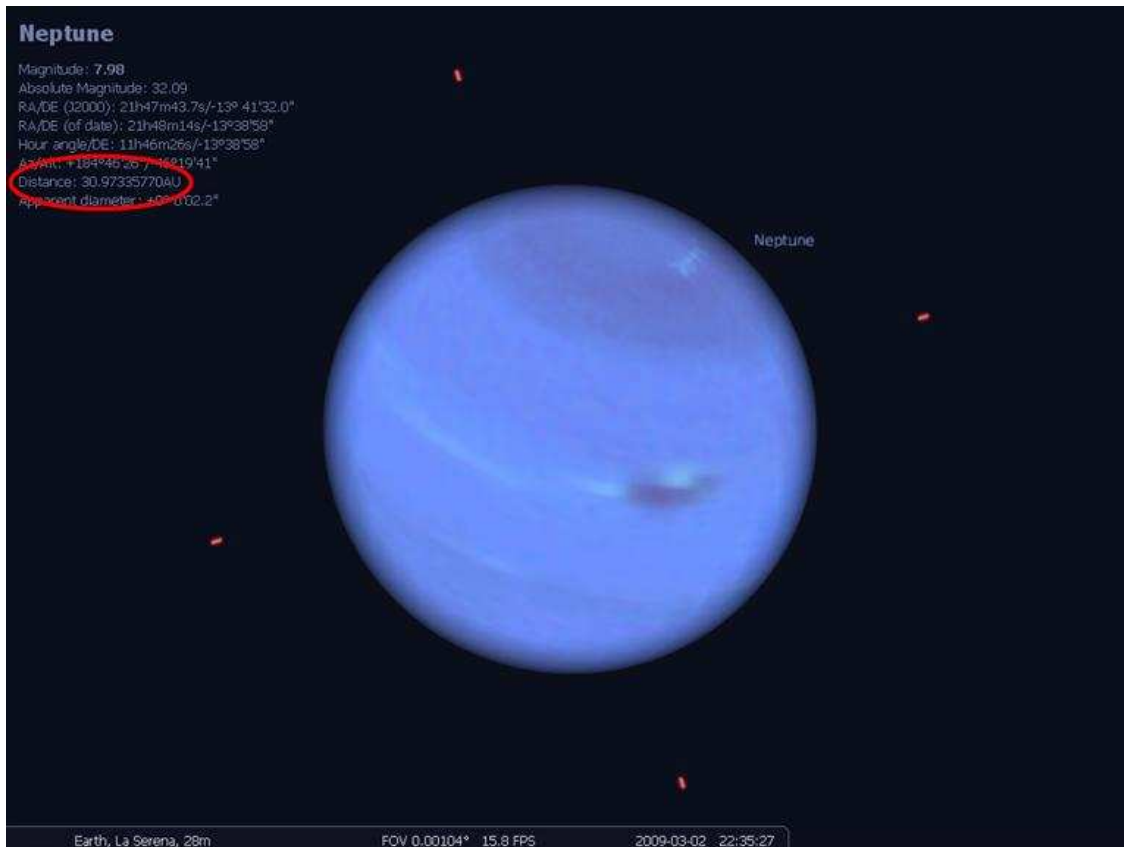
Measure the angular diameter of the planet to the nearest 0.1 arcseconds.

$\theta =$ _____

Note: This value should be larger than the true value due to atmospheric blurring, but this effect will cancel out and not affect your mass measurement.

