EXPLORATION 3: VOYAGE TO EUROPA!

What are Jupiter and its moons like?

The purpose of this exploration is to observe the motions of Jupiter's moons, and to use these observations to determine various physical properties of the planet Jupiter and its moons.

- The force of gravity extends beyond a planet's surface far out into space, where it holds moons and artificial satellites in orbit.
- The time it takes a moon to orbit once around a planet depends on the mass of the planet and also on the distance between planet and moon.
- Relationships among physical properties are important, because they can be used to determine one property if the related properties are known.

The motivation for this exploration is the recent discovery that one of Jupiter's moons, named Europa, is likely to have a warm, deep, salt-water ocean hidden under its icy surface. This prospect—and the possibility of life under the ice on Europa—makes Jupiter and its moons one of the most exciting destinations in the solar system to explore.

The focus of this exploration is on what we can learn about Jupiter and its moons by observing the motions of the moons and applying our knowledge of Newton's laws of gravity and motion. Students' are challenged to use their own observations of Jupiter and its moons (supplemented with images of the moon Europa's surface, taken by NASA's Galileo spacecraft), to prepare a report on what a mission to Jupiter and Europa might be like.

GRADE LEVEL:
9-12

TIME OF YEAR:
January through June
2004-2006

SCIENCE STANDARDS:
Laws of motion
Law of gravity
Orbits

MATERIALS NEEDED:
✔Online telescopes (or use archived images.)
✔ Software, provided
✔ Printer (optional)

TIME NEEDED:
2- 4 class periods

TEXTBOOK LINK:

A key learning goal is for students to become proficient in using relationships among physical variables. This exploration focuses on Kepler's relation for circular orbits. Students use this relationship repeatedly, in a variety of guises and for a variety of purposes. They deepen their understanding of how to work with relationships in physics, through interactive simulations, through interpretating their own data, and through puzzles and calculations.

In Part 1 of this exploration, students gain experience with Kepler's relation by doing a couple of virtual experiments using an interactive simulation. Then they use Kepler's relation to estimate the distance from Jupiter to the Sun.

In Part 2, students use the telescopes to take images of Jupiter and its four largest moons. They create a digital movie of the moons motions. From the motions of the moons, students identify which moon is Europa.

In Part 3, students measure their images. They determine:

- the scale of their image
- the size of Jupiter compared to Earth,
- the distance from Jupiter to Europa, and
- the period of Europa

In Part 4, students apply Kepler's relation to the results of their measurements. They calculate:

- the mass of Jupiter compared to Earth
- the surface gravity of Jupiter
- the density of Jupiter

In this part, students also examine images of Europa from a NASA space probe, to see what they can deduce about the surface of Europa.

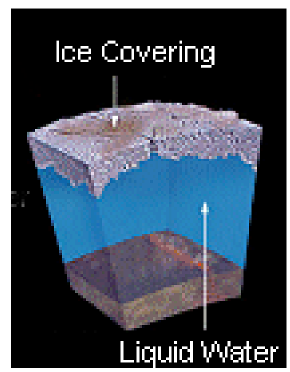
In Part 5, students incorporate their findings into a report that assesses—in human terms—the suitability of Europa and Jupiter as landing sites.

Background

When Galileo peered through his telescope in 1610 and discovered the four largest moons of Jupiter, he could not have imagined what amazing worlds these moons would turn out to be. At the time, he described the moons as appearing like "stars" that moved back and forth around the planet Jupiter. His discovery was important, because it showed that *not* everything in the heavens revolved around the Earth: These four specks of light clearly revolved around the planet Jupiter. Thus Earth was not the center of the universe.

Today, nearly four centuries later, we have close-up views of these four moons, sent to us from spacecraft that have made the long journey to Jupiter. The views reveal four very different worlds.

This exploration focuses on the most exciting of Jupiter's moons: Europa, which is the second nearest moon to Jupiter. Europa is completely encircled by a salt-water ocean thought to be miles deep. This liquid ocean is topped by a thick layer of ice. It is though to be the likeliest place in our solar system to harbor life, beyond Earth.



