

# Astronomy 1 – Introductory Astronomy

## Spring 2014

### Lab 3: Jupiter's moons and Kepler's third law

#### Introduction

When Galileo viewed Jupiter through his telescope, he saw four small bodies lined up next to the giant planet. As he observed Jupiter over several nights, he noticed these bodies changed position while staying in a line. Galileo realized that these tiny bodies are moons in orbit about Jupiter. Collectively, these moons are called the Galilean satellites in his honor. They were later named after four of Jupiter's many romantic conquests from Greek myth: Io, Europa, Ganymede, and Callisto. With better telescopes and later space probes to Jupiter, many more moons – but none nearly as large as the Galilean satellites – and even a thin ring have been discovered. At last count there are 65 Jovian moons, with the most recent one discovered in 2011. At this point, astronomers are basically finding smaller and smaller chunks of rock thanks to improved telescope technology. (You can see the full list at <http://www.dtm.ciw.edu/users/sheppard/satellites/jupsatdata.html> and a family portrait of the four Galilean satellites at <http://antwrp.gsfc.nasa.gov/apod/ap001118.html>. Search for images of the moons and Jupiter once you're on APOD.)

The moons orbit Jupiter in elliptical orbits (but they are very nearly circular) at varying distances from the planet. Of the Galilean satellites, Io is the closest, followed by Europa, Ganymede and Callisto. (A handy mnemonic device for recalling the order is “I Eat Green Carrots”!) Since we are looking at the orbital plane of the moons nearly edge-on, the moons appear to be lined up. As they orbit Jupiter, they seem to move along this line toward and away from the planet. We can only measure the apparent distance of each moon from Jupiter. We must determine how this apparent distance,  $R_{app}$ , is related to the moon's distance from Jupiter.

In Figure 1 below, the position angle  $\square$  depends upon the time at which you observe the planet. If you plot  $R_{app}$  vs.  $t$ , the result should be a sine curve.

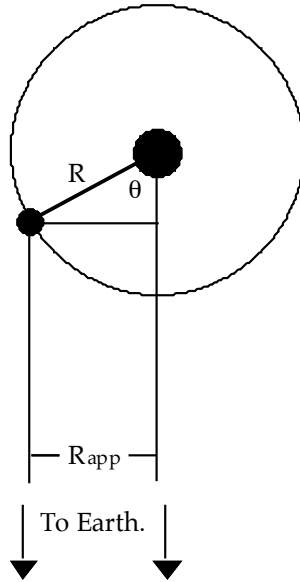


Figure 1. Looking down on a moon's orbit around Jupiter.

$$R_{app} = R \sin\left(\frac{2\pi}{T}t - T_o\right)$$

Where  $R$  is the actual distance of the moon to Jupiter and  $T$  is the orbital period. Note that the quantity in parentheses is an angle, and it's expressed in radians (there are  $2\pi$  radians in 360 degrees), and that the  $T_o$  term sets the "zero-point" of the variability – it is some specific time when  $R_{app} = 0$ , with the moon passing directly in front of Jupiter.

### Some Astronomy Terminology

You'll need this to understand the output of the computer simulation.

**Universal Time (UT):** The standard time at the Prime Meridian in Greenwich, England. Astronomers report their observations in terms of UT to avoid confusion about time zones and Daylight Savings Time.

**Julian Date (JD):** Julian dates are a continuous count of days and fractions since noon Universal Time on January 1, 4713 BCE (on the Julian calendar). Julian dates are often used as time variables in astronomy. They are especially useful in astronomical software since computers can base calculations on a single floating point number rather than having to make

conversions from Month, Day, and Year. There are the usual 24 hours in a Julian Day.

## **Part I: The Observations**

We will use the computer program “The Revolution of the Moons of Jupiter,” one of the programs produced by the CLEA Project at Gettysburg College. (CLEA stands for “Contemporary Laboratory Experiences in Astronomy.”) The program simulates the techniques used at a modern computer-controlled research telescope. The images you will see on the screen are like those obtained with a CCD (charge coupled device) camera. The program allows you to make measurements directly at the computer console, and you can adjust the telescope’s magnification from the console as well.

