

Name: \_\_\_\_\_

Section: \_\_\_\_\_

Date: \_\_\_\_\_

## PRELAB 3: REVOLUTION OF THE MOONS OF JUPITER

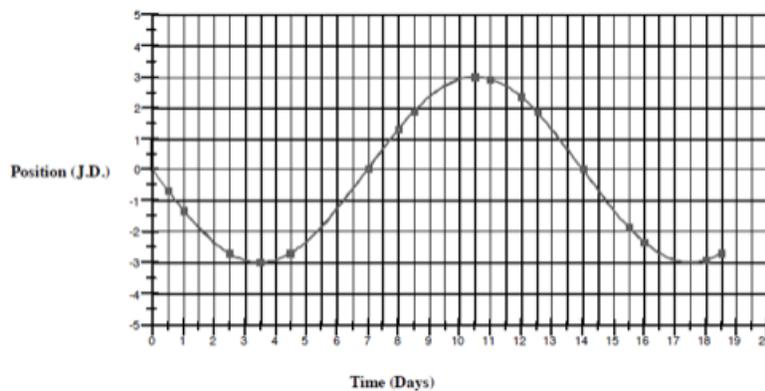
Many of the parameters astronomers study cannot be directly measured; rather, they are inferred from properties or other observations of the bodies themselves. The mass of a celestial object is one such parameter—after all, how would one weigh something suspended in mid-air?

In 1543, Nicolaus Copernicus hypothesized that the planets revolve in circular orbits around the sun. His contemporary Tycho Brahe, famous for his observations, carefully charted the locations of the planets and hundreds of stars over a period of twenty years, using a sextant and a compass. These observations were eventually used by Johannes Kepler, a student of Brahe's, to deduce three empirical mathematical laws governing the orbit of one object around another. Kepler's Third Law is the one that applies to this lab.

In the early 17th century, with the recent invention of the telescope, Galileo was able to extend astronomical observations beyond what was available to the naked eye. He discovered four moons orbiting Jupiter and made exhaustive studies of this system. Galileo's work is of particular interest, not only for its pioneering observations, but because Jupiter and the four Galilean moons (as they came to be called) can be viewed as a miniature version of the larger Solar System in which they lie. Furthermore, Jupiter provided clear evidence that Copernicus's heliocentric model of the Solar System was physically possible; it is largely from these scientists' work that the modern study of Astronomy was born.

The purpose of this lab is to determine the mass of Jupiter by observing the motion of the four Galilean moons: Io, Europa, Ganymede, and Callisto. Jupiter is the largest planet in our solar system and is made of gas (as opposed to rock). It has 63 known satellites, of which the Galilean moons are the largest. Before we begin, let's explore some of the terms and concepts that will be used during the lab:

**A Brief Review of Sine Curves:** In this lab, the period of the sine curve corresponds to the orbital period of the moons around Jupiter. The amplitude corresponds to the radius of the moon's orbit.



1. (2 points) The amplitude of a sinusoidal curve is given by:  $A = \frac{(\text{maximumvalue} - \text{minimumvalue})}{2}$ . What is the amplitude of the graph above? Remember units!

2. (2 points) The period of a sinusoid is defined to be the time from one maximum (or minimum) to the next maximum (or minimum). In the graph above, what is the period?
  
3. (2 points) The x-intercept of the sine curve is the place where  $y = 0$ . In this lab, we define T-Zero to be the time at the beginning of the sine curve. The beginning of the sine curve is where the curve slopes upwards from zero (ie, starting from the x-intercept). In the above graph, what is T-Zero?

**Kepler's Third Law:**



Kepler's 3rd law of planetary motion states that the square of the orbital period of a planet ( $P$ , also known as the orbital period) is directly proportional to the cube of the semi-major axis ( $a$ , also called the amplitude) of its orbit. We write this as

$$P^2 \propto a^3$$

For two objects that orbit the same central mass, the ratios of their periods and semi-major axes can be set equal.

$$\frac{a_1^3}{P_1^2} = \frac{a_2^3}{P_2^2}$$

Once we know the semi-major axis and period of a celestial body, we can determine its mass using

$$M = \frac{a^3}{P^2}$$

For example, this can be used to determine the mass of the planet a moon is orbiting, or the mass of the star a planet is orbiting. Note that for this lab, the period is recorded in years and the amplitude is expressed in astronomical units (AU, where one AU is defined to be the distance between the Earth and the Sun, that is,  $1.496 \times 10^8$  kilometers). Resulting mass values are recorded in solar mass units (SMU).

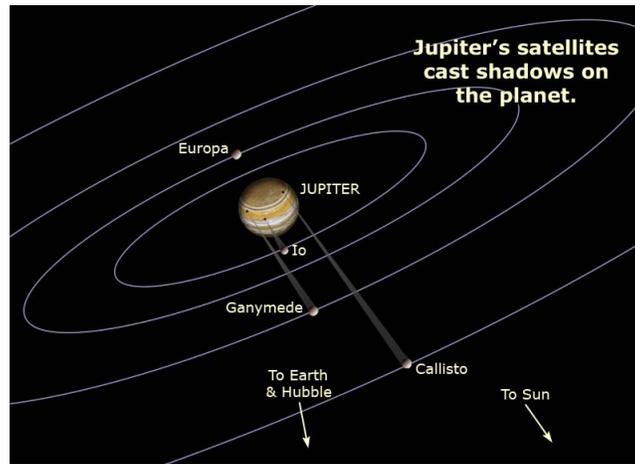
4. (2 points) If Moon 1 has a semi-major axis of seven Jupiter diameters (JD) and a period of 3.5 days, and Moon 2 has a semi-major axis of 20 JD, what is Moon 2's period of revolution in days?
  
