STARS RESOURCES
Student workbook

Jupiter and the Galilean Moons

ACTIVITY

Calculate the mass of Jupiter by observing and collecting data on the orbits of its four largest moons.

NOTE: This activity takes about a month of data collection to complete.

BACKGROUND INFORMATION

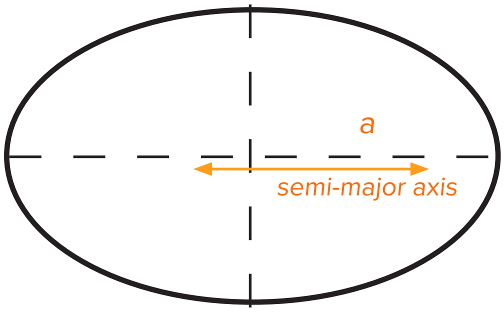
In 1609, Galileo Galilei observed four objects near Jupiter through his newly improved telescope. At first he thought they were distant stars, but they moved in the wrong direction compared to background stars, and stayed close to Jupiter.

Galileo took extensive measurements of their movements and identified patterns which led him to conclude that these objects were in fact moons orbiting Jupiter. We now know these moons as Io, Callisto, Ganymede and Europa.

Around the same time as Galileo was observing the sky, Johannes Kepler was using mathematics to describe the motion of objects in the sky. One equation became known as Kepler's Third law and applies to two objects orbiting around each other, whether that's the Earth around the Sun, or moons around a planet. The equation needs three properties: the time to complete an orbit, how far apart the objects are from each other, and how massive the objects are.

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

In this equation, ***a*** is the radius of the largest point of the orbit. Technically, this is known as the semi-major axis.



T is the period of the orbit (i.e. the time it takes to complete one orbit)

M is the mass of the larger object (in this case, Jupiter) and ***m*** is the mass of the smaller object (in this case, a moon)

BACKGROUND INFORMATION

Since the mass of Jupiter will be far greater than the mass of the moons, we can simplify the above equation to:

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

where:

T is in unit of years

a is in units of AU (astronomical units, which is the distance between the Earth and the Sun)

M is in units of solar masses.

For a useful explanation of this Law see 'Kepler's Third Law of Motion - Law of Periods (Astronomy)' YouTube (5.54 min) https://youtu.be/KbXVpdlmYZo.

EQUIPMENT

You will need the following to complete this activity.

- The telecope provided by your school
- Smartphone camera adapter which you will attach to the telescope
- A pen or pencil
- A print-out of the data table
- A clock/watch and a calendar
- The Internet
- Calculator
- Ruler

NOTE: You will need clear skies for your observations, so keep an eye on the weather and cloud cover.

OBSERVATIONS

1. Set up your telescope.

Find a spot where you can see most of the sky, and keep using this spot for all your observations. Locate Jupiter in the night sky. The magnification on your telescope should be strong enough for you to see at least three of Jupiter's four Galilean Moons. Below you can see an image of what you might see through the telescope. Keep in mind that you can't tell which moon is which. You must use the same magnification each time to help keep your measurements comparable throughout this activity.

By Jan Sandberg - desert-astro.com/Solar_System.htm, Attribution, https://commons.wikimedia.org/w/index.php?curid=7572710

2. Connect smartphone camera adapter.

Take a photo of Jupiter and the moons (you will use this image to collect your data). Note the time and date of your observation in the data table, as this will be important for your analysis later on.

For each observation, make sure you are consistent in how you mount the smartphone on the adapter so that it is at the same angle relative to the telescope.

3. Collect your data.

You only need to take one observation per night. Repeat your observations over a minimum of a month and try and observe every night. It is not detrimental to your analysis if you miss a night due to bad weather, but you may need to re-observe if you do not collect enough data. Ideally, you should collect 25-30 images of Jupiter and the Galilean Moons as well as the date and time of each of the observations.

RESULTS

1. Upload your data.

Upload each image to the following website: https://eleif.net/photo_measure.html

2. Calculate the distance of each moon.

For each of your photos, do the following.

a) Measure the reference size of Jupiter (red) by click-and-dragging the measurement line across the diameter of Jupiter.