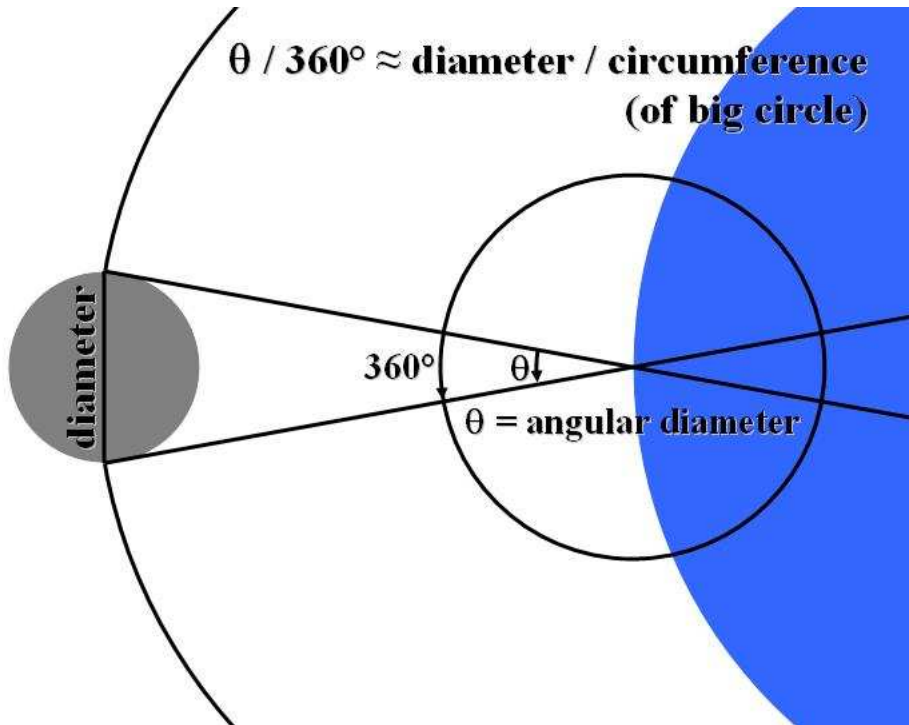
Use Stellarium to find the distance to the planet when Skynet took your image, in AU:

distance = _____



Note: In Lab #4, you will learn how to measure distances to solar system objects directly using parallax, instead of having to look them up in Stellarium. But this will do for now.

Once the angular diameter of the planet and the distance to the planet are known, the physical diameter of the planet can be determined:



The physical diameter of the planet as a fraction of the circumference of the big circle is the same as the angular diameter of the planet as a fraction of 360° :

$$\text{diameter} / \text{circumference} = \theta / 360^\circ$$

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

$$\text{diameter} / (2\pi \times \text{distance}) = \theta / 360^\circ$$

Solving for the physical diameter of the planet yields:

$$\text{diameter} = 2\pi \times \text{distance} \times (\theta / 360^\circ)$$

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

$$\text{diameter} = \underline{\hspace{2cm}}$$

Note: Since in AU, this should be a very small number.

Note: This value should be larger than the true value since θ should be larger than its true value due to atmospheric blurring, but these effects will cancel out and not affect your final mass measurement.

EXERCISE 3: MEASURE THE ORBIT OF A MOON

Next you are going to measure the orbit of one of your planet's moons:

If your planet is Jupiter, you will measure the orbit of Ganymede.

If your planet is Saturn, you will measure the orbit of Titan.

If your planet is Uranus, you will measure the orbit of Oberon.

If your planet is Neptune, you will measure the orbit of Triton.

For each of your successful observations:

1. Select the better of the two images.
2. For that image, select the information window and record the system (not universal) date and time that the image was taken in Data Table 1. Also record the Julian date that the image was taken in Data Table 1, to the nearest 0.1 days.
3. Adjust the max value and zoom in/out until you can easily see the moons. Use Stellarium to identify which one is Ganymede, Titan, Oberon, or Triton. (If the moon is too close to the planet to see, or so far from the planet that it is off the image, skip this observation.)
4. Measure the angular distance between the center of the planet and the center of the moon. Record it to the nearest 0.1 arcseconds in Data Table 1.

EXERCISE 4: MEASURE THE MASS OF THE PLANET

Go to:

<http://skynet.unc.edu/ASTR101L/graph>

and select “Moon”. In the following tutorial, you will learn how to graph your data and measure an orbit’s semi-major axis in arcseconds and period in days.

<http://skynet.unc.edu/ASTR101L/videos/graph-moon/>

Make a graph of angular distance vs. Julian date and adjust a , P , and the phase and tilt of the orbit until the curve best matches your data.