Click on the “WineSkin” icon on the Dock. This is a Windows emulator that runs the Jupiter Lab. Choose “file” > “login” and you will see the “Student Accounting” screen. You don’t need to enter anything here, just check “OK.” The next window to pop up is “Select Exercise”. Choose “Revolution of the Moons of Jupiter”. At the next screen, choose “file” > “run.”

On this screen are boxes for the date and Universal Time. You may set the initial date and time to whatever you wish. Click “OK” to exit this screen. Choose “File” > “timing” and set the observation interval to one hour initially.

On the observation screen, you see the first “image”. At the bottom of the screen is a “control panel” which displays the date and time and the magnification controls. (You will need to reduce the magnification to 100X to see all four moons at all times.) To measure the position of a moon, move the mouse arrow to the moon and hold down the mouse button. The name of the moon appears at the bottom of the screen along with some numbers. The only number you need is the “X” value (listed in the lower right of the data box). This is the apparent distance of the moon from Jupiter measured in Jupiter diameters. Notice that you need to keep track of whether the moon is to the east or west of Jupiter. (Label east positions as negative and west positions as positive.) Note that you can experiment around with the “file” > “features” menu. Can you figure out how to color-code each moon?

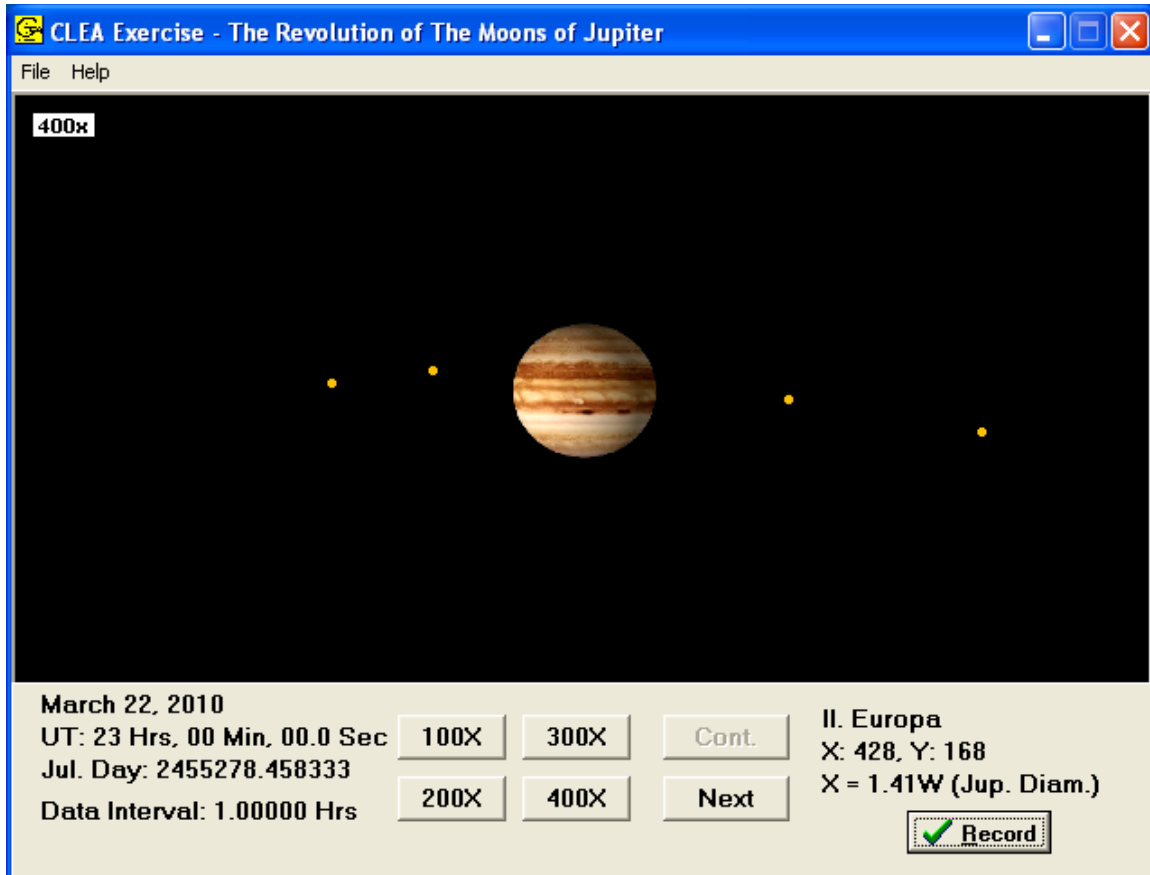


Figure 2. The Observation Window.