You might think that liquid water could not exist on Europa. Jupiter and its moons are so far from the Sun—about 5 times farther than Earth—that they are very cold worlds, at least on the surface. But Europa is being heated from inside: As the moon orbits Jupiter, it is constantly flexed by Jupiter's strong gravity. This flexing of the moon creates friction deep inside Europa, and produces enough heat to keep the ocean melted. In fact, the moon that is nearest to Jupiter, called Io, is flexed and heated even more than Europa—so much that Io's surface is covered with volcanoes; Io has more volcanoes than Earth!

NASA is considering sending a spacecraft to explore Europa. However, no one has yet discovered a way to drill through the surface ice, which may be several miles thick. This remains one of the great explorations for our time.

Materials Needed

	For each team of students
	Straightedge Optional: Rulers for measuring printed images
	For the class
	Internet access to the MicroObservatory online telescopes
	Image-processing software (MOImage) on your local computer
	Browser with Shockwave Plug-In
	Printer (black-and-white)
	For the teacher

Two ways to use Kepler's Relation

As a Relationship

Kepler's relation can be used to *compare* two different orbits.

$$T^2 \sim d^3 / M$$

The ~ sign means "proportional to". The units don't need to be specified.

M is mass of the planet
d is distance from planet to moon
T is the time for one orbit (the "period")

For example, suppose Earth had another moon that was *twice* as far as our familiar Moon. How would the period of this moon compare to the Moon?

From the relation, you see that if the distance **d** doubles, then d^3 becomes eight times larger. So the period **T** must be the square root of 8 times larger, or about 2.8 times the Moon's period. Note that we have not needed any units to do the comparison.

Advantages:

- Best way to *compare* astronomical quantities, such as Jupiter's mass compared to Earth's.
- Uses familiar units, helps conceptualization

As an Equation

Kepler's relation can be derived from Newton's law of gravity and law of motion. Then the units are in centimeters, grams, and seconds.

$$M = \frac{(2\pi)^2}{G} \frac{d^3}{T^2}$$

M is the mass of planet, in grams
d is the distance from planet to moon, in centimeters
T is the period of moon's orbit, in seconds
G is Newton's gravitational constant
($G = 6.7 \times 10^{-8}$ cm^3 / g sec^2) .

Advantages:

- Allows quantities to be calculated from first principles.
- Makes visible the fundamental physics, through explicit inclusion of Newton's gravitational constant.

Disadvantages:

- Encourages "plug and chug" rather than focus on relationship among variables.
- Units are less familiar to non-science students, less intuitive to all students.
- Computations harder, constants more confusing.

• Easy to use proportions, rather than "plug and chug." • Emphasizes the relationship among variables. Disadvantages: • Can't calculate quantities from first principles; *must* use comparison to known system.	

Part 1. Introduction and background

Students' ideas about planets and moons

Have students discuss and write about the questions in their science journals.

> *The days of the week are named after the Sun, Moon, and the five planets visible to the unaided eye. Why do you think the planets were so important to people thousands of years ago?*
>
> *If you had the opportunity to go to another planet or its moons, would you go? To which one and why?*
>
> *What do you think are the prospects for finding life on another planet or its moon? What kind of evidence for life would you look for?*

Encourage students to revisit their responses after they carry out the exploration.

Sunday = Sun day
Monday = Moon day
Tuesday = Mars day
Wednesday = Mercury day'
Thursday = Jupiter day
Friday = Venus day
Saturnday = Saturn day

Introducing Kepler's Relation

This exploration is meant to deepen students' understanding of Kepler's relation for circular orbits. This relation describes the motion of one body in circular orbit about another, such as a moon circling a planet, or a planet circling the Sun, or even a star circling a black hole.

As applied to a moon circling a planet, say, the relationship says that the period of the moon's orbit depends on the mass of the planet, and on the distance between planet and moon:

$$\mathbf{T^2 \sim d^3 / M}$$

M is mass of the planet
d is distance from planet to moon
T is the time for one orbit (the "period")

The squiggly line, ~ (tilde), means "is proportional to" or "varies as."

