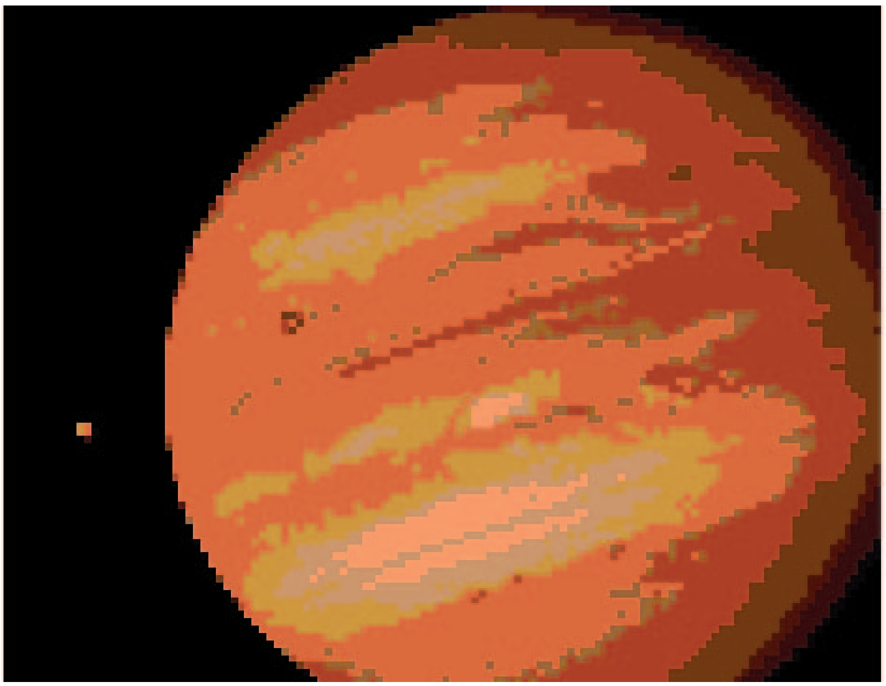
The Revolution of the Moons of Jupiter

Student Manual

A Manual to Accompany Software for
the Introductory Astronomy Lab Exercise
Document SM 1: Version 1



Department of Physics
Gettysburg College
Gettysburg, PA 17325

Telephone: (717) 337-6028
email: clea@gettysburg.edu

Contemporary Laboratory
Experiences in Astronomy

Contents

Goals

You should be able to determine the mass of Jupiter by measuring the orbital properties of Jupiter's moons and analyzing their motions using Kepler's Third Law.

Objectives

If you learn to ....

Interpret the back and forth motion as the linear projection of a circular motion and use that interpretation to measure he orbits of satellites.

Discover the relationship between the radius of an orbit and the period for a gravitationally bound system.

Plot the results and fit a sin curve to them.

You should be able to.......

Apply the laws of motion (or Kepler's Third Law) to calculate the mass of Jupiter.

Estimate the orbital period or radius for another moon of Jupiter.

Equipment

The equipment used in this experiment consists of an IBM pc clone running the **CLEA** program ***The Revolution of the Moons of Jupiter*** and a scientific pocket calculator.

Historical Background

We can deduce some properties of celestial bodies from their motions despite the fact that we cannot directly measure them. In 1543 Nicolaus Copernicus hypothesized that the planets revolve in circular orbits around the sun. Tycho Brahe (1546-1601) carefully observed the locations of the planets and 777 stars over a period of 20 years using a sextant and compass. These observations were 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 for a moon orbiting a much more massive parent body is

$$\mathbf{M} = \frac{\mathbf{a}^3}{\mathbf{T}^2}$$

where M is the mass of the primary body, in units of the solar mass.

a is the length of the semi-major axis of the elliptical orbit in units of the mean Earth-Sun distance, 1 A.U. (astronomical unit). If the orbit is circular (as will be assumed in this lab) the semi-major axis is the same as the radius of the orbit.

