

*Instructions for Writing Lab Reports*

# SAMPLE LAB REPORT

## MEASURING THE MASS OF JUPITER

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(Note: Some of Ms. Asbell's remarks have been deleted or slightly altered. Most of the changes were made to avoid giving away answers to a lab you will likely perform. While you may write a lab report on this lab, you may not copy, in whole or in part, the material you see written here as that would be plagiarism. This report is provided as a sample only and represents the best lab report submitted to the author.)

### Introduction:

For many millennia, the idea that Earth was located at the center of the universe was widely accepted. During the 16th century, Nicholas Copernicus [1473-1543] championed the heliocentric "Sun centered" model. And the eventual realization that Earth occupies no central position in the universe is now known as the "Copernican Revolution". Several years after the death of Copernicus two astronomers, Galileo Galilei and Johannes Kepler, made great strides toward confirming the heliocentric model. In 1610 Galileo became one of the first people to make telescope-aided observations of space. With his telescope, Galileo studied the solar system's largest planet, Jupiter, and noticed four large moons orbiting it. The names of these moons are Io, Europa, Ganymede, and Callisto or as they are collectively known "the Galilean moons" after Galileo, who discovered them. This was the first physical evidence that not everything orbited Earth.

Johannes Kepler, a contemporary of Galileo, was an observational astronomer who accurately interpreted numerous observations of planetary orbits. Kepler used these observations to form three laws of planetary motion. These laws portray the Solar system in a way that is consistent with Copernicus's model. Although Kepler's laws were able to describe the motions of planets, they didn't explain why a planet orbits the Sun or what keeps it in orbit.

Isaac Newton [1642-1727] who first identified gravity, the force of attraction that exists between any two objects, later answered these questions. In his law of universal gravitation, Newton stated that the strength of the gravitational force between two objects depended on their masses and the distance between them. Therefore Kepler's laws are now known to be direct consequences of gravity.

The correlation between the radius of a planet's orbit and the time it takes to complete one revolution of the Sun is summarized in Kepler's third law which states that the square of a planets orbital period is proportional to the cube of its orbital radius. Newton revised Kepler's third law to express the true relationship between a planet's orbital radius and time. For any object orbiting a much more massive object, Kepler's third law now states that the orbital radius cubed divided by the orbital time squared equals the mass of the larger

object divided by the mass of the Sun (in solar units). This modified form of Kepler's third law holds true in all relevant cases in and outside the Solar system.

During the evening of April 28th, 2004 the "Measuring the Mass of Jupiter" lab was preformed by an astronomy lab class at El Camino College. This lab was conducted using a computer program that is designed to show the accurate positions of the Galilean moons relative to Jupiter at any designated time. The purpose of this lab was to estimate the mass of Jupiter by measuring the locations of Io, Europa, Ganymede, and Callisto. These measurements were evaluated using Newton's revised version of Kepler's third law. A working knowledge of this process is quite pertinent today because it can be applied to any object orbiting a more massive object to discover the unknown mass of the larger object. For example, a similar method is currently employed by astronomers trying to detect planets around other stars.

Like Galileo, we observed the orientation of Jupiter's four largest moons over an extended period of time. This lab was divided into four stages. The first task of the evening was learning to use the software. After this, preliminary estimates of each moon's orbital radius and orbital time were made. The next step was to gather 25 clear night observations that measure the positions of each moon relative to Jupiter. The computer program allows its user to make realistic observations over the course of weeks or even months all in one evening. Finally the raw observations had to be analyzed. The data was graphed and the best possible sine curve was fit to it. A sine curve is an edge-on projection of a circle, which is appropriate for interpreting measurements of circular orbits. A sine curve shows the relationship between the size of an angle and its sine and can be plotted using successive values as coordinates. From these graphs we were able to determine the orbital time, in days, and the orbital radius, in Jupiter diameters, for each moon. This information is all that is needed to calculate Jupiter's mass using the formula for Kepler's 3rd law  $(\text{Orbital radius})^3 / (\text{Orbital time})^2 = (\text{Mass of the larger object})$ . This formula is valid as written when Earth's year is used as the unit of time and the astronomical unit (AU) is used for distance. If more standard units are used, (meters, seconds, kilograms) a correction factor must also be used. Therefore in order to fit the original formula the final measurements were converted from days to years and Jupiter diameters to AU.

The remainder of this document contains sections detailing the observations and results of this lab. The observations section gives a description of the processes involved in obtaining the data as well as a record of what happened during this lab. The findings of the lab are analyzed and discussed in the results section. All data records, graphs, and calculations are located at the end of the report.