Watch how the moons move as you click through several observing intervals. Not surprisingly, some moons move much more quickly in twelve hours than others. It is entirely possible to get only two or three observations per orbit for the closest moon, Io, while not getting a complete orbit for the most distant moon, Callisto. If you click the “Cont.” button, the moons move continuously around in 1-hour steps. (“file” > “features” > “animation” may have to be chosen before this option is enabled.) Follow each moon and estimate how long it takes to complete a revolution. This does not need to be exact; you just need a suitable observing interval for each moon (2 hours, 3 days, etc.). Start by focusing on each moon one at a time and **estimate its orbital period**. Next, think about **what observing interval you’d need to get about 15 observations to cover roughly two orbital periods**. Note, while you’re watching the moons orbit, how their motion is sinusoidal (do you see how they appear to move slower when they’re farthest from Jupiter? Yet their orbits are circular so their actual speeds are constant...can you convince yourself, by looking at Figure 1, that this effect

is because we're looking at the moons' orbits projected onto the sky? You can also see this using the "top view" feature in the program.)

## **1. What are the observing intervals you chose for each moon?**

We will analyze each of the four moon's separately. Set the observing interval for the value you determined for the first moon, measure the moon's, position, record the value using the "record" button, hit the "next" button, and repeat the process until you have approximately 15 measurements. Repeat the process for each of the other three moons.

Save your data frequently, in case the program crashes ("data" > "save" > "binary").

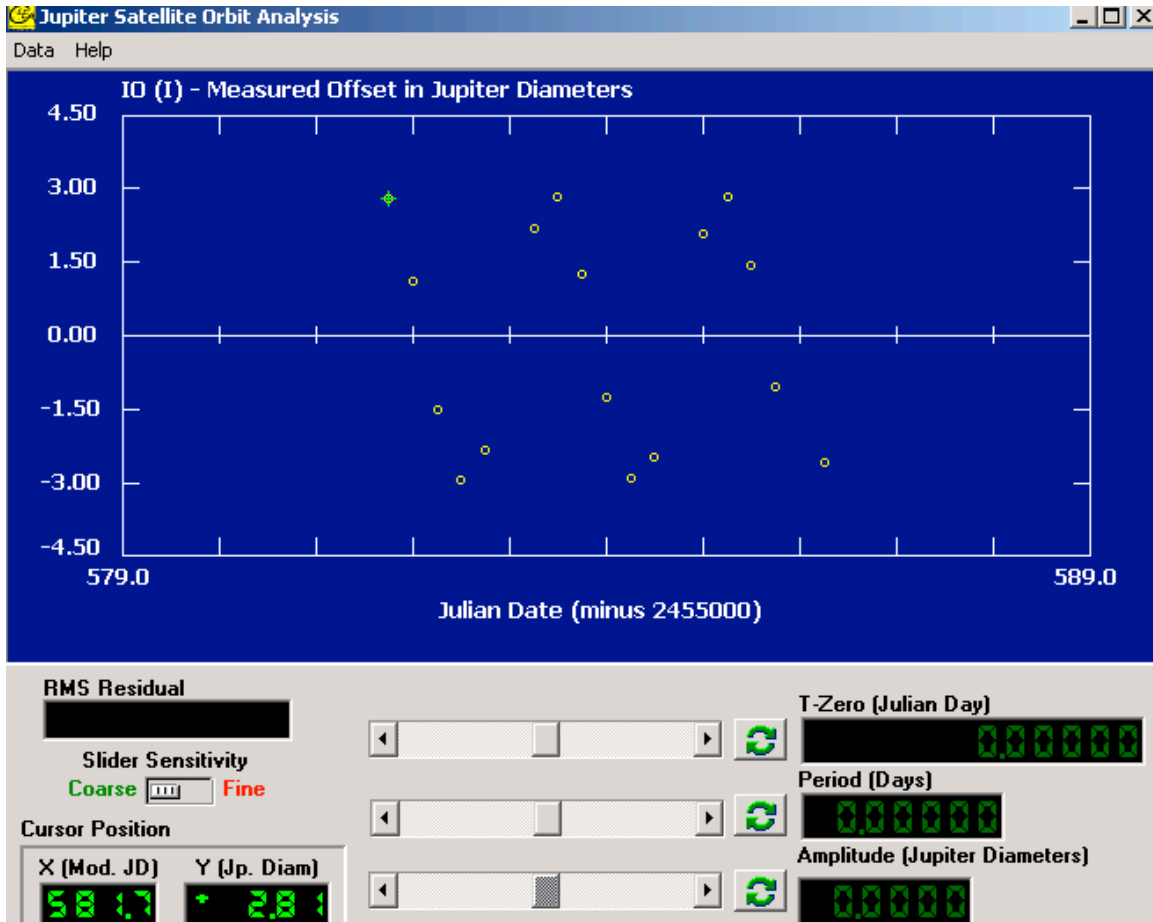
Your data should consist of four two-column tables: Julian Date and position (in – or + Jupiter diameters), each with 15 rows. You can view it via "file" > "data" > "Review/Edit/Print Measurements." Print out your four data tables, and include them in your lab write-up.