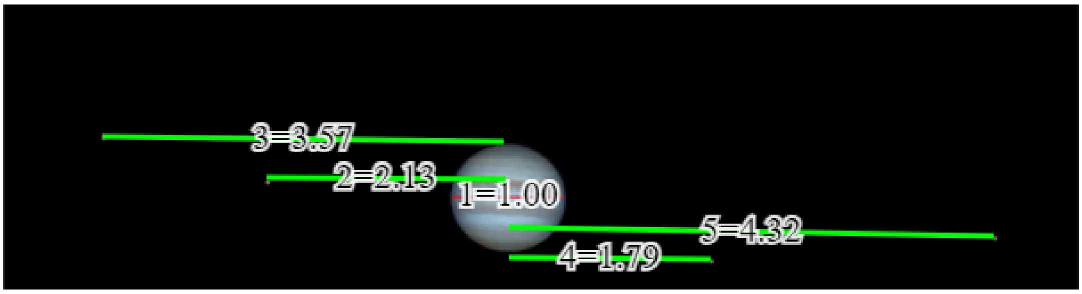
b) Measure the distance of each moon from Jupiter by creating measurement lines (green) by click-and-dragging from each moon to the centre of Jupiter.

c) Enter the reference measurement of Jupiter as "1.00" - the other measurements will be scaled accordingly. In other words, the diameter of Jupiter is 1 JuD.

d) Record each moon distance measurement in the data table.

3. Record each moon's position.

In the order that you see them from east to west (left to right), record each moon's position in the data table. Remember to specify if they are east (left) or west (right) of Jupiter. An example has been provided in the first row of the table with the related image included below.



DATA TABLE

Date	Time	Day	Distance to Jupiter (JuD)			
			(1)	(2)	(3)	(4)
15 Jun 21	6:48pm	0	3.57E	2.13E	1.79W	4.32W

DATA ANALYSIS

You should now have a table full of data ready to analyse. You will need to transfer this onto the graph on the next page (note that it is turned sideways, so that it will fit all your data).

1. Starting with day one, mark a dot for each moon, lining up with where it was on that day. (Note that this is only for your observations and not for the example one.) Each day should have four dots which represent the four moons. Keep going for all your observations.

2. Now we have to look for patterns in the data. Fortunately, the orbits of the Galilean moons are circular, so the path of each moon in your graph of position-versus-time will look like a sine curve. An example of what you might see is included at the back of this booklet.

Let's do a quick refresher on the properties of sine curves.

i) They are repetitive;

ii) they have maximum and minimum values; and

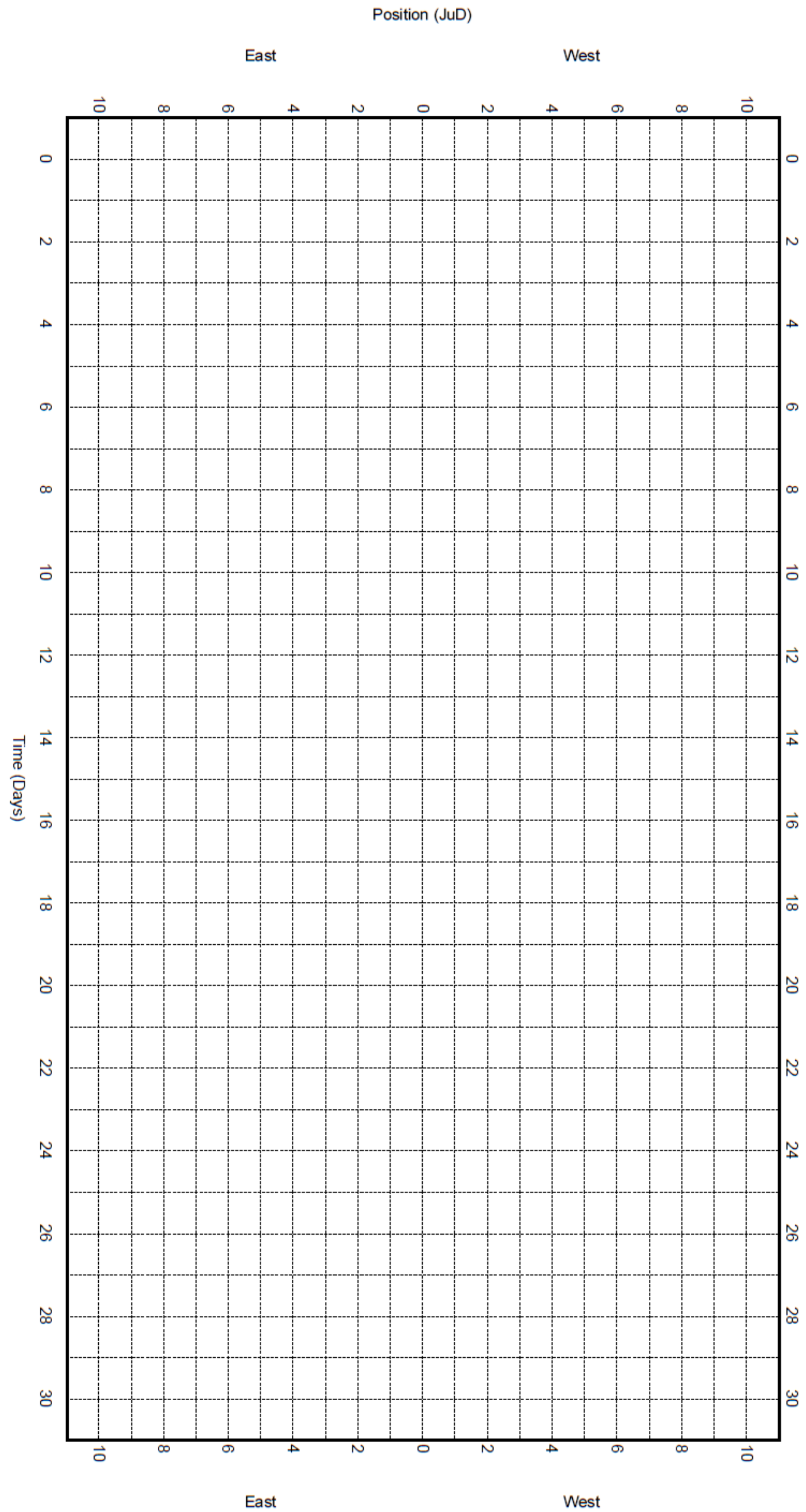
iii) the distance peak-to-peak is the period (i.e. the length of time, in this case) for the pattern to repeat.