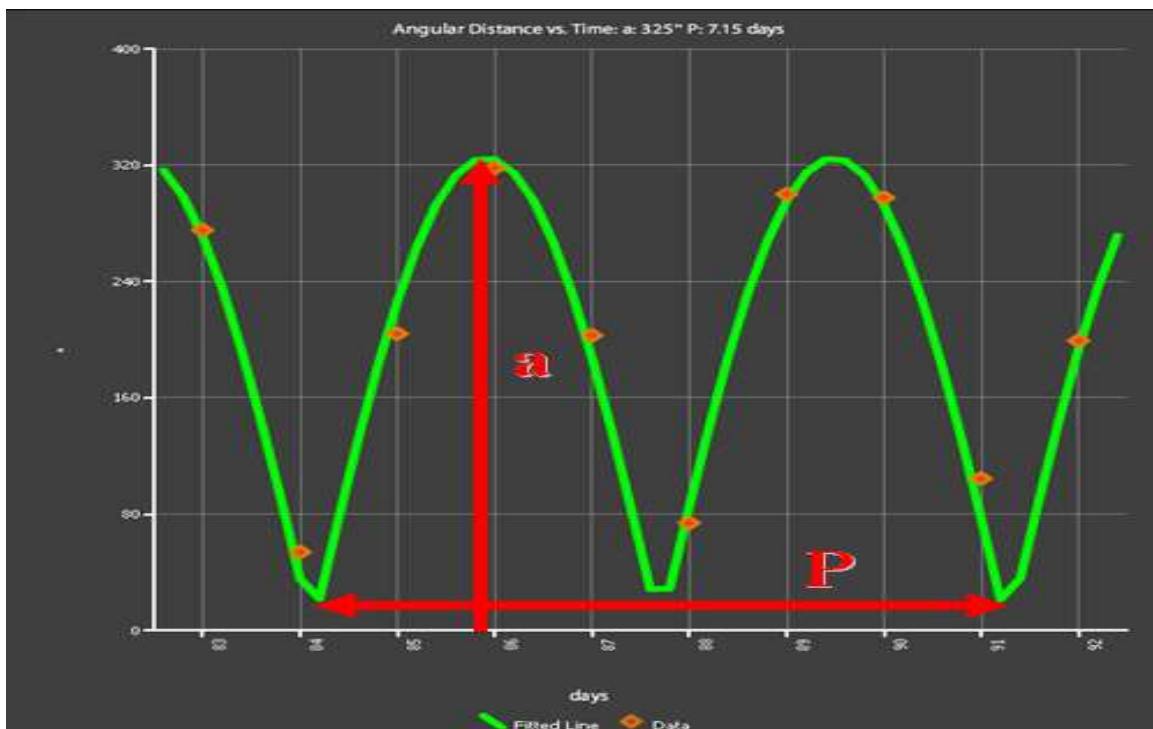
The maximum angular distance between the moon and the planet is the semi-major axis of the moon’s orbit, in arcseconds:

a in arcseconds = _____

The time between peaks is the time it takes for the moon to move from one side of the planet to the other. This is half of the moon’s orbital period. The time between two peaks is the moon’s orbital period, in days:

P in days = _____

P in years = _____



Next, use your measurements of the planet's angular diameter in arcseconds and physical diameter in AU from Exercise 2 to convert your measurement of the moon's orbital semi-major axis from arcseconds to AU:

$$\mathbf{a \text{ in AU} = (a \text{ in arcseconds}) \times (\text{diameter in AU} / \theta \text{ in arcseconds})}$$

$$\mathbf{a \text{ in AU} = \underline{\hspace{2cm}}}$$

Note: Since in AU, this should be a very small number.

By Newton's form of Kepler's Third Law, the mass of the planet must then be:

$$\mathbf{M = [(a / 1 \text{ AU})^3 / (P / 1 \text{ year})^2] \text{ solar masses}}$$

$$\mathbf{M = \underline{\hspace{2cm}}}$$

Finally, convert the planet's mass to Earth masses: 1 solar mass = 333,000 Earth masses.