### **Observations:**

On April 28th, 2004 the "Measuring the Mass of Jupiter" lab was preformed from room #8 of El Camino College's computer lab using a computer program titled "*The Revolution of the Moons of Jupiter*" by CLEA (Contemporary Laboratory Experiences in Astronomy) produced by Gettysburg college's department of

physics. With this program, the basic orbital properties of Io, Europa, Ganymede, and Callisto, were measured every twelve hours over the course of twelve and a half days. Graphing and interpreting these measurements yielded an estimate of each of the moon's orbital time and radius.

The program was first used to watch a time-lapse animation of the Galilean moons orbiting Jupiter as they would appear from an earthly perspective. The goal was to notice each moon's side-by-side motion and how it correlates to their true circular motion while becoming acquainted with the software. To run the program we first entered the date and universal time (which is Pacific Daylight Time plus 7 hours or Pacific Standard Time plus 8 hours). From this, the computer displayed the Jovian (Jupiter) system as it would appear through a telescope on the same date and time. The program offers four possible magnifications for which the image can be viewed and an option to color-code the moons for easy identification. Located below the image is the date, universal time, and Julian day (the numerical way to keep track of the date). This information was used to chronologically record measurements in data sheet A.

The next task was to make preliminary estimates of the data that would later be obtained; in particular each moon's orbital radius, time, and T-zero date, which is the Julian date when a moon crosses in front of the center of Jupiter. The radius of each orbit was measured by watching the animation closely and pausing it when each moon appeared to be furthest from Jupiter. Clicking on the center of a moon with the mouse showed the distance between Jupiter and the moon using Jupiter's diameter as the unit of distance. At this point a much smaller time step was chosen to slow down the animation and make subtle movements easier to see. For each moon, the animation was stopped when the moon appeared to be far from Jupiter and its distance was measured. Then the animation was restarted to see if the moon would move further away from Jupiter. If it did, then the moon was re-measured. This continued until an approximation for each moon's greatest distance from Jupiter was found. The orbital time period for each moon was estimated by noting the Julian date when the moon was in front of Jupiter's center and allowing the animation to run until the moon orbited once and returned to the front of Jupiter's center. The Julian date when the moon completed this revolution was subtracted from the starting Julian date to find the time for one orbit. To estimate a moon's T-zero the program was reset to the present date and time and as before the animation was allowed to run until each moon crossed the front of Jupiter's center. All estimates can be seen at the top of data sheet B.

To measure the actual values of the above estimates, the program was reset to the current date and time and set to make observations in twelve-hour intervals. Instead of watching fast pace animation, the position of each moon was measured on a still picture. As before, clicking on the moon's center revealed its location. When a moon was successfully hit upon, its name and a value like 1.98W or 5.45E would appear below the image. The numerical value represented how many Jupiter diameters the moon was from the center of Jupiter. The "E"

or “W” stood for East or West, which corresponded to left and right respectively. In addition to each moon’s distance, the date, universal time (UT), and Julian date were recorded for each observation in data sheet A.

Starting on April 28th, 2004 Julian day #123.6 at 3 hours and 49 minutes UT, the first measurements for all four moons were taken and recorded both by hand and logged into the computer record. This process was repeated by moving ahead twelve hours to the next observation time. The gathering of measurements continued in this exact fashion with little disruption until twenty-five clear night observations were recorded. There were no cloudy nights during the time these measurements were taken. Only when a moon was located behind Jupiter, and therefore out of view, was measuring hindered. This happened three times on three separate occasions. For this reason, Ganymede, Io, and Callisto each lack one observation (see data # 18, 19, and 22 on data sheet A.).

After recording all observations, the program’s data analysis function was used to graph the measurements. By selecting any of the four moons the program will automatically plot each measurement of that moon’s location against time. Then by entering the moon’s preliminary estimates, mentioned above, the program will overlay the sine curve to the data. All of the initial estimates were close to the actual values so every curve ran through or close to all of the points on the graph. Each graph was modified so that the curve better fit the measured data by adjusting the T-zero, period, and amplitude estimates; see graphs. The RMS residual value located below each graph measures how well a curve fits the input data. A RMS value with a negative power of ten means that the curve is similar to a perfect curve, thus the more negative the power the better the curve. Callisto’s measurements were the first to be graphed followed by Ganymede then Europa and finally Io. After manipulating each curve the RMS residuals as well as the actual T-zero, radius, and orbital time were recorded in data sheet B. In the final stage of this lab each moon’s measurements were converted to fit the formula for Kepler’s 3rd law and the mass of Jupiter was calculated four times from each moon’s measurements and then averaged (see data sheet B.).