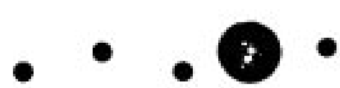
T is the period of the orbit in Earth years. The period is the amount of time required for the moon to orbit the parent body once.

In 1609 the telescope was invented, allowing the observation of objects not visible to the naked eye. Galileo used a telescope to discover that Jupiter had four moons orbiting it and made exhaustive studies of this system. The Jupiter system was especially important because it is a miniature version of the solar system which could be studied in order to understand the motions of the solar system. The Jupiter system provided clear evidence that Copernicus' heliocentric model of the solar system was physically possible. Unfortunately for Galileo, the inquisition took issue with his findings; he was tried and forced to recant.

Introduction

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.

You can remember the order by the mnemonic "**I E**at **G**reen **C**arrots". If you looked through a small telescope, you might see the following:



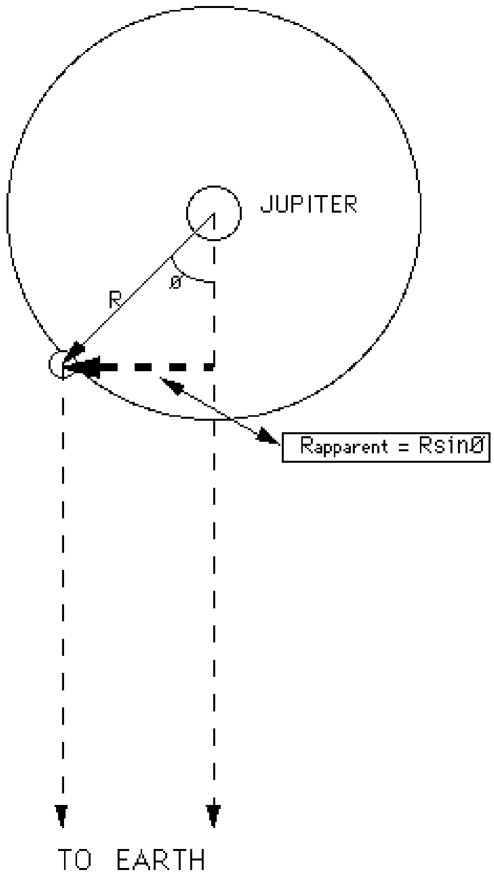


Figure 1

Geometry of Kepler's Third Law

The moons appear to be lined up because we are looking edge-on to the orbital plane of the moons of Jupiter. As time goes by, the moons will move about Jupiter. While the moons move in roughly circular orbits, you can only see the perpendicular distance of the moon to the line of sight between Jupiter and Earth.

Therefore, the perpendicular distance of the moon should be a sinusoidal curve if you plot it versus time. By taking enough measurements of the position of a moon, you 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 you know the radius and period of the orbit of that moon and convert them into appropriate units, you can determine the mass of Jupiter by using Kepler's Third law. You will determine Jupiter's mass for each of the four moons; there will be errors of measurement associated with each moon, therefore your Jupiter masses may not be exactly the same.

The Jupiter 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 is a sophisticated computer program that allows convenient measurements to be made at a computer console, as well as adjusting the telescope's magnification. The computer simulation is realistic in all important ways, and using it will give you a good feel for 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.