Note that the distance of the moon from Jupiter is the quantity  $R_{app}$  in Fig. 1.

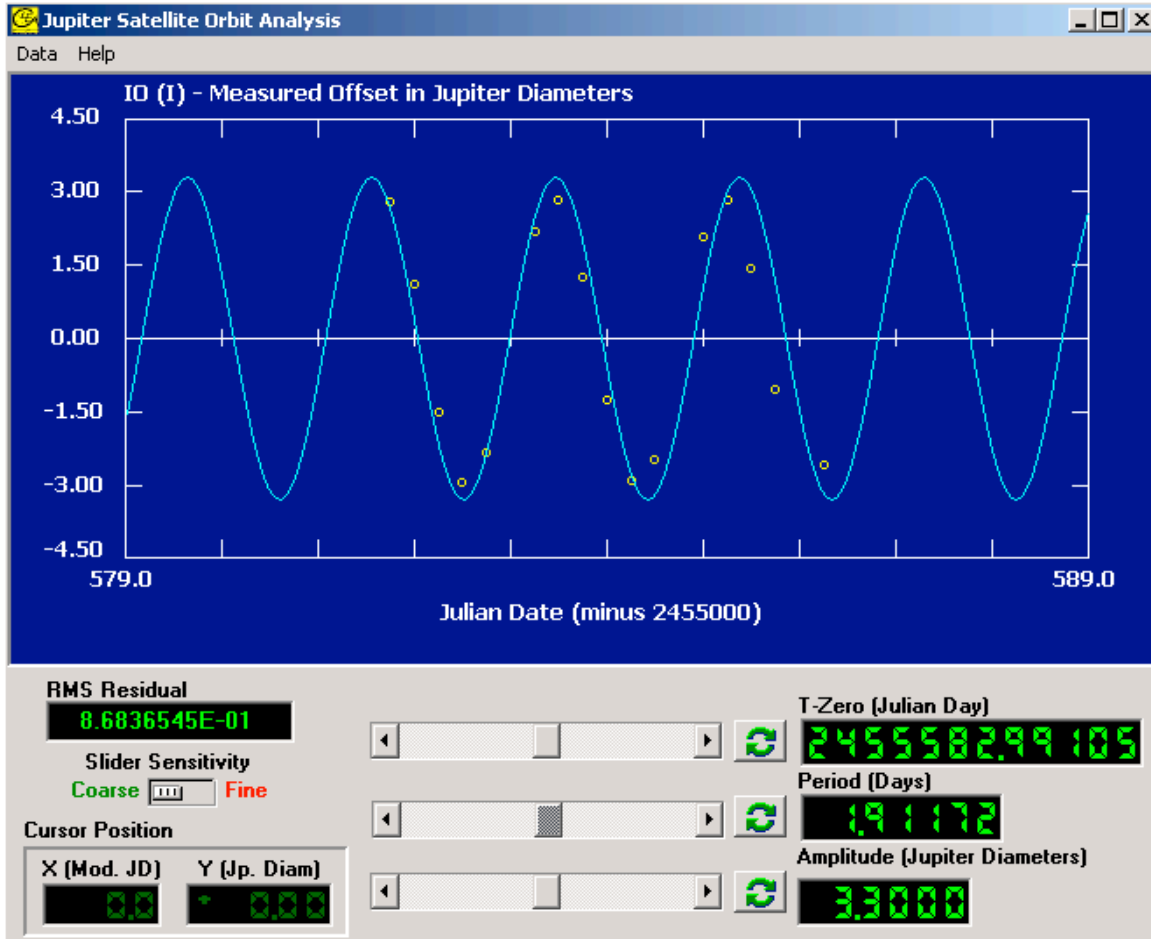
## **Part II: Interpreting Your Data**

Now that you have completed your observing run, you have to do something with your data. From your data, you want to find the distance of each Galilean moon from Jupiter (the radius of its orbit) and its orbital