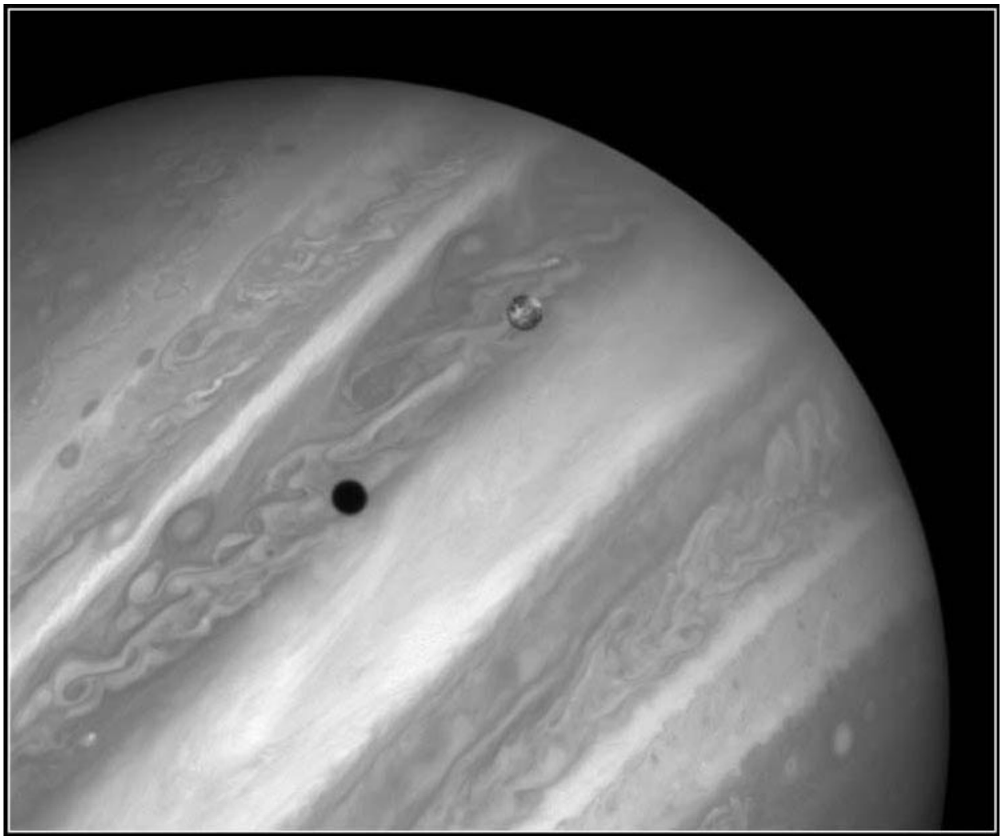
The Moons of Jupiter



Laboratory 10

Astronomy 120. The Copernican Revolution

Name	Full	Partial	None

Purpose

To measure the orbital properties of Jupiter's moons, and to analyze their motions using Kepler's third law in order to obtain the mass of Jupiter.

Apparatus

PC and CLEA software. This software was created by the good people of the Gettysburg College Department of Physics and Astronomy and is FREE over the Internet. The project was supported by a grant from the National Science Foundation and thus is a shining example of your tax dollars at work.

The Moons of Jupiter program like all CLEA labs is designed to simulate observation and data taking as done by an actual astronomer. The idea, of course, is that if you are presented with real-world data and asked to analyze it then you may come to know something of the way science is actually done. The MoJ program is based on actual orbital data for each of the planet's four major satellites. In fact, if you were to set the simulation for today's date and time, you could verify the position of the Jovian moons by direct observation at Berry's own Pew Observatory!

Introduction

We have already discussed the telescopic observations that Galileo reported in his *Siderius Nuncius*: mountains on the Moon, stars composing the Milky Way, the phases of Venus, etc. One of the most important discoveries was that of Jupiter's four major moons. Galileo made such exhaustive studies of these satellites' motions that they have come to be known as the *Galilean satellites*. This miniature solar system was the first clear evidence that an earth-centered solar system was not physically necessary.

Because he was developing a worldview which did not square with the dominant philosophical and religious (and in that time, political) paradigm, Galileo was compelled by the authorities to neither "hold nor defend" the Copernican hypothesis. Nevertheless, in 1632 he published his *Dialogue on the Great World Systems* which was a thinly disguised defense of the Copernican view. This led to the forced denunciation of the theory and confinement to his home for the rest of his life.