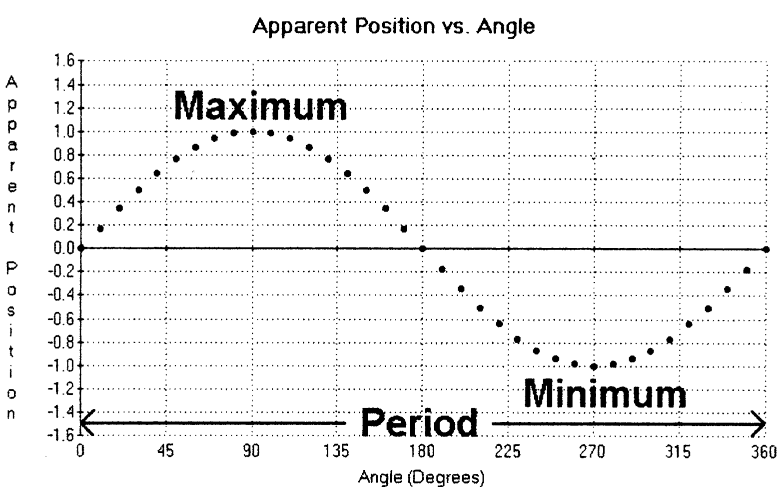


Figure 2

Apparent Position of a Moon

The apparent position of a moon varies sinusoidally with the changing angle form the line of sight, θ , as it orbits Jupiter. Here the apparent position is measured in units of the radius of the moon's orbit, **R**, and the angle measured in degrees.

Overall Strategy

This is the overall plan of action for this laboratory exercise.

- Use the Jupiter program to observe and measure the apparent positions of the moons of Jupiter. Your instructor will specify the moons to be observed, the assigned starting date, the interval between observations , and the total number of days to be covered. Note that different lab groups may be asked to make different sets of observations.

- Plot your observations for each moon on the appropriate graph paper supplied with this write-up.

- Carefully sketch in the curve (sine curve) best representing the data on each graph.

- Determine the period and semi-major axis for the orbit of each moon form its graph, then convert the values to years and AU, respectively.

- Calculate the mass of Jupiter from your observations of each moon, them determine the average value for Jupiter's mass form your individual values.

Using the Jupiter Program

1. Open the Jupiter program by double-clicking on it with the mouse.

2. At any time, you may select **Help** from the menu to receive on-line help. Within the help menu are four choices that you can select: **Getting Started**, **Taking Data**, **User** and **About This Exercise**. **Getting Started** advises you on how to set up the program before taking data. **Taking Data** explains how to manipulate the program in order to take data. There is no user help for this program therefore **User** is disabled. **About This Exercise** displays the title and version number of the program as well as copyright information. To close the help windows, select **Close** from the box in the upper left corner of the window. You may leave the help windows open if you prefer while working, in which case you will want to select **Size** from the box in the upper left corner of the window. Your pointer will change to a pair of arrows; move the pointer to any edge you want to move and drag the edge to the desired position.

3. You must first select **Log In...** from the menu before taking data. You can then enter the names of each student working at that particular table as well as the table number. Do not use punctuation marks. Press the tab after each name to skip to the next entry, or place the cursor in the next field by clicking on the mouse button. When all the information has been entered to your satisfaction, click **OK** to continue.

4. Select **Start** to begin the program**.** The next dialog box to appear is **Start Date and Time.** Enter the appropriate date and time. The default is the current date. The observational time interval can also be changed. If you wish to return to the original information, click **Cancel**. When all the information has been entered to your satisfaction, click **OK** to continue.

5. You can display the screen at four scales of magnification by clicking on the **100X**, **200X**, **300X** and **400X** buttons at the bottom of the screen. In order to improve the accuracy of your measurement of a moon, you should use the largest possible magnification which leaves the moon on the screen.

6. In order to measure the perpendicular distance of each moon from Jupiter, move the pointer until the tip of the arrow is centered on each moon and click the mouse. Information about the moon will appear at the lower right corner of the screen. This includes the name of the selected moon, the x and y pixel location on the screen, and the perpendicular distance (in units of Jupiter's diameter) from the Earth-Jupiter line of sight for the selected moon as well as an E or W to signify whether it is east or west of Jupiter. If the moon's name does not appear, you did not center the arrow exactly on the moon; try again.

7. When you have recorded the Universal Time and the perpendicular distances for every moon, you may make the next set of observations by clicking on the **Next** button.

8. When you have finished taking readings, you may quit the program by selecting **Quit.**

Procedure

1. Start up the program and select **Log In...** to enter your names and table number. Each table will perform and observe a different set of observing sessions. The starting dates of observations for each table will be listed on the blackboard. Fill in this table first, then select **Start** and enter the information into the program as shown in section 4 of *Using the Jupiter Program*.