It is possible to *derive* Kepler's relation from Newton's laws of gravity and motion (see Appendix). In that case, the result is an equation:

$$\mathbf{M} = \frac{(2\pi)^2}{G} \frac{\mathbf{d^3}}{\mathbf{T^2}}$$

M is the mass of planet, in grams
d is the distance from planet to moon, in centimeters
T is the period of moon's orbit, in seconds
G is Newton's gravitational constant
($G = 6.7 \times 10^{-8}\ cm^3 / g\ sec^2$).

In this exploration, we use the relationship rather than the equation. The relationship is in some ways *more fundamental* than the equation: the relationship does not depend on units, and it focuses attention on the physical variables (mass, distance, and time) and their connection—unfettered by any constants. The relationship is most useful for *comparing* one system to another.

In other ways, however, the equation is more fundamental: It allows you to calculate values from first principles, without comparison with a known system. It also introduces Newton's gravitational constant, which incorporates the idea that nature sets a fundamental strength of gravity which is the same everywhere. The table on the next page shows the relative merits of each approach.

Note: Historically, Kepler discovered only the relationship between distance and period, but did not understand the role of mass. After Newton developed his laws of motion and gravity, Kepler's relation was rewritten to include the role of mass. For simplicity, we call the relation above "Kepler's relation."

To answer these questions...	**You'll need these...**	**But how will you determine them?**
How far am I going? How long will it take to get there? How much sunlight will there be?	**Distance** from Earth to Jupiter **Distance** from the Sun to Jupiter	____________________ ____________________ ____________________ ____________________
How much will I weigh on Jupiter's surface? How dense is Jupiter? Will I sink in when I land?	Jupiter's **mass** compared to Earth's Jupiter's **size** compared to Earth's	____________________ ____________________ ____________________ ____________________
How far is Europa from Jupiter?	(**Distance** from Jupiter to Europa.)	____________________ ____________________ ____________________ ____________________
On Europa, how often does it get dark? How long is night on Europa? How often will I be out of touch with Earth?	**Period** of Europa (= time it takes to orbit Jupiter once)	____________________ ____________________ ____________________ ____________________

Orbital simulator

Although not required for this exploration, the orbital simulator provides a visualization of Kepler's relation that will be useful to many students. The two experiments provide practice in using Kepler's relation to determine one quantity (e.g. the period), when the other two are known. Most important, the simulator provides early feedback to students about whether they understand and can successfully use Kepler's relation.

The Simulator shows a moon in circular orbit around a planet. Students can change the *mass* of the planet, to see how the change affects the period of the moon's orbit. They can also change the *distance* between planet and moon, to see how that affects the period.

Have students access the Orbital Simulator at:

http://cfa-www.harvard.edu/webscope/inter/jupiter

The Shockwave plug-in is required to use the simulator. If it is not already on your computer, you can download it free from:

http:// ADD HERE

Experiment 1

In this experiment, students investigate, "How does the period of a moon depend on how heavy the planet is?" The experiment illustrates that the larger the planet's mass, the smaller the moon's period (for a given distance between planet and moon). That is, "moons orbit faster around more massive planets."

1. Students set the mass of planet A and the distance to its moon, as indicated in their science journals.

2. Using the timer, students measure the resulting period of the moon, and record the results in their science journal.

3. For planet B, students set the same distance to the moon.

4. Have students *predict*, using Kepler's relation: How much heavier should planet B be for its moon to orbit in 1/3 the time? Have students record their prediction in their science journals.

   From Kepler's relation:

   $$\mathbf{M \sim d^3 / T^2}$$

   If **T** is replaced by **(1/3 T)**, then **M** will become **9** times larger. The moon will orbit in 1/3 the time around a planet that is 9 times more massive.

5. Students set the mass of planet B to their predicted value.

6. Students check their prediction by using the simulator's timer to measure the period of the moon. Is it 1/3 the period measured for the moon of planet A? (**Note:** The timer is only approximate.)

Experiment 2

In this experiment, students change the distance from planet to moon to see how that affects the moon's period. The greater the distance between planet and moon, the longer the moon takes to orbit.