Therefore, in our experiment:

* The **period** of the curve is the amount of time (***T***) it takes for a given moon to orbit once around Jupiter.

* The maximum and minimum values of the curve are equal to the distance of a moon to Jupiter (***a***).

GRAPH


Position (JuD)
East
West
10 8 6 4 2 0 2 4 6 8 10
Time (Days)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
East
West

CALCULATIONS

Now that you have graphed your results and drawn your curves, it's time to calculate the semi-major axis of each of the moons' orbits. The semi-major axis of the orbit of a moon is found by its maximum distance from Jupiter as shown on the graph.

Find the maximum or minimum value of your sine curve for each moon by finding the crest (maximum amplitude) of each curve and holding a ruler horizontally across to the JuD axis and record the number below.

Of course, semi-major axis measurements (***a***) are in JuD, and the period measurements (***T***) are in days, but Kepler's Third Law requires years and AU.

To convert your period (in days) to a period in years, divide by 365.25 days in a year.

To convert your semi-major axis in JuD to a semi-major axis in AU, divide by 1050 Jupiter diameters in an AU.

Moon One

T (period) = __________ days	***a*** (semi-major axis) = _________ JuD
T (period) = __________ years	***a*** (semi-major axis) = _________ AU

Moon Two

T (period) = __________ days	***a*** (semi-major axis) = _________ JuD
T (period) = __________ years	***a*** (semi-major axis) = _________ AU

Moon Three

T (period) = __________ days	***a*** (semi-major axis) = _________ JuD
T (period) = __________ years	***a*** (semi-major axis) = _________ AU

Moon Four

T (period) = __________ days	***a*** (semi-major axis) = _________ JuD
T (period) = __________ years	***a*** (semi-major axis) = _________ AU

You now have all the information we need to use Kepler's Third Law to calculate Jupiter's mass remembering that:

$$\frac{a^3}{T^2} \approx M$$

RESULTS

Moon One

Jupiter mass = __________ Solar masses ($M_\odot$)

Moon Two

Jupiter mass = __________ Solar masses ($M_\odot$)

Moon Three

Jupiter mass = __________ Solar masses ($M_\odot$)

Moon Four

Jupiter mass = __________ Solar masses ($M_\odot$)

The mass of Jupiter is 1047.57 Solar masses, so how close did you get?!

FOLLOW-UP QUESTIONS

1. Compare each calulation you made for each moon to the actual mass of Jupiter. Which moon was the closest and why do you think that was?