   Table Number ______________________

   Year of Observations ______________________

   Month ______________________

   Day ______________________

   Time Zone ______________________

   Number of Observations ______________________

   Interval Between Observations ______________________

2. After you have clicked the **Ok** button, you will see a display similar to the following:

Figure3
JUPITER AND ITS MOONS

Jupiter is in the center of the screen, while the small point-like moons are to either side. Sometimes a moon is behind Jupiter, so it cannot be seen. Even at high magnifications, they are very small compared to Jupiter. The current telescope magnification is displayed at the upper left hand corner of the screen. The date, UT (the time in Greenwich, England) and J.D. (Jupiter's diameter in A.U.) are displayed at the lower left hand corner of the screen.

Click on each of the moons to find the number of J.D. (Jupiter diameters) the moon is away from the center of Jupiter. Notice the edge on Jupiter is 0.5 J.D. To measure each moon accurately, switch to the highest magnification setting that leaves that moon on the screen. If the moon is behind Jupiter, record the distance for that moon as zero. Below is an example of how to record your data:

Example:

(1) Date	(2) Time	(3) Day	(4) Io	(5) Europa	(6) Ganymede	(7) Calisto
7/24	0.0	1.0	+2.95	+2.75	-7.43	+13.15
7/24	12.0	1.5	-0.86	+4.7	-6.3	+13.15

Column 1:	Local Date
Column 2:	Universal Time
Column 3:	Day - number of day (e.g. 1.0, 1.5, 2.0, ...) **NOT** counting cloudy days. Enter cloudy days in the space provided below.
Columns 4-7:	Record each moon's position under the column for that moon. ***Use + for west and - for east***. If Europa were selected and had an X = 2.75W, you would enter that in column 5 as +2.75.

Record your data on the following data sheet.

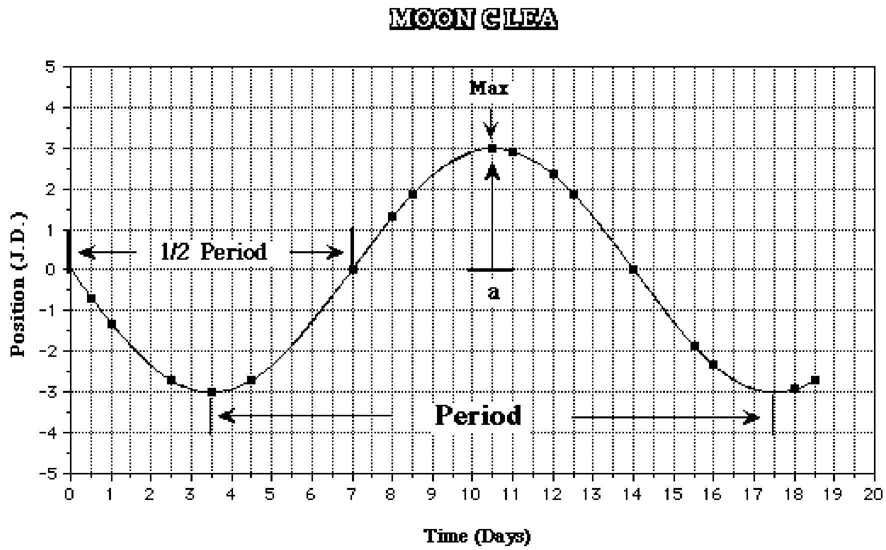
Data Sheet

Your Data: Collect 18 lines of data

(1) Date	(2) Time	(3) Day	(4) Io	(5) Europa	(6) Ganymede	(7) Callisto

(1) Date	(2) Time	(3) Day

3. You now need to analyze your data. By plotting position versus time, you will use the data to obtain a graph similar to the one below. (The data shown are for an imaginary moon named CLEA, not one of the moons in the laboratory exercise.)



P = _14 days__ **a = ________3 J.D._**

= __.0383 years **= ____.00286 A.U.**

Each dot in the figure is one observation of moon CLEA. Note the irregular spacing of dots, due to poor weather and other problems on some nights. The curve drawn through the points is the smooth curve that would be observed if you decreased the observation interval enough. The shape of the curve is called a sine curve.