In this lab, you are going to repeat Galileo's observations. But no one will demand that you renounce your conclusions, unless you are blatantly wrong.☺ Plus, we'll do Galileo one better: we'll use our observations and our knowledge that Jupiter's diameter is about 150,000 kilometers (11 earth diameters) to determine the mass of this celestial giant.

Kepler's Third Law

When one body orbits a parent body that is much more massive, Kepler's third law may be used to relate the mass of the parent body to the average separation between the bodies and the period of the orbit thus:

$$m = \frac{a^3}{p^2},$$

where m is the mass of the primary body in units of the mass of the Sun ($M_\odot$), a is the radius of the orbit (we will assume a circular orbit) in AU, and $p =$ the amount of time required for a single orbit (that is, the period), measured in earth years. This law applies to planets orbiting the Sun or to any moon orbiting its planet.

Note that Galileo could not have made use of this procedure to determine the mass of Jupiter. Galileo made his observations in 1609 and published the *Siderius Nuncius* in 1610. Kepler published his "third law", in which he stated that the ratio a^3/p^2 is the same for all planets, in his *Harmonices Mundi* in 1619. The relationship between this constant ratio and the mass of the Sun was not clear until Newton published his *Principia* in 1687. But thanks to these great pioneers we have all the tools we need to figure out the mass of Jupiter.

You will be determining a in Jupiter diameters (JD) and p in Earth days (ED) for the Galilean moons of Jupiter and then $m_{♃}$, the mass of Jupiter. You will convert these units near the end of the lab, but right now we need to figure out the conversion factors.

1. First of all, let's think about the conversion from Earth days to Earth years. There are ______________________________ Earth days in one Earth year.
2. Now we need to figure out the conversion from Jupiter diameters to Astronomical Units. In the Copernican system Jupiter's orbit has a radius of 5.2 AU. Earth's orbit, of course, has a radius of 1 AU. When Jupiter is in *opposition*, how far away is it from Earth? (Hint: you may want to draw a diagram to help you figure this out.)
3. Observations show that Jupiter's angular diameter when it is in opposition is about $47''$. Convert this angular diameter to degrees.
4. Now determine Jupiter's physical diameter (in AU) using the relationship between angular diameter, physical diameter, and distance we have used before: $D = \pi d\delta/180°$ where δ is the angular diameter in degrees, D is the physical diameter, and d is the distance.
5. There are ______________________________ Jupiter Diameters in one Astronomical Unit.

The Galilean Satellites

We could do this lab for any one moon of Jupiter. If we did the experiment very accurately, the answer for Jupiter's mass should be the same whatever moon we use. But there will be errors, and we shall use data for all four major moons of the planet; by averaging the results we will arrive at a better value. The moons have wonderful names: Io, Europa, Ganymede, and Callisto, in order of distance from Jupiter. (Remember them by the mnemonic **I E**at **G**reen **C**arrots.) All but Ganymede were mistresses of Zeus (Jupiter)[1] and Io and Callisto suffered ugly fates because of the jealousy of Hera, Zeus' mercurial wife.

Jupiter and its moons look something like this through any small telescope:

[1]Ganymede was male, and thus would not qualify as a "mistress" but there are some indications in the myths of an erotic relationship between Zeus and Ganymede. Eventually Zeus would make Ganymede immortal and have him serve as cupbearer to the Gods. He is identified with the constellation Aquarius (the water giver) as well as with one of Jupiter's moons.

The moons appear to be lined up because we are looking edge-on at the orbital plane of the moons. They will look similar to this on the computer screen. West is to the right and east is to the left since we are looking up at the sky, not down on a map. It will be necessary to record the distance of a moon from Jupiter's center in JD. Lucky thing: the computer equipment you will use provides a direct readout in JD.

Procedure

Setup

First, open the CLEA lab by clicking on the `Revolution of Jupiter Moons` icon on the desktop.

The first screen you should see will be dominated by a large CLEA logo. Click on `File` at the top of the screen, then `Login`. You will be presented with a window in which you will be asked to type your name and that of your partner(s). Simply click `OK` (twice); there is no reason to enter any information. The next screen shows a big beautiful picture of Jupiter; click on the `File` item at the top, then click `Run`. This will bring up a window in which you will be asked to enter the starting date and time. For now, the starting date and time is not important. Information on the correct numbers will be given during the lab session. Now, click `OK`. You should now see the main telescope screen. Next click `File..Timing`. This screen is where you enter a value for the time interval between observations. Enter "24 hours" for the time interval, then click `OK`. Before we begin, let's get a feel for the program.