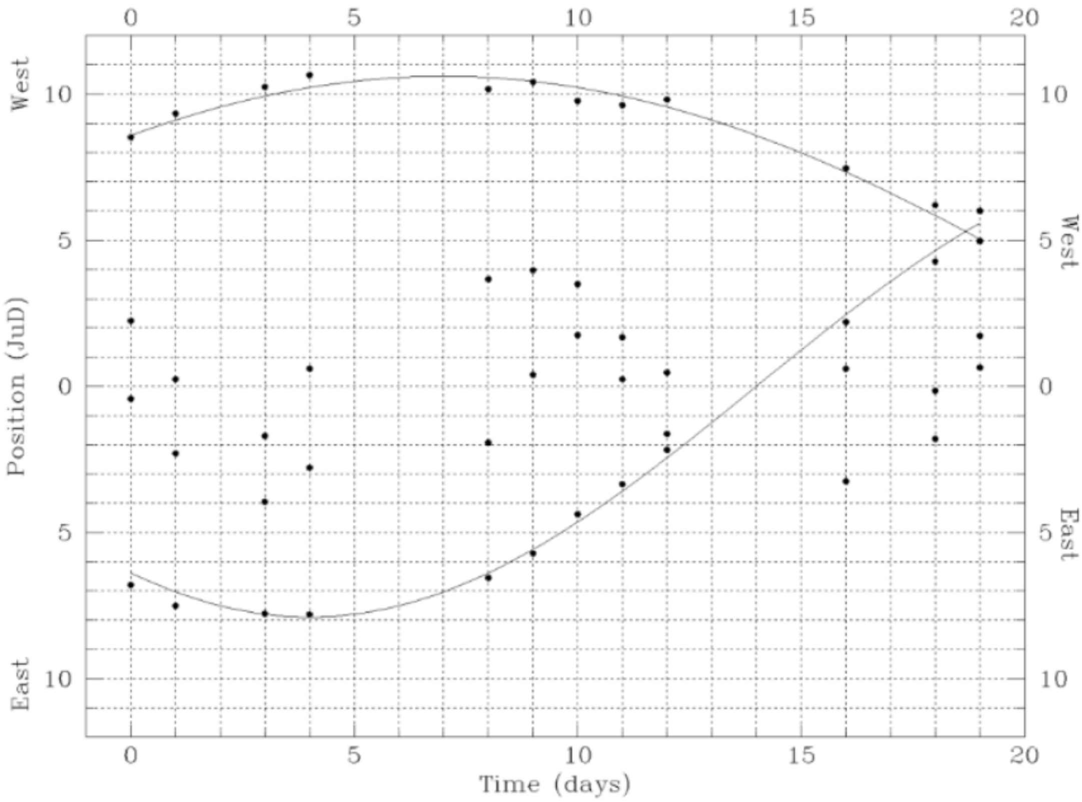
2. Can you determine which of your moons is Io, Callisto, Ganymede and Europa? Explain how you know. (You may have to look up their distance from Jupiter to help you.)

3. How much bigger is Jupiter compared to the Earth? What about other planets in our Solar System?

4. What did you notice about the way Jupiter and the Galilean Moon's moved?

EXAMPLE

Below is an example of what your graph may look like.



FURTHER RESOURCES

- Watch this short video about the life of Galileo and his discovery of the moons of Jupiter:

'Galileo: Discovering Jupiter's Moons', PBS Learning Media website (3:05 mins), https://www.pbslearningmedia.org/resource/ess05.sci.ess.eiu.galileomoon/galileo-discovering-jupiters-moons/ (2006)

- Read more about Galileo:

'Galileo and astronomy', Royal Museums Greenwich website, https://www.rmg.co.uk/stories/topics/what-did-galileo-discover

'Galileo's Battle for the Heavens', NOVA website, https://www.pbs.org/wgbh/nova/galileo/life.html (July 2002)

- Watch the Galilean moons orbit Jupiter in this time-lapse movie by NASA's Jet Propulsion Laboratory:

'Juno's Final Approach to Jupiter', YouTube (0:21 min), https://youtu.be/wJiYoNN9lKk (5 July 2016)

- Find out more about Jupiter and its moons:

'Jupiter', Solar System Exploration, NASA website, https://solarsystem.nasa.gov/planets/jupiter/overview/

'Jupiter Moons', Solar System Exploration, NASA website, https://solarsystem.nasa.gov/moons/jupiter-moons/in-depth/

- Learn more about Kepler's Laws:

'Kepler's Three Laws Explained', YouTube (18:48min), https://youtu.be/kyR6EO_RMKE

'Orbits and Kepler's Laws', Solar System Exploration, NASA website, https://solarsystem.nasa.gov/resources/310/orbits-and-keplers-laws/

All websites accessed 10/3/2022.