You will need to determine the sine curve that fits your data best in order to determine the orbital properties of each moon. Here are a few hints: *the orbits of the moons are regular*, that is, they do not speed up or slow down from one period to the next, and *the radius of each orbit does not change* from one period to the next. The sine curve that you draw *should therefore also be regular*. *It should go through all of the points*, and not have a varying maximum height nor a varying width from peak to peak.

Using the data from the imaginary moon CLEA, it is possible to determine the radius and period of the orbit. The period is the time it takes to get 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 form the front of Jupiter to the back of Jupiter, or half way around. For your moons, you may not get data from your observations for a full period. You may find the time between crossings at 0 J.D. to be of use to you in determining the period, even though the moon has not gone through a complete orbit. In the other hand, if you have enough observations for several cycles, you can find a more accurate period by taking the time it takes for a moon to complete, fro example 4 cycles, and then divide that time by 4.

When a moon is at the maximum position eastward or westward, it 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.

4. Enter the data for each moon on the graphs provided. Along the horizontal scale, write the date starting on the left with the number of the first day for which you have data. The vertical scale is already marked. Each day's measurement of a moon's apparent separation form Jupiter should give you one dot on the graph for that moon. Remember, each day has two observing sessions, so be sure each point on the graph on the horizontal axis represents only one session.

5. For each moon, draw a smooth curve through the points. Mark all maxima and minima on the curve by crosses. They need not all fall on one of the grid lines. The curve should be symmetric about the horizontal axis; i.e. the maxima and minima should have the same values, except for their sign.

6. Read off the period, **T**, and the orbital radius, **a**, from your graphs in the manner shown for moon CLEA. These values will have units of days for **T** and J.D. for **a**. In order to use Kepler's Third Law, you need to convert the period into years by dividing by the number of days in a year (365), and the orbital radius by dividing by the number of Jupiter diameters in an A.U. (1050). Enter your converted values in the spaces provided with each graph. You now have all the information you need to use Kepler's Third Law to find the mass of Jupiter.

$$\mathbf{M} = \frac{\mathbf{a}^3}{\mathbf{T}^2}$$

where $\mathbf{M_J}$ the mass of Jupiter in units of the solar mass

$\mathbf{a}$ is the radius of the orbit in units of A.U.

$\mathbf{T}$ is the period of the orbit in Earth years

Calculate a mass of Jupiter in each of the four cases. Hint: If one of the values is very different from the other three, look for a source of error. Perhaps the data are not adequate for a better result, in which case leave the value as you obtained it.

From Callisto $\mathbf{M_J}$= ____________________

From Ganymede $\mathbf{M_J}$= ____________________

From Europa $\mathbf{M_J}$= ____________________ **in units of solar masses**

From Io $\mathbf{M_J}$= ____________________

Average $\mathbf{M_J}$ = ____ **solar masses**

Use the space provided below for your calculations.

Questions and Discussion

1. Express the mass of Jupiter in earth units by dividing it by 3.00×10^{-6}, which is the mass of Earth in solar mass units.