The Main Telescope Screen

NOTE: DO NOT YET CLICK ON THE `NEXT` BUTTON. You control the observing session from this screen; the window simulates the operation of an automatically controlled telescope with a charge-coupled device (CCD) camera that provides a video image to a computer screen. You can adjust the telescope's magnification from this screen as well, just as you can with a real computer-controlled scope. Jupiter is in the center and to the sides are the point-like satellites. Even at high magnification, they are small compared with Jupiter itself.

UT (time at Greenwich, England) is displayed in the lower left, as well as the date. (Note: The Jul. Day you see on the bottom left of the screen means *Julian day*. The Julian day is a way that astronomers like to record dates.) The magnification can be controlled by clicking the magnification buttons; try it. The current magnification is in the top left corner. Now click the `Next` button. This moves the satellites up in time by 24 hours.

Now position the cursor very near, and just under a moon. Click and hold and you will see some crosshairs. Center these crosshairs on a moon. The measurement system at the bottom right of the window displays several parameters. You are interested only in the number that is followed by `E` or `W`. This is the apparent Jupiter-moon distance in units of JD. Sometimes a moon is behind or in front of Jupiter, so it can't be seen at all. When this happens, record the moon's distance as zero.

You have a data sheet for each moon. Since the periods of the moons vary significantly, you need to change the time interval between observations for each. To do this, you'll need to look under the `File` menu, select `Set Date/Time`, and reenter your start date and time information, then click `File..Timing` to enter the time interval. Use the data in the following table.

Moon	Time Interval	Magnification
Io	4 hours	400×
Europa	8 hours	300×
Ganymede	24 hours	200×
Callisto	48 hours	100×

ALSO: In the real world, some nights are cloudy and no observations are possible. The software nicely includes this real-world effect and on those nights you get NO DATA.

Steps In Data Analysis

1. On the main telescope screen, click `File` then `Set Date/Time` and enter today's date and 03 hours, 00 minutes UT. Since Greenwich is 5 hours east of us and we're using a 24-hour clock, this corresponds to 10:00 PM local time. Make sure you set the time interval and magnification as described above.
2. Begin the data collection process by recording the data on the attached sheet. Make 20 readings per moon, each time advancing one time interval. The relative time begins at zero. I suggest filling in the date, time (UT), and relative time for the each table BEFORE you do the distance measurements. Since you know the time increment you can figure all of that out ahead of time. This will make your distance measurements go much faster.
3. Record all data for Io before you proceed to Europa etc. IF THE DISTANCE IS FOLLOWED BY A *W* THEN ASSIGN A POSITIVE SIGN; IF IT'S FOLLOWED BY AN *E* THEN ASSIGN A NEGATIVE SIGN!
4. Plot your data for Io on the attached graph paper and draw a smooth sine curve through your points. On a sine curve, all peaks have equal heights and all troughs have equal depths; all peaks and troughs are also separated by equal time amounts. Drawing a smooth curve can be tricky given the no-data nights; again, welcome to the astronomer's world of less-than-ideal observations!
5. Find the value of p by finding the number of ED between peaks or troughs on your graph. For Io and Europa the value is in hours; divide by 24 to get ED. Record this number below your graph. Then convert this number to earth years by dividing by 365.25.
6. Find the value of a by finding Io's *maximum* distance from zero; that is, the maximum position reading along the y-axis. Record this in the space provided. To convert this to AU you need to divide your result by 1050 since there are 1050 Jupiter diameters in an AU. Enter this in the space provided.
7. We can now calculate the mass of Jupiter by using equation Kepler's third law. Place the number in the appropriate blank on the Mass of Jupiter Data sheet.
8. Repeat steps 1-6 for Europa, Ganymede, and Callisto. Start each at the same date and time, but be sure to assign each the proper time interval and magnification (see table on previous sheet).
9. Average the four numbers and get a final reading for the mass of Jupiter; record this number!
10. Think about and answer the questions on the last page.