period. The way to do this is to graph the apparent distance (" $R_{app}$ ") versus the day of the observation ( $t$ ) for each moon.

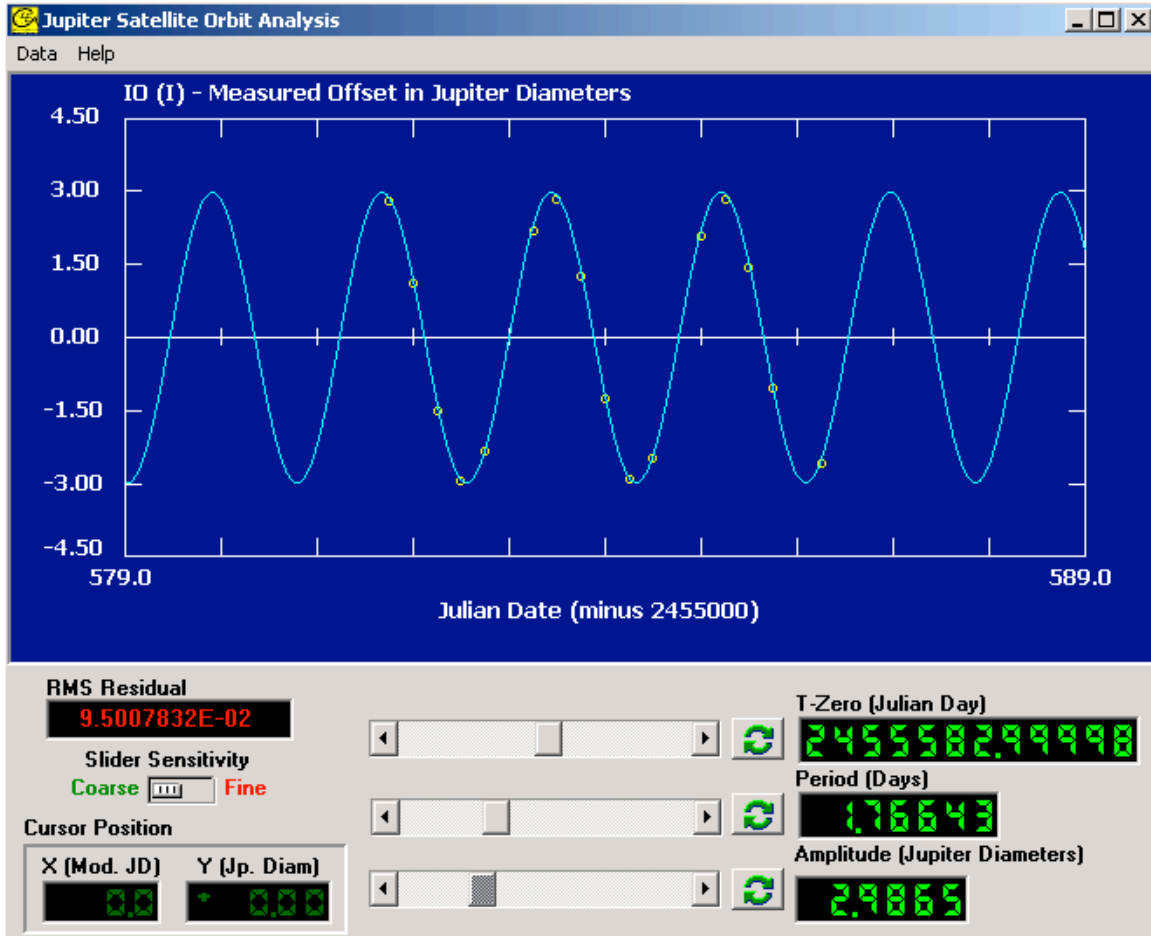
Next we will want to graph  $R_{app}$  vs.  $t$  for each moon. Go to "file" > "data" > "analyze" and a new window opens. Plot your data via "Data" > "choose moon." You should see something like this:



We want to fit these data with a sine function, which we can do via “Data” > “plot” > “fit sine curve” > “set initial parameters.” The parameters are T-Zero (a time when the sine curve goes through  $y=0$  (the x-axis) heading upward), the period (time between successive peaks), and the amplitude (height of a peak). Estimate a value for each one, based on the way your data look. Click “OK” and the sine function you specified will be plotted over your data. It will look something like this:



Use the three sliders below the plot to adjust the values of each parameter, until your fit looks good. You can check the residuals, which are a sum of the distance between each point and the curve, and thus should be small for good fits. Here is an improved fit for the data shown above:



Print out a plot of your fitted data (for each moon) and include it in your write-up in your lab notebook. You'll formally record your fits in Q. 3 below.

## 2. Comment on the quality of your fits to each moon's data.

According to Kepler's third law, the orbital period,  $P$ , and semi-major axis,  $a$ , of the orbit of two objects orbiting each other is:

$$P^2 = \frac{4\pi^2 a^3}{G(M + m)}$$

where  $G = 6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2$  is the universal gravitational constant and the two objects' masses are  $M$  and  $m$ . Note that when one object is much less



massive than the other ( $m \ll M$ ) we can ignore the mass of the lighter object. That's what we'll be doing in this lab, since Jupiter's moons are light compared to Jupiter.

When the period,  $P$  is expressed in years, the semi-major axis,  $a$ , is in Astronomical Units (AUs), and the mass is in solar masses ( $M_{\text{Sun}}$ ) this law may be written as:

$$P^2 = a^3/M$$

(Note that this equation ONLY works when the quantities are in these units! Otherwise you have to use the previous equation – Newton's version of Kepler's third law – and plug in the value of the constant  $G$  in the appropriate units.) And regardless of which set of units you use, you will have to convert  $a$  and  $P$  into the appropriate units from those that you used in the Kaleidagraph fit.

Calculate the mass of Jupiter using the results from the four moons independently. (The Galilean moons have nearly circular orbits. Therefore, the distance  $R$  is the semi-major axis. There are 1050 Jupiter diameters in 1 AU.) Do your answers agree with one another? If not, try to find sources of error. If none are found, average the four results together for your final best-estimate.

**3. Make a table of distance (semi-major axis), orbital period, and calculated mass of Jupiter for the four Galilean moons.**

**4. What is the average of your four values? That is your best-estimate of Jupiter's mass. And what is the uncertainty on that estimate? Take half the range of the four values to be the uncertainty.**

**5. The accepted value for Jupiter's mass is  $9.53 \times 10^{-4} M_{\text{Sun}}$ . Does your result agree with the accepted value?**

**6. For more perspective on your result, convert your derived mass to units of  $M_{\text{Earth}}$  ( $1 M_{\text{Sun}} = 3.329 \times 10^5 M_{\text{Earth}}$ ). Comment on whether Jupiter is more like a planet or more like a star, based on its mass.**

## **Guidelines for your write-up**

Note that there are several numbered questions in this document. The answers to these questions (or in the case of question 3, the table) should be included in your write-up. They don't have to be listed with their numbers, they can be woven into the text of your write-up, if you prefer. Here is an itemized list of the elements of the write-up:

- Title, date, lab partner
- Purpose statement describing the goal of the lab and a brief (really) overview of how you'll meet that goal
- A description of the process with any information you think is relevant and certainly any information the lab manual tells you is relevant. The description does not have to be long, but it should enable someone who hasn't done the lab to understand how you got your data and how you analyzed it.
- Your data table and graphs.
- Your analysis of the data.
- A concluding section, which can be just a paragraph and should restate your main result(s).