Average M_J = ___________________________________earth masses

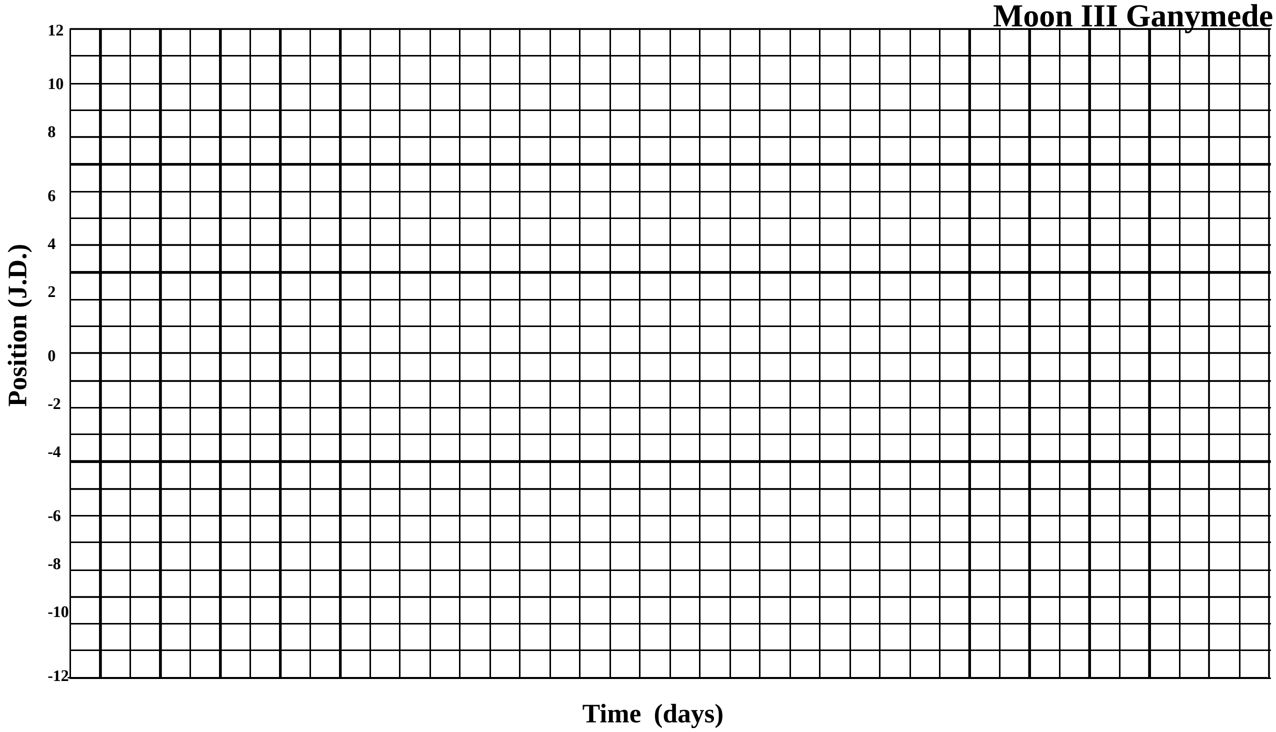
2. There are moons beyond the orbit of Callisto. Will they have larger or smaller periods than Callisto? Why?

Extra Credit

1. Which do you think would cause the larger error in : a ten percent error in T or a ten percent error in a? Why?

2. The orbit of earth's moon has a period of 27.3 days and a radius (semi-major axis) of 2.56 x 10^{-3} A.U. (= 3.84 x 10^{5} km). What is the mass of Earth? What are the units? Show your work.