Worksheet 1: Io

Time interval = ____________________________

	Date	UT	Relative Time (hours)	x (JD)
1			0	
2				
3				
4				
5				
6				
7				
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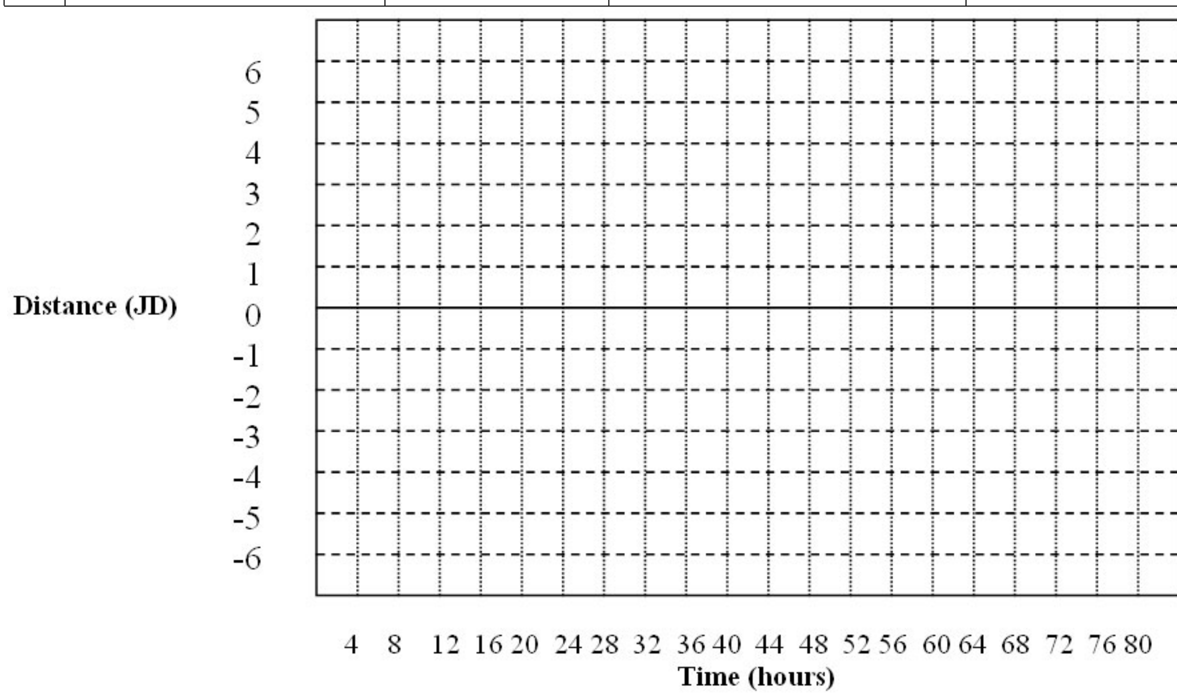
20				



$p =$ ______________ hours = ______________ earth days = __________________ earth years