5. (2 points) If Moon 1 has an orbital period of 1.4 years and a distance of 0.25 AU, what is the mass of the body it orbits in solar mass units?

Name: \_\_\_\_\_

Section: \_\_\_\_\_

Date: \_\_\_\_\_

## LAB 3: REVOLUTION OF THE MOONS OF JUPITER



### 1 Introduction and Review

During our lab, we will observe the four moons of Jupiter that Galileo saw through his telescope. They are named Io, Europa, Ganymede and Callisto, in order of distance from Jupiter. The moons appear to be in a straight line because we are looking edge-on at the orbital plane. If we were to observe the moons over a succession of clear nights, as Galileo did, we would see the moons shuffle back and forth, more or less within this same plane. Though the moons actually move in roughly circular orbits, our vantage point only yields the perpendicular distance of the moon to the line of sight between Jupiter and Earth. If we viewed Jupiter from “above,” we would see the moons traveling in apparent circles.

As we will find, the perpendicular distance of the moon should be a sinusoidal curve if plotted versus time. By taking enough measurements of the position of a moon, we can fit a sine curve to the data and determine the radius of the orbit (the amplitude of the sine curve) and the period of the orbit (the period of the sine curve). Once we obtain these values and convert them to the appropriate units, we can determine the mass of Jupiter using Kepler’s Third Law. From there too we will determine Jupiter’s approximate mass.

We know that the orbits of the moons are regular (that is, they do not speed up or slow down from one period to the next), and that the radius of each orbit does not change from one period to the next. The sine curve should therefore also be regular. It should go through all of the points, and not have a varying maximum height or a varying width from peak to peak. Note that the period of the orbit is the time it takes for the moon to circle the planet and return to the same point in the orbit; thus the time between two maxima is the period. The time between crossings at 0 J.D., is equal to half the period because this is the time it takes to get from the front of Jupiter to the back of Jupiter, or half way around. For some of your moons, you may not get data from your observations for a full period, and you may find the time between crossings at 0 J.D. to be of use to you in determining the period (hint: find half the period and multiply by two!). The radius of an orbit is equal to the maximum position eastward or westward, that is, the largest apparent distance from the planet. Remember that the orbits of the moon are nearly circular,

but since we see the orbits edge on, we can only determine the radius when the moon is at its maximum position eastward or westward.

This program simulates the operation of an automatically controlled telescope with a charge-coupled device (CCD) camera that provides a video image to a computer screen. It also allows convenient measurements to be made at a computer console, as well as adjustment of the telescope's magnification. The computer simulation is realistic in all important ways, and using it will give you a good understanding of how astronomers collect data and control their telescopes. Instead of using a telescope and actually observing the moons for many days, the computer simulation shows the moons to you as they would appear if you were to look through a telescope at the specified time.

## 2 Instructions

From the Prelab, we know:

1. The amplitude of a sinusoidal curve is given by:  $A = \frac{(\text{maximumvalue} - \text{minimumvalue})}{2}$ .
2. The period of a sinusoid is defined to be the time from one maximum (or minimum) to the next maximum (or minimum).
3. The x-intercept of the sine curve is the place where  $y = 0$ . In this lab, we define T-Zero to be the time at the beginning of the sine curve. The beginning of the sine curve is where the curve slopes upwards from zero (ie, starting from the x-intercept).
4. Kepler's 3rd law of planetary motion states that the square of the orbital period of a planet (P, also known as the orbital period) is directly proportional to the cube of the semi-major axis (a, also called the amplitude) of its orbit. We write this as

$$P^2 \propto a^3$$

For two objects that orbit the same central mass, the ratios of their periods and semi-major axes can be set equal.

$$\frac{a_1^3}{P_1^2} = \frac{a_2^3}{P_2^2}$$

Once we know the semi-major axis and period of a celestial body, we can determine its mass using

$$M = \frac{a^3}{P^2}$$

Note that for this lab, the period is recorded in years and the amplitude is expressed in astronomical units (AU, where one AU is defined to be the distance between the Earth and the Sun, that is,  $1.496 \times 10^8$  kilometers). Resulting mass values are recorded in solar mass units (SMU).

5. For this lab, you will need a calculator.
6. A brief word on curve fitting (ie. fitting a line to a set of data points): A "linear fit" is characterized by the slope and the y-intercept, here called T-Zero (the x-value, or time, where the line crosses the zero point of the y-axis). The slope refers to how much the line is tilted. It is important to write down the entire T-Zero value.
7. Open the CLEA lab entitled "The Revolutions of the Moons of Jupiter." Click on File, Login. Enter the names of each group member, click OK and then YES.