The experiment asks students to use Kepler's relation to *predict* how the period will change if the moon's distance is made **3** times farther from the planet. From Kepler's relation

$$\mathbf{M \sim d^3 / T^2}$$

or

$$\mathbf{T^2 \sim d^3 / M}$$

If the distance increased by three-fold, then $\mathbf{d^3}$ will be 27 times larger. So the period **T** will be **27** times longer, or roughly 5 times longer.

Have students check their prediction by using the simulator's timer to measure the period of the moon.

How far is the planet Jupiter?

Students now apply Kepler's relation in order to estimate the distance to Jupiter.

1. Explain to students that the planet Jupiter takes about 12 years to orbit the Sun. (We can observe Jupiter moving very slowly relative to the background constellation of stars; it returns to the same spot in the sky, relative to the background stars, after about 12 years.)

2. Have students use the period of Jupiter's orbit, and Kepler's relation, to answer the questions in their journal. Make sure that students record their results on their DATA PAGE. They will need the results later.

   Based on the periods of their orbits around the Sun, which planet is farther from the Sun: Jupiter or Earth? How do you know?

   How many times farther from the Sun is Jupiter, compared to Earth? (Use either Kepler's relation, or the Simulator, to find out.)

   The Earth is about 93 million miles from the Sun.
   How far is Jupiter from the Sun?

According to Kepler's relation, Jupiter should be farther from the Sun, because it takes longer to orbit.

To figure out how far Jupiter is from the Sun, compared to Earth's distance, use Kepler's relation:

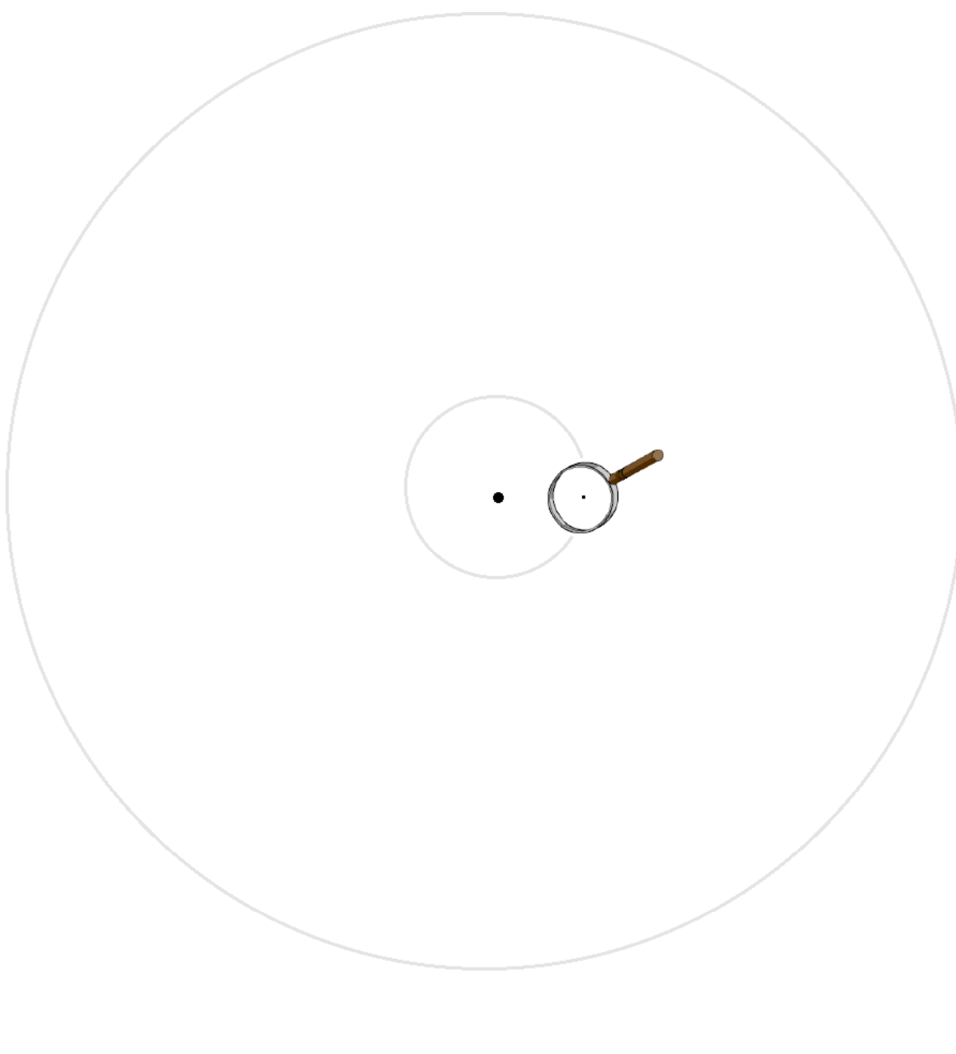
$$\mathbf{T^2 \sim d^3 / M}$$

Since Jupiter's period, **T**, is 12 times greater than Earth's, then $\mathbf{T^2}$ is 144 times greater. Since $\mathbf{d^3}$ is proportional to $\mathbf{T^2}$ then Jupiter's distance **d** will be the cube-root of 144, or a little more than 5.
So Jupiter is *about* 5 times farther from the Sun than Earth is.

Since the Earth is about 93 million miles from the Sun, then Jupiter must be about 470 million miles from the Sun.

Scale drawing

Have students use their result to make a drawing in the journal showing the relative size of Earth's and Jupiter's orbits around the Sun. Their drawings should look something like this:



The magnifying glass in the drawing indicates that the planets are too small to see, at the scale of this drawing.

Have students use their drawing to discuss and answer the question:

What is the closest *that Jupiter gets to Earth? What is the farthest?*

Jupiter will be farthest from Earth when it is on the opposite side of the Sun. Then the distance from Earth will be 470 million + 93 million miles—about 563 million miles.

Jupiter will be closest to Earth when it is on the same side of the Sun. Then it will be 470 million – 93 million miles—about 377 million miles from Earth.

For this exploration, students will need to know the actual distance from Earth to Jupiter during your current month. This distance is listed in the table in the margin.

Jupiter's Distance from Earth

Date	Distance from Earth
	1 a.u. = 93 million mi.
2003	
Dec	5.5 a.u.
2004	
Jan	4.8 a.u.
Feb	4.5
Mar	4.4
Apr	4.5
May	4.9
Jun	5.4
Jul	5.8
2005	
Jan	5.4 a.u.
Feb	5.0
Mar	4.6
Apr	4.5
May	4.6
Jun	4.9
Jul	5.3
2006	
Jan	5.9 a.u.
Feb	5.4
Mar	5.0
Apr	4.6
May	4.4
Jun	4.5
Jul	4.8

Reflecting on the results

Have students discuss the questions in their journal, and have them record their answers for use in their mission report. Numbers in astronomy mean little unless they can be related to something more familiar to students.

About how long will it take you to get to Jupiter? Assume that your spacecraft can average about 100,000 miles per hour. (This is several times faster than current spacecraft.)

How would you choose your crew members for a trip this long? What qualities should they have?

How much sunlight would you expect to find at Jupiter, compared to Earth?

What can you conclude about the temperature you might expect to find on Jupiter or its moons?

To travel to Jupiter would take *no less than* (377 million miles/ 100,000 miles per hour) = 3770 hours. This is a little less than six months. In reality, it would take much longer, because spacecraft don't travel in a straight line, and speeds are considerably slower. NASA's *Galileo* spacecraft took more than 3 years to get to Jupiter! Providing enough food, water, and air for multi-year trips in space is just one of the challenges of space travel. Another is the difficulty of having crew members get along with each other in confined quarters over a long period of time. (Think of traveling cross-country with the family!) Still another is the danger of radiation coming from the Sun. (On Earth we are largely protected from this radiation by the Earth's magnetic field.) And of course, the cost of such a trip would be enormous.