$a =$ ______________ JD = ______________ AU

Worksheet 2: Europa

Time interval = ______________________

	Date	**UT**	**Relative Time (hours)**	x (JD)
1			0	
2				
3				
4				
5				
6				
7				
8				
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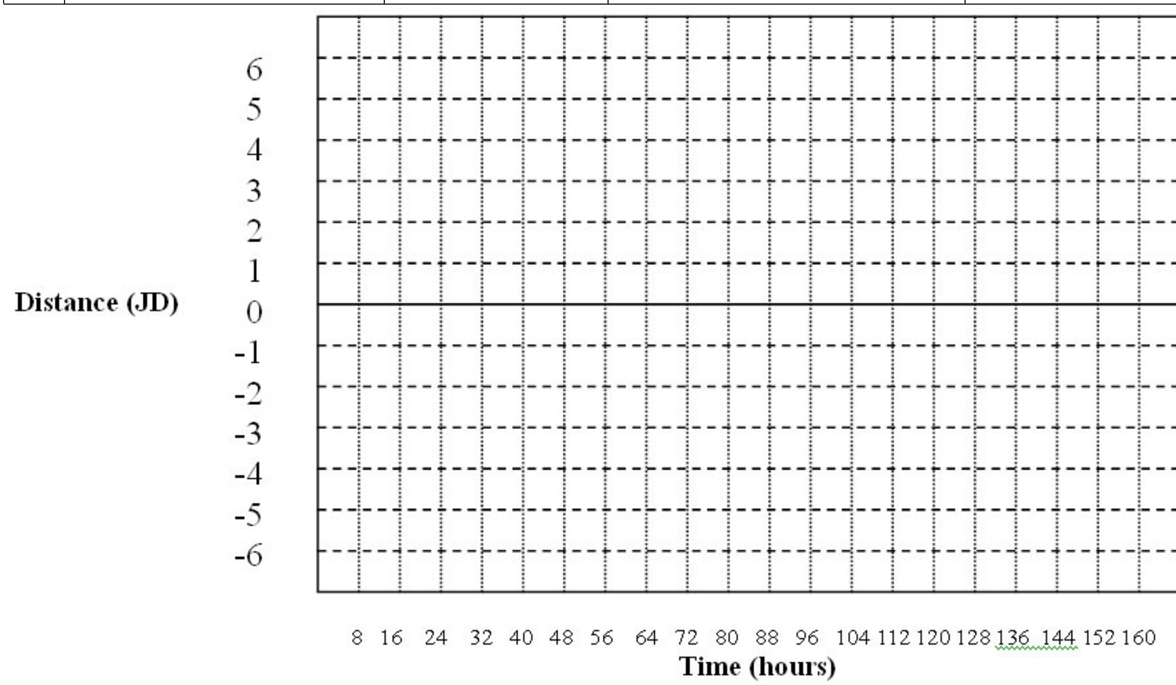

$p =$ ____________ hours = ____________ earth days = ______________ earth years

$a =$ ____________ JD = ____________ AU

Worksheet 3: Ganymede

Time interval = ____________________________

	Date	**UT**	**Relative Time (days)**	x (JD)
1			0	
2				
3				
4				
5				
6				
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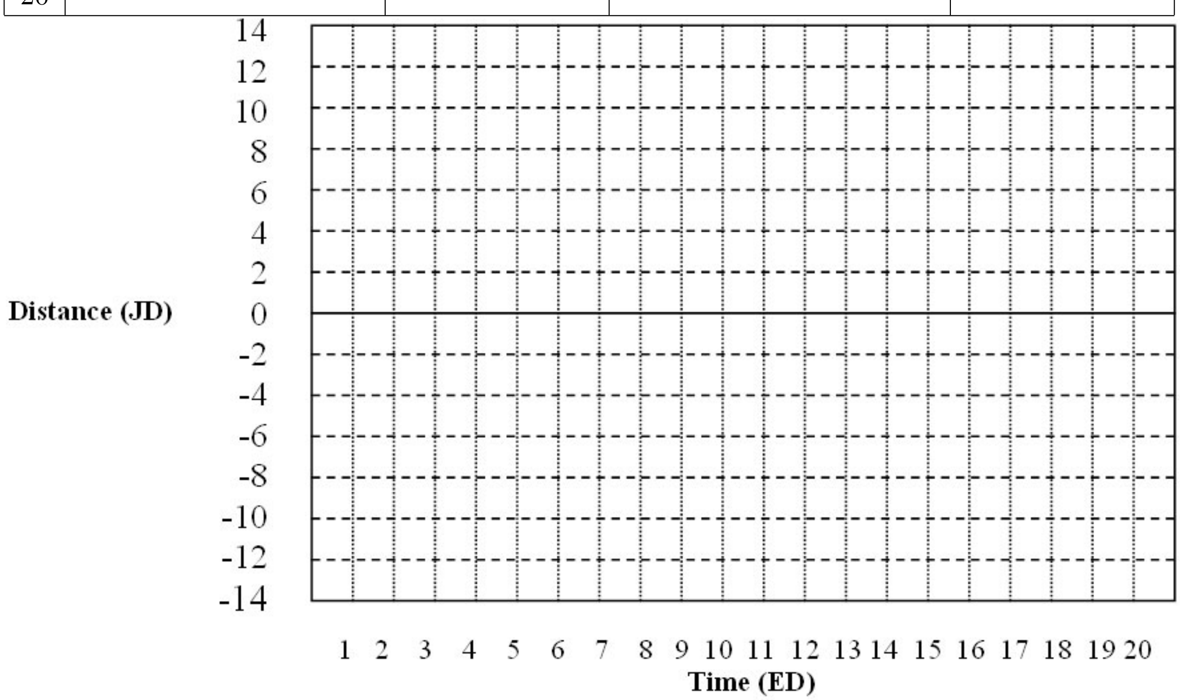