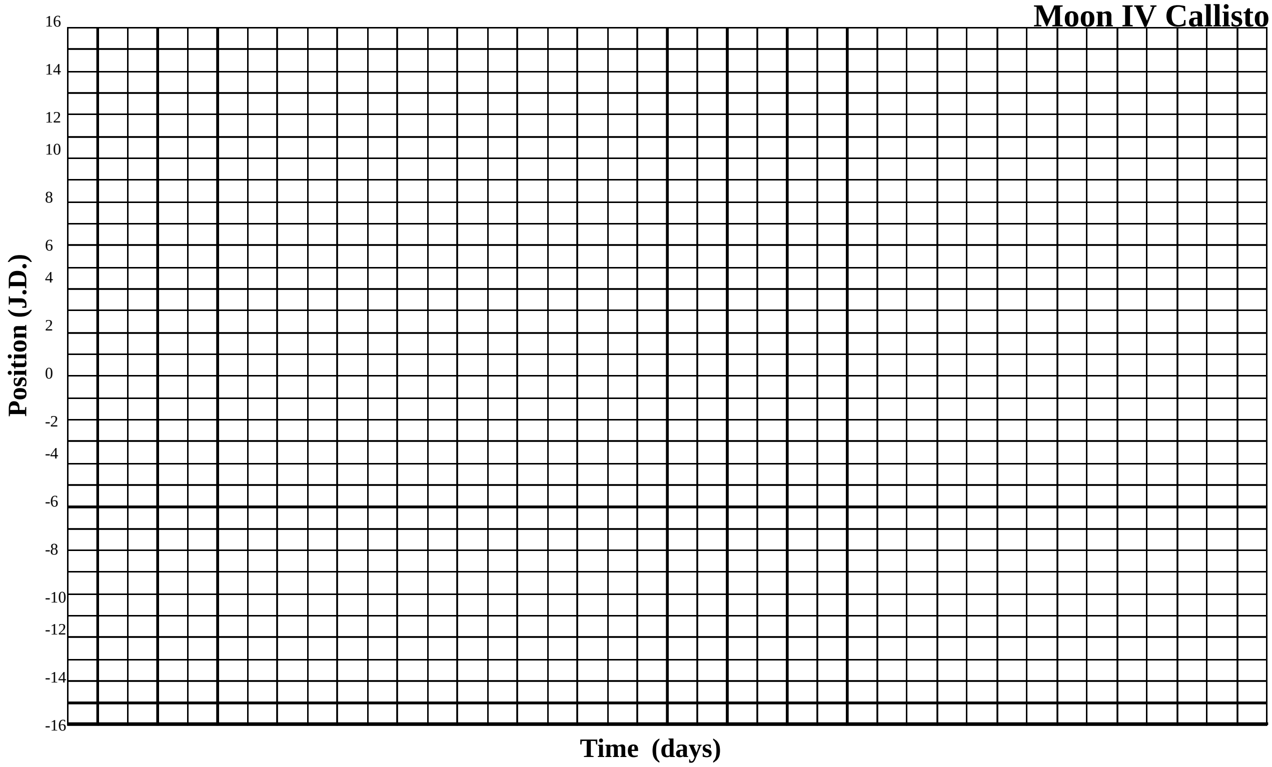
Moon III Ganymede



p (period) = ____________ days **a (semi-major axis) = __________________ J.D.**

p (period) = ____________years **a (semi-major axis) = __________________ A.U.**

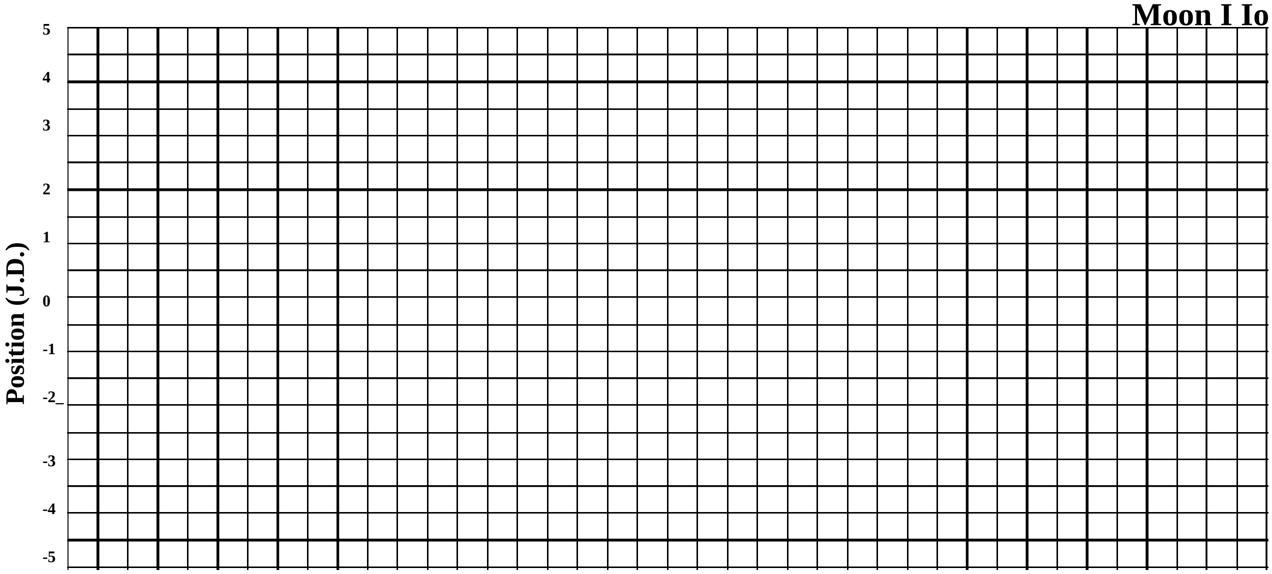
Moon IV Callisto



p (period) = ____________ days **a (semi-major axis) = __________________ J.D.**

p (period) = ____________years **a (semi-major axis) = __________________ A.U.**