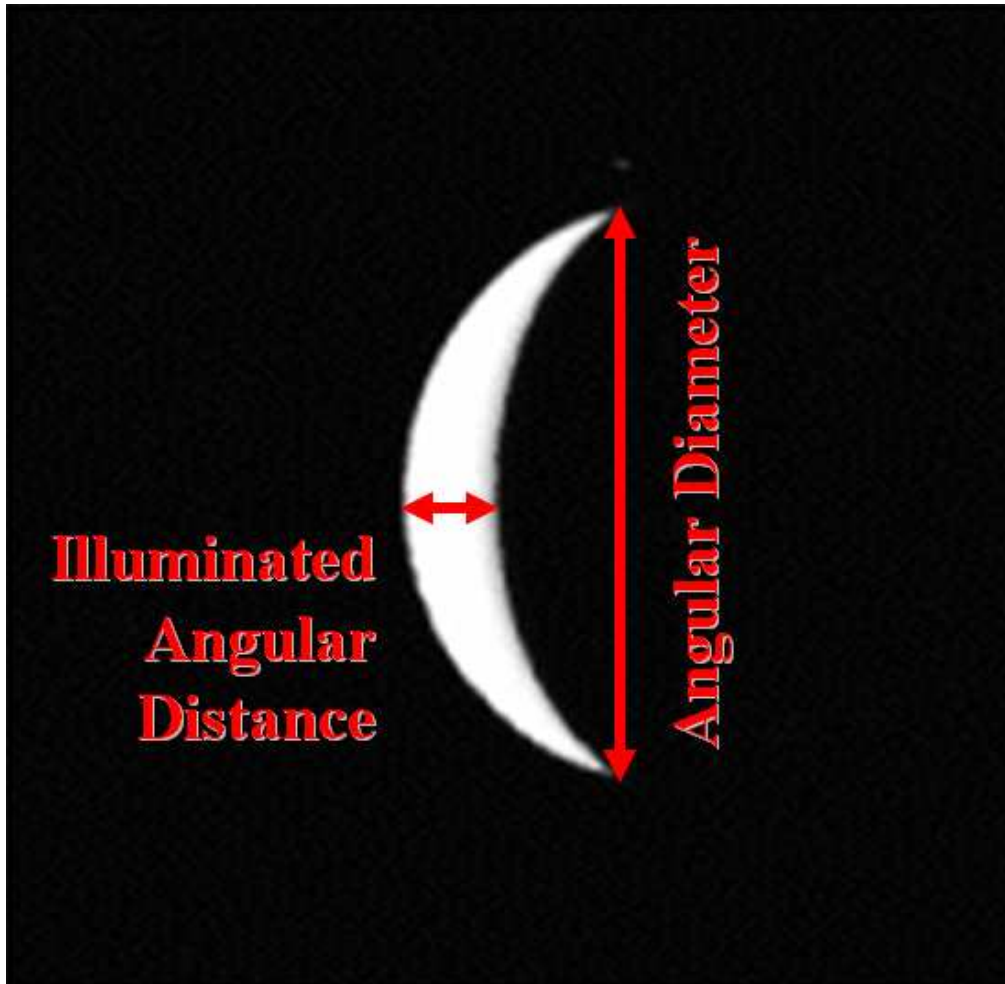
$$\mathbf{M = \underline{\hspace{2cm}}}$$

Google the true mass of your planet in Earth masses and compute your percent error. Discuss sources of error.

In your lab report, include Data Table 1 and your graph of angular distance vs. Julian date.

C. VENUSIAN PHASES

Venus's angular diameter and illuminated angular distance are defined as follows:



Use Afterglow to measure the angular diameter and illuminated angular distance of Venus (1) in your image from Lab #1, if you got one of Venus, and (2) in archival images (in Afterglow, go to “File”, “Open Image(s)”, “Sample Images”, “Astro 101 lab”, “Lab 3 – Galilean Revolution”, “Venus”). Record these to the nearest 0.1 arcseconds in Data Table 2.

Note: For each image, zoom in until Venus fills your window. Select the histogram window and select minmax.

Venus's phase is given by:

phase = illuminated angular distance / angular diameter

Compute Venus's phase for each image and record this to two decimal places in Data Table 2.

Go to:

<http://skynet.unc.edu/ASTR101L/graph>

and select "Venus".

Make a graph of Venus's phase vs. angular diameter.

Are your observations more consistent with the geocentric model of the universe or the heliocentric model of the universe? Discuss sources of error.

DATA TABLE 2: VENUSIAN PHASES

Image	Angular Diameter (arcseconds)	Illuminated Angular Distance (arcseconds)	Phase
1			
2			
3			
4			
5			
6			
7			