8. Next, click File, Run, and enter today's date and the current time. Click File, Timing, and make sure the observation step is set to 12 hours.
9. Set up the features: click File, Features, and check the box next to "use ID colors," "show top view," and "show eclipsed moon." Finally, click ok.
10. To begin, click on one of the moons and make sure that it is circled in the top view. Next, click "record." Write down the position of the moon in the chart on the data sheet provided, using the "E" or "W" labels. Click on the next moon, again making sure it is circled in the top view. Click record again and write down its position. Continue this process for the other two moons. Each time you click on a moon you MUST hit record to store its position. Click OK on the pop-up box to save the data. Move on to the next observation time (12 hours later). If the day is cloudy, then just write "cloudy" in the data sheet provided.
11. If a moon is behind Jupiter, use the top view to make sure the moon gets selected and to help you see where to click. If after several tries, you cannot click on the eclipsed moon, leave the space blank and record "eclipsed" in your chart.
12. Continue to record the positions of Jupiter's moons every 12 hours for 15 days (a total of 30 measurements).
13. After you have finished collecting data, click File, Data, Analyze to begin plotting the movement of the Galilean moons across our line of sight. In the new window, click Data, Select Moon. Begin with Callisto, then Ganymede, then Europe, and finally Io.
14. Once you've selected your first moon, click Plot, Fit Sine Curve, Set Initial Parameters. Look at your graph and estimate the T-Zero value (Julian date), the period (days), and the amplitude (Jupiter diameters) of the sine curve in front of you. If you are unsure of the values, ask your TA or take a guess! Enter your estimates in the dialogue box provided. A solid curve should appear between the data points. If you'd like, you can connect the data points by clicking Data, Plot, Plot Type.
15. Use the scroll bars to adjust the T-zero, Period, and Amplitude until the RMS residual (which represents how well the sine curve fits the data) is less than one-half (written 5E-01 on the screen).
16. Here are some hints on creating the correct sine curves: when the graph of your initial data points appears, try to find a pattern by eye, and take note of any data points that seem to be out of place. Click on a point at which the line connecting the points crosses from negative to positive; if this happens several times, choose a point toward the left of the screen. Find the next point at which the line passes from negative to positive (that is, when the moon has completed one orbit). Subtract the earlier date from the later date and enter this as **period** in the dialog box. You can estimate the **amplitude** of the sine curve by clicking on the peaks and valleys of your graph and reading off the approximate value. Feel free to ignore outlying data points, but these should be few and far between! Note that when you use the slider bars, each change in one slider will affect the other two, so make sure to toggle between all three to get a more accurate measurement.
17. Once the solid curve fits the data points exactly, record the T-zero, Period, Amplitude, and RMS on your worksheet. **Print the final result. Complete this process for each moon.**

Name: \_\_\_\_\_

Section: \_\_\_\_\_

Date: \_\_\_\_\_

### LAB 3 WORKSHEET: REVOLUTION OF THE MOONS OF JUPITER

#### TABLE OF OBSERVATIONS

1. (2 points)

	Date	Time	Io	Callisto	Europa	Ganymede
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						
22						
23						
24						
25						
26						
27						
28						
29						
30						

2. (4 points) Record values of sine curve fit:

Moon	Period (days)	Amplitude (JD)	T-Zero (days)	RMS
Io				
Callisto				
Europa				
Ganymede				

3. (4 points) Convert to years and AU. Note that 1050 JD = 1 AU (where one JD is measured in km):

Moon	Period (days)	Period (years)	Amplitude (JD)	Amplitude (AU)
Io				
Callisto				
Europa				
Ganymede				

4. (4 points) Calculate the mass of Jupiter:

Moon	Period (years)	Amplitude (AU)	Jupiter Mass (SMU)
Io			
Callisto			
Europa			
Ganymede			

5. (1 point) What is the average mass of Jupiter (in smu)?

6. (1 point) If there are  $3 \times 10^{-6}$  solar masses in one Earth mass, what is the mass of Jupiter in Earth masses?
7. (1 point) Moon A is 1 JD from Jupiter and goes around in 1 day. Moon B is 4 JD from Jupiter. What is the period of Moon B? Show your work.
8. (1 point) The orbit of Earth's moon has a period of 27.3 days and a radius (semi-major axis) of  $3.84 \times 10^5 km$ . What is the mass of Earth? Show your work.
9. (2 points) True or False: Moons located a further distance from Jupiter have a shorter period. Explain your answer.

---

Picture Credits: Prelab, Sinusoidal Graph: CLEA Student Manual; Lab, Jupiter System: [http://www.nasa.gov/images/content/68503main\\_hst\\_jupiter\\_illustration.jpg](http://www.nasa.gov/images/content/68503main_hst_jupiter_illustration.jpg)

DISCLAIMER: This lab has been edited from the CLEA simulations and student manuals: Lucy Kulbago, ed. Project CLEA Software. Project CLEA. John Carroll University. Web. 15 July 2014. <http://www3.gettysburg.edu/~marschal/clea/CLEAhome.html>.