$p =$ ______________ earth days = __________________ earth years
$a =$ ______________ JD = ______________ AU

Worksheet 4: Callisto

Time interval = ______________________

	Date	**UT**	**Relative Time (days)**	x (JD)
1			0	
2				
3				
4				
5				
6				
7				
8				
9				
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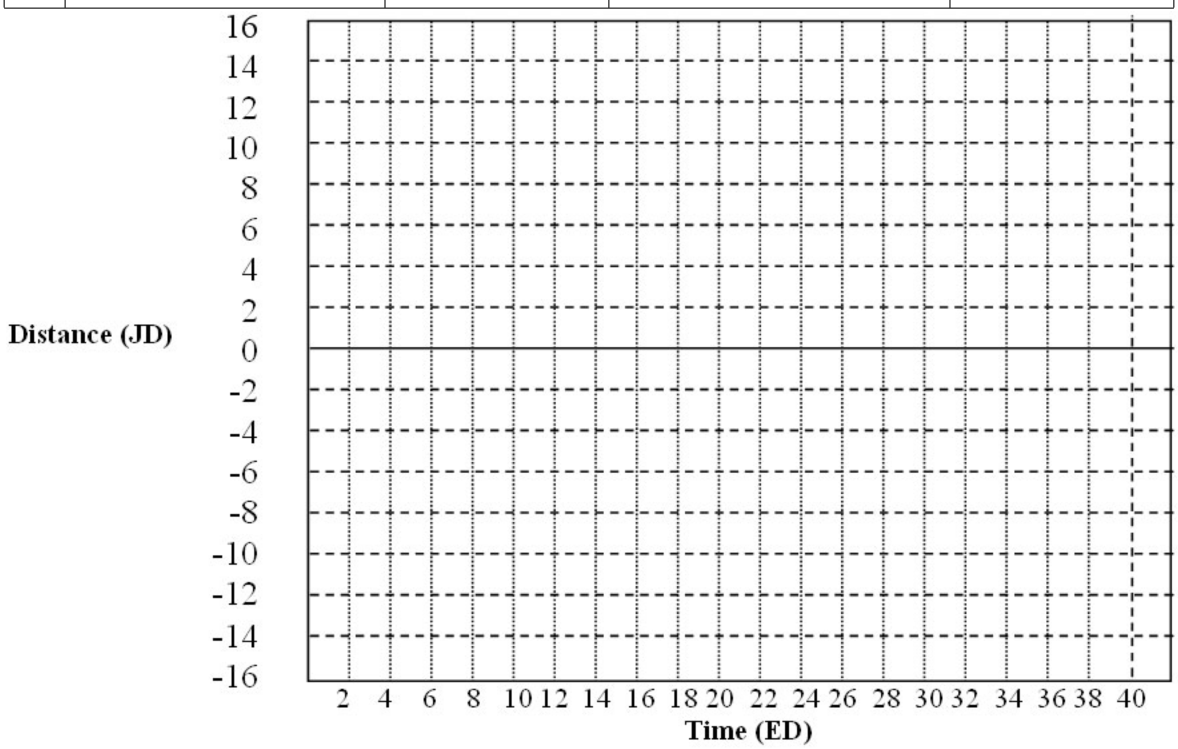

$p =$ ____________ earth days = ________________ earth years

$a =$ ____________ JD = ____________ AU

Mass of Jupiter Data

$m_{♃} =$ ____________________________ from Io data

$m_{♃} =$ ____________________________ from Europa data

$m_{♃} =$ ____________________________ from Ganymede data

$m_{♃} =$ ____________________________ from Callisto data

$m_{♃} =$ ____________________________ average (final number)

Questions and Discussion

1. The Earth's moon has a (sidereal) period of 27.3 days and is (on the average) 0.00256 AU away from Earth. What is the mass of the Earth? In what units? Show your work.

$m_{\oplus} =$ ____________________________

2. To express the mass of Jupiter in earth units, divide it by the mass of the earth in solar mass units (which you just found). Show your work.

$m_{♃} =$ ____________________________ $M_{\oplus}$. The accepted value is 317 earth masses.

3. There are lots of moons beyond Callisto's orbit. Will their periods be larger or smaller than Callisto's? Why?