

# Revolution of Jupiter's Moons

## Introduction

In 1543 Copernicus hypothesized that the planets revolve in circular orbits around the sun. Not much later, Tycho Brahe carefully observed the location of the planets over a period of 20 years using a sextant and compass. These observations were used by his student, Johannes Kepler, to deduce three empirical mathematical laws governing the orbit of one body around another.

His first law is that the planets orbit the sun as ellipses, rather than circles. This solved the “horribly complex” issue with the Ptolemaic model of the solar system, with its epicycles, although it wasn't until more accurate data was available that it could be tested more thoroughly.

His second law was that a planet travels its orbit with equal areas in equal times. In other words, when a planet is closest to the sun, it moves fastest, and when it's farthest it moves slowest. For planets, which move nearly on circles, this isn't a big difference. For comets, it can be!

Kepler's third law notes that you can measure the mass of the sun by measuring the period and semi-major axis of a planet orbiting the sun.

In 1609 the telescope was invented. When Galileo turned his telescope to the skies the next year, he could see Jupiter's four largest moons. His observations of their orbit was part of his argument that the Earth orbited the Sun, rather than the other way around: since he could see things orbiting Jupiter, he argued, it only made sense that it was a possibility for the Earth to orbit the Sun. Unfortunately for Galileo, the Inquisition took issue with his findings; he was tried and forced to recant and spent the rest of his life under house arrest.

Today we'll follow in the footsteps of Galileo in making observations of the four brightest moons of Jupiter. Since they behave like a miniature solar system, we can then use Kepler's 3<sup>rd</sup> Law to calculate Jupiter's mass. Fortunately for us, the Pope apologized to Galileo about the whole Inquisition thing (400 years after Galileo's death), so we won't have to worry about that.



## Part 1: Conceptual View

### Step 1: Setting up the Telescope

1. Click on the **CLEA** folder on the desktop
2. Start the program **Jupiter's Moons**
3. Log in, using initials for each group member and your group number
4. Go to **File** → **Run**
5. A dialogue box will open:
  - a) Check that **Calendar** is checked under Date/Time Format
  - b) Check that the date is correct
  - c) Set the time to 22:00:00 (this corresponds to 10:00pm)
  - d) Click **OK**

The screen will show Jupiter in the center, along with several (usually three or four) of its moons. If you were taking pictures, all you would get at one time would be exactly what you see here – a static image. But, since this is a simulation, we can take a quick look at how things move over time.

6. Go to **File** → **Features** and check the box next to **Animation**
7. Click **OK** to return to the main window
8. Click on the **Cont.** button

You should be able to see the moons moving around Jupiter now. Watch the motion a little to get a sense of how the moons appear to move.

9. Answer questions 1-4 in the packet based on what you observe.
10. Click on the **Cont.** button again to stop the motion
11. Go to **File** → **Features** and uncheck the box next to **Animation**
12. Go to **File** → **Observation Date** → **Set Date/Time**
13. Reset the **date** to the current date and the **time** to 22:00:00
14. Go to **File** → **Timing...** and change **Observation Step** to 12 hours

## Part 2: Taking Data

You will now begin taking data. In this simulation, clicking on one of the moons will give you information about it, such as its name and how far from Jupiter it is. If you were just going to do observations, you wouldn't have that information. Instead, you would have to physically measure the distances. That's not too hard, but somehow you would have to figure out which moon was which. Kepler got around this by using lots and lots and lots of measurements. Fortunately for you, we already know which moon is which, so you don't have to figure that out.

1. Click **and hold** on the image to get a cross-hairs
2. Center the cross-hairs on one of the moons, then release
3. Click the **Record** button. A window will pop up, just move it out of the way
4. Repeat 1-3 for the other moons in the image
5. When you are done, click **Next** for the next observation. **NOTE: the little window will disappear. That is OK.** As long as you hit "record" your data will still be there.
6. Repeat until you have made 20 sets of observations (This will be more than 10 days, since some nights it will be cloudy.)
7. View your data by going to **File** → **Data** → **Review/Edit/Print**
8. Print your data sheet by going to **List** → **Print** → **OWS 166**. Be sure to attach it to the answer sheet!

## Part 3: Graphing

We want to find the period and radius of each moon's orbit. Since we're not observing constantly, we can't just take the biggest distance we see and use that for the radius. Instead we need to plot the data on a graph, and fit a curve to it. We'll plot our observational data – distance from Jupiter vs. time – on a **separate graph for each moon**.

1. Make the x-axis long enough for all your observations. Be sure to keep a space if you missed an observation due to clouds!
2. Review your data. For each moon, find the largest distance from Jupiter (either East or West).

3. **Start with Callisto.** The y-axis will need to go positive and negative. Use the “positive” side for E and the “negative” side for W. (It doesn't really matter, but this way all the groups are the same). Make the y-axis the same height above and below zero (0 = Jupiter's location).
4. Plot the points for Callisto on your graph.
5. Try to draw a smooth curve through the points (don't just connect point to point, as this will lead to a jagged line). *Hint: It may help to put a dashed line along the maximum distance from Jupiter. Use the largest (either E or W) but use it for both E and W.*
6. Label your graph with the moon's name.
7. Next, do steps 1-6 for **Ganymede** (remember to make a separate graph).
8. And **Europa**.
9. Finally, do the same for **Io**.

You should now have four separate graphs. *Be sure to attach these to the answer packet before you leave.*

10. Answer questions 5-7

#### **Part 4: Analysis**

We're now ready to measure the mass of Jupiter! To do this we are going to use Kepler's 3<sup>rd</sup> Law:

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

- M** is the mass of the central object (in this case, Jupiter)
- a** is the semi-major axis (which is the *radius*, if the orbit is a circle)
- P** is the period (the time it takes to go around once)

M is the mass of Jupiter, but you can also do this for the Sun if you observe the planets going around to measure a and P. In fact, you can do this for any object which has another one orbiting it – the only trick comes in if the two are close to the same mass. Then instead of M, you have  $M_1 + M_2$  and can't really separate them. Here, this isn't a problem because the mass of the moons is very, very small compared to Jupiter, so we can pretend they're zero.

Let's find **a** and **P** for each of our moons. Remember that the moons are in circular orbits, so for distance we need the amplitude of our curve.

1. Measure the total distance from top to bottom of your curve (amplitude).
2. Divide by 2 to get the average Jupiter-moon distance. Write this number in column 2 of Table 1.
3. Measure the period by measuring one wavelength: crest to crest. Alternately, you can measure trough to trough, or where it crosses the line as long as you make sure to include one whole revolution. Write this in column 3 of Table 1.
4. Repeat for all of the moons

Now, the trouble is currently these numbers are in the less-than-useful "Jupiter Diameter" (for distance) and "Days" (for time). To calculate the mass of Jupiter, it's more useful to use the special units of "A.U." and "years".

5. Convert your numbers for **a** to astronomical units by dividing by 1050 (this may seem arbitrary, but it is the number of Jupiters that can fit in one A.U.)
6. Convert your days to years.
7. Write your new numbers in columns 4 and 5 of Table 1

Now, we can calculate the mass of Jupiter! Let's see how well the different moons match up.

8. Calculate the mass of Jupiter four times, once for each moon. Use Kepler's 3<sup>rd</sup> Law,  $M = a^3 / P^2$  and write your answers in Table 3
9. Calculate the average and write that in Table 2
10. Answer the remaining questions in the answer packet.