Moon I Io



Time (days)

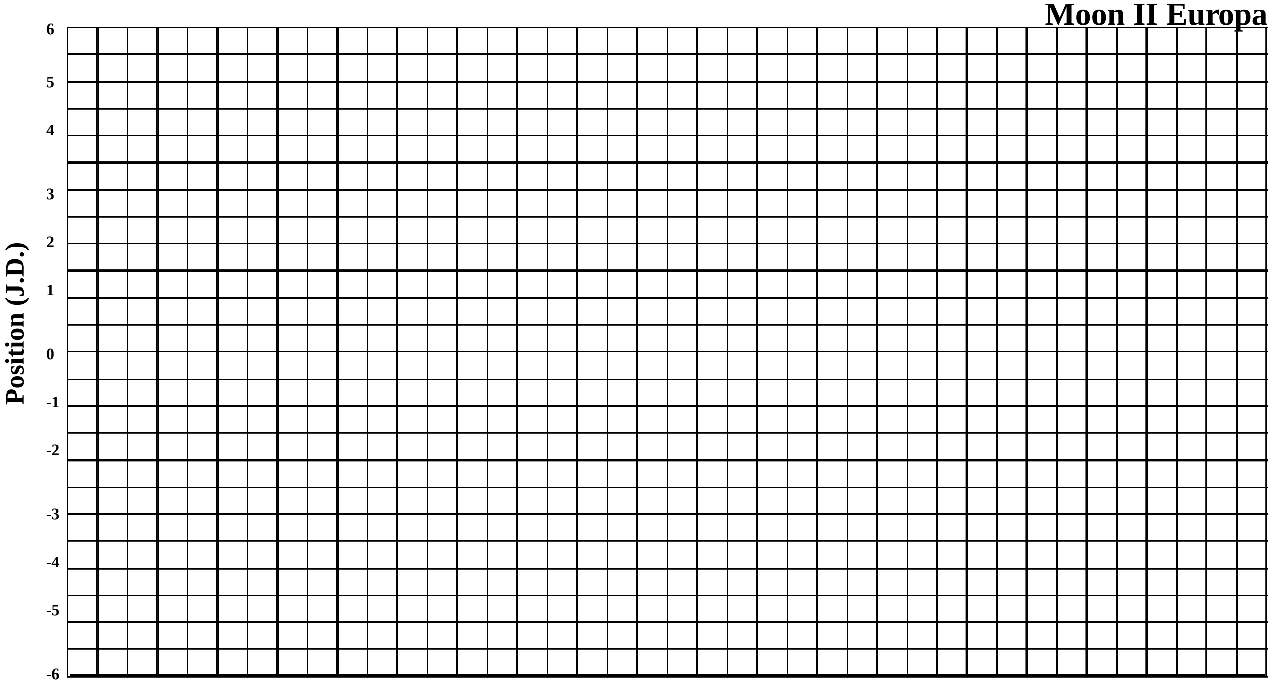
p (period) = ______________ days

a (semi-major axis) = ____________________ J.D.

p (period) = ______________years

a (semi-major axis) = ____________________ A.U.

Moon II Europa



Time (days)

p (period) = ______________ days

a (semi-major axis) = ____________________ J.D.

p (period) = ______________years

a (semi-major axis) = ____________________ A.U.