Since Jupiter is five times farther from the Sun than is Earth, it receives only 1/25 as much sunlight. (The amount of light received drops off with the square of the distance.) The Sun would look 5 times smaller in the sky from Jupiter (i.e., 1/5 the diameter as seen from Earth, and 1/25 the area). With this little sunlight, the surfaces of Jupiter and its moons are much colder than Earth!

Planning: How can you "weigh" Jupiter?

Students work in teams of five or six students each. Each team is responsible for taking a sequence of images of Jupiter and its moons, and each team prepares a mission report.

Have students discuss the following question with their teams:

> What information about Jupiter and one of its moons could you get, using the telescope, that would help you compare Jupiter's mass with Earth's?
>
> How will you get this information from your images of Jupiter and its moons?

You could compare Jupiter's and Earth's mass *if* you could find out the period of one of Jupiter's moons and its distance from Jupiter. Since we know the distance and period of Earth's Moon (230,000 miles and 27 days, respectively), we can use Kepler's relation to determine Jupiter's mass relative to Earth's.

Explain to students that as part of their exploration, they will use the telescope and its camera to follow the moons of Jupiter as they orbit the planet. By determining the period of one of these moons, and its distance from Jupiter, they will be able to use Kepler's relation to "weigh" Jupiter relative to Earth.

Mass vs. "Weight"

In these explorations, we use the colloquial expression "weigh" Jupiter, when we refer to determining its mass. Although it is important in physics to distinguish between weight (which is a force) and mass, some studies have found that students achieve better understanding when the more colloquial term is used. There is little opportunity for confusion here because we are only interested in relative weights or masses.

Part 2: Carrying out the exploration

Have each team take up to six images of Jupiter and its moons. The images should be spaced about 1 hour apart to be able to distinguish the motions of the moons. To ensure that students get useful data, have students pay attention to the following:

When is Jupiter visible tonight?

Have students use the chart in their journals, which shows the times when Jupiter is visible for at least several hours. If possible, the middle image should be taken when Jupiter is highest, but this is not essential.

How do I locate Jupiter?

Use the handy pull-down menu to select Jupiter. The computer will automatically target Jupiter.

What exposure time should I use?

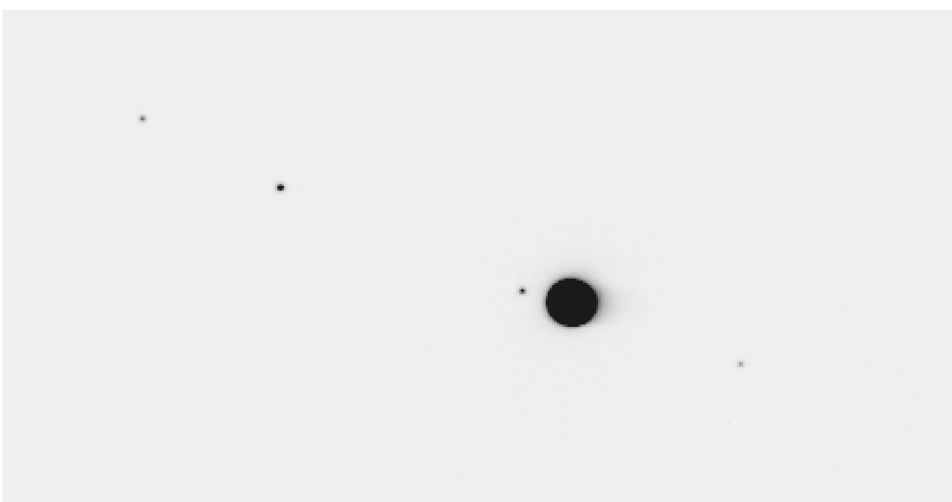
Try a 1-second exposure with no filter (“clear filter”). But see next question.

What are those vertical white spikes coming from the top and bottom of Jupiter in my image — and will they spoil my project?

The spikes are a form of glare, since Jupiter is so bright. If you reduce the exposure time, you will reduce these spikes, but you will also make it harder to observe the fainter moons of Jupiter. The spikes will not obscure the moons of Jupiter, and they should not affect students’ projects.

Should I use zoomed-in or zoomed-out images?

Taking zoomed-in images is preferred, since it will make it easier to measure the motions of the moons. However, with a zoomed-in image, you may not see all four moons in the image if Jupiter is not well-centered in your image. You may ask different teams to try zoomed-out or zoomed-in images and compare their results.



Jupiter and its 4 innermost moons. This zoomed-in image was inverted before printing. Exposure time: one second. ***By S. Rapp, Linwood Holton Governor’s School, VA. Oct. 1999.***

Should I download the GIF-format image (the one I see on the Web)—or do I need the FITS-format image as well?

The GIF-format image should be sufficient, provided that you can clearly see the moons in the image. If the moons are faint, you can download the FITS-format as well, and open it in the MOImage program.

IMPORTANT:

Make certain that students download the Image Info file for each image, or at the least record the time that each image was taken, as listed in the Image Info file. This information is needed to determine the period of the moon.

If students have downloaded the FITS-format image, then information about the image will also be contained in the "FITS-header" which can be read by opening the image in the MOImage program and choosing the appropriate menu command.

How do I print black on white?

When printing images of Jupiter and its moons, you can save your printer's toner by first *inverting* the image, so the background appears grey or white. To do this, you can open the image in MOImage or similar image processing program, and choose Invert from the appropriate menu. Then print as usual.

Make sure that students print in landscape format without scaling the image to fit the page. (That would change the scale of the image and lead to errors in measurement.)

Reflecting on the images

After students have examined their images of Jupiter and its moons, have them discuss the questions with their team and record their answers in their journals.

> **Size of Jupiter**. Why does Jupiter appear so small, compared to, say, an image of our Moon?
>
> **Point of view**. Why do we see Jupiter's moons arranged on a more or less straight line?

Forces and motion. What keeps the moons in orbit around Jupiter? Why don't they fly off into space?

Universal gravity. How far into space do you think Jupiter's gravity extends? What about Earth's?

Speed of the moons. Which moons appear to have moved, from image to image? Why have some moons moved more than others?

Getting the big picture. Jupiter and its moons look like a miniature "solar system." How does the plane of the moons compare to the plane of the solar system? Why might that be?

The discussion offers an opportunity to reinforce several basic ideas.

Jupiter appears much smaller than Earth's Moon because it is so far away. (It is several thousand times farther than Earth's Moon.)

The moons are arranged on a nearly straight line because their orbits are all the same plane, and we view that plane edge-on from our vantage point on Earth. (To help students visualize this, you might draw Jupiter and the orbits of its moons as circles on a sheet of paper, and then view the paper from along an edge.) The orbits of the planets and their moons all lie in roughly the same plane—the plane of the solar system. That's because these bodies were formed billions of years ago from the same, flattened disk of spinning material.

The moons are held in orbit by the force of Jupiter's gravity. This is an opportunity to point out that Jupiter's gravity—like Earth's—extends far into space. In fact, gravity from both planets extends infinitely far into space; but since the *strength* of the force decreases with the square of the distance, the effect of this gravity is not noticeable if you are far enough away. For example, Earth's gravity extends to the Moon and beyond—but at the distance of the Moon Earth's gravity is only a few thousandths as strong as it is here on Earth's surface. (The Moon is 60 times farther from the center of the Earth than we are, so Earth's gravity at that distance is only 1/3600 times as strong. Near the Moon, therefore, the Moon's own gravity dominates.)

Misconception alert. Many students think that gravity ends at the Earth's surface. Some think that gravity is related to air pressure in some way. Others note that the astronauts are weightless and conclude that gravity must not exist in outer space. (The astronauts feel weightless because they are continuously falling and they orbit the Earth—not because gravity doesn't exist in space.)

In examining the sequence of images, students will note that some of the moons will have moved more than others. Here is evidence for Kepler's relation. The moons that orbit closest to Jupiter will haved moved the most, from image to image. This motion will be a clue to help students determine which moon is which.

Create a movie of Jupiter and its moons

Have each team create a digital movie made from the images they took of Jupiter and its moons. This activity will help students visualize the motions of the moons, and will help students identify the Europa. Have them follow this procedure:

1. On your computer, launch the MOImage processing software, and close any other programs.

2. From the MOImage program, open each of your Jupiter images, one after the other.

3. From the **Edit** menu, select **Shift**. This features lets you move each of the images relative to each other, so that the Jupiters line up on top of each other. Choose one of the images as a background image. Carefully align the other images, one by one, using the mouse and arrow keys.

4. When you are satisfied that all the Jupiters are in the same spot in each of your images, then go to the **Edit** menu and select **Stack / Create Stack**.

5. To see your animation, select **Edit / Play Animation**.

6. To save your movie as an "animated GIF" file, which can played in any Internet browser, select **Edit / Save as Animated GIF**.

Which moon is Europa?

Have each team examine their sequence of images and try to determine which moon is Europa. Students have only two clues to go on: How fast is the moon moving? And how far is it from Jupiter?

The moon that moves the most in the sequence of images must be the innermost moon, Io (because the closer a moon is to its planet, the faster it moves). The moon that moves *not quite* as much must be Europa, which is the second nearest moon to Jupiter. The two outer moons, Callisto and Ganymede, are the ones that barely move at all in the sequence of images. To help students visualize the motions of the moons as seen edge-on to the plane of their orbit, have them look at the animation at:

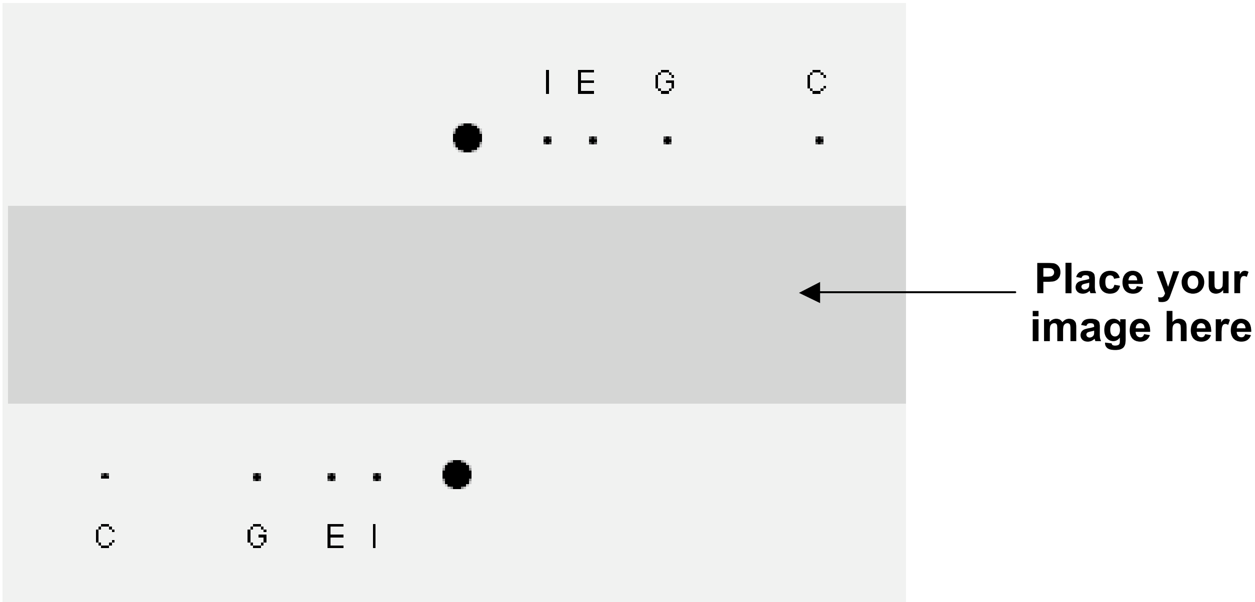
http://cfa-www.harvard.edu/webscope/inter/jupiter2

Another clue is how far the moons appear from Jupiter. Have students compare their images to the handy *turning-point chart*, in their journals, that shows the *maximum* distance that each moon appears to move from Jupiter. A moon that is too far from Jupiter cannot be Europa. But if the moons all happen to appear close to Europa, this method may not help sort out which moon is which.