### **Results:**

When using Callisto’s measurements the mass of Jupiter, in solar units, was shown to be  $X.XX \times 10^{-x}$ . Both Ganymede and Europa’s measurements gave a mass of  $X.XX \times 10^{-x}$  Suns. Io gave a mass of  $X.XX \times 10^{-x}$  Suns. All of these figures are similar to each other with only a X% difference between the Ganymede/Europa measurement and the Io measurement. The average mass of Jupiter as calculated in this lab is approximately  $X.XX \times 10^{-x}$  Suns. This is about  $X.XX \times 10^{xx}$  kg. These figures imply that the Sun is X times more massive than Jupiter and Jupiter is in turn about X times heavier than Earth. In actuality Jupiter is  $X.XX \times 10^{xx}$  kg, which is  $X/X^{\text{th}}$  the mass of the Sun and X times more massive than Earth.

These estimations of Jupiter’s mass were calculated using the formula for the revised version of Kepler's 3rd law. Beyond measuring Jupiter’s mass, which has been known for some time, this formula can be used to

answer many interesting and hypothetical questions. For instance if Jupiter's mass were to double but the moons remained at their current positions, their orbital times would XXXX by a factor of XXXX. Likewise, if Jupiter's mass were to double but the orbital times of each moon remained constant, the distance between Jupiter and its satellites would have to XXXX by a factor of XXX in order to compensate for XXXXX. If a moon existed at a distance of 3.6 Jupiter diameters away from Jupiter's center its orbital period would likely be about X days long. All of these and many other possible or even impossible situations can be described by understanding the relationship between orbital radius and revolution time.

Like Newton said, the strength of a gravitational force between any two objects is a result of their multiplied masses divided by the distance between them squared. Therefore the closer any two objects are to one another the XXX the gravitational pull between them will be. The closer an object, like a moon, orbits to its parent the XXX it must travel in order to remain in orbit. The further away from their parent an object is located the XXX it will move. This effect was clearly visible during this lab. Io, the closest moon to Jupiter, traveled XXX than Europa and completed one of its revolutions in about XXX the time it took Europa to orbit. The ratio of Europa's orbital period to Io's orbital period is X:X. Europa is closer to Jupiter than Ganymede and it too orbited in XXX time than Ganymede. The Ganymede to Europa ratio is X. These moons are in what is called an orbital resonance, meaning they always exert a pull on each other at the same point in their orbits. Callisto is the Galilean moon furthest from Jupiter and the only Galilean moon not to be in resonance with the others. Because of its distance from Jupiter, Callisto moves X and has a X distance to travel in one orbit than any other Galilean moon. This means that of the four, Callisto has the X orbital period. For the same reasons mentioned above any moon located beyond the orbit of Callisto would have X orbital time than that of Callisto.

In this activity, certain errors were made while recording and analyzing data. Some were quickly corrected and had no lasting effect on the results; others were not and did influence the outcome. There were three errors associated with recording measurements. Twice measurements were recorded only by hand and not in the computer record. On one occasion, Ganymede was located at 7.33E but 7.33W was recorded. All of these problems were easily remedied by returning to the date and time that the errors were made and recording accurate information. The fact that all observations were computer generated made it convenient to quickly fix problems like these. Fortunately these errors did not bear a lasting impression on the results because they were corrected before the data was analyzed. However after calculating Jupiter's mass four times, three different values were obtained. I believe these differences were caused by XXXX. [Justification sentence deleted]. But perhaps even more damaging was the fact that XXXX. The final estimates used in performing the calculations were obtained from the graphs and XXXX. The RMS residuals for Callisto, Ganymede, and Europa were 5.76E-02, 1.40E-02, and 4.13E-02 respectively. Io's graph had a RMS of 1.06E-01 and therefore was XXXX. The value of Jupiter's mass given from Io was also the most unlike the other values. These errors [verb deleted]

however dramatically affect the overall outcome of this study. Jupiter's mass as calculated in this lab was X to the actual mass of Jupiter.

**Special Astronomy 12 Section:**

4 & 5. Based on my common sense, If Jupiter got heavier but each moon's location stayed the same, their orbital times would have to X. A more massive Jupiter would X. This would cause them to move X and complete their revolutions in X time. I think if Jupiter's mass increased but each moon kept their same orbital times then the distance between Jupiter and its moons would X. For each moon's orbital time to stay the same they would have to be X in order to X.

**Summary:**

I really enjoyed this lab; in fact this has probably been my favorite so far. The instructions given on the lab handout were clear and easy to follow. I can't think of any task that was overly difficult or problem that I had that wasn't dealt with at the time of the lab. I'm glad that we did this lab before the outdoor Jupiter lab. It's a little easier and I think it helped me understand the outdoor version better.

[Note: data that were obtained during the lab were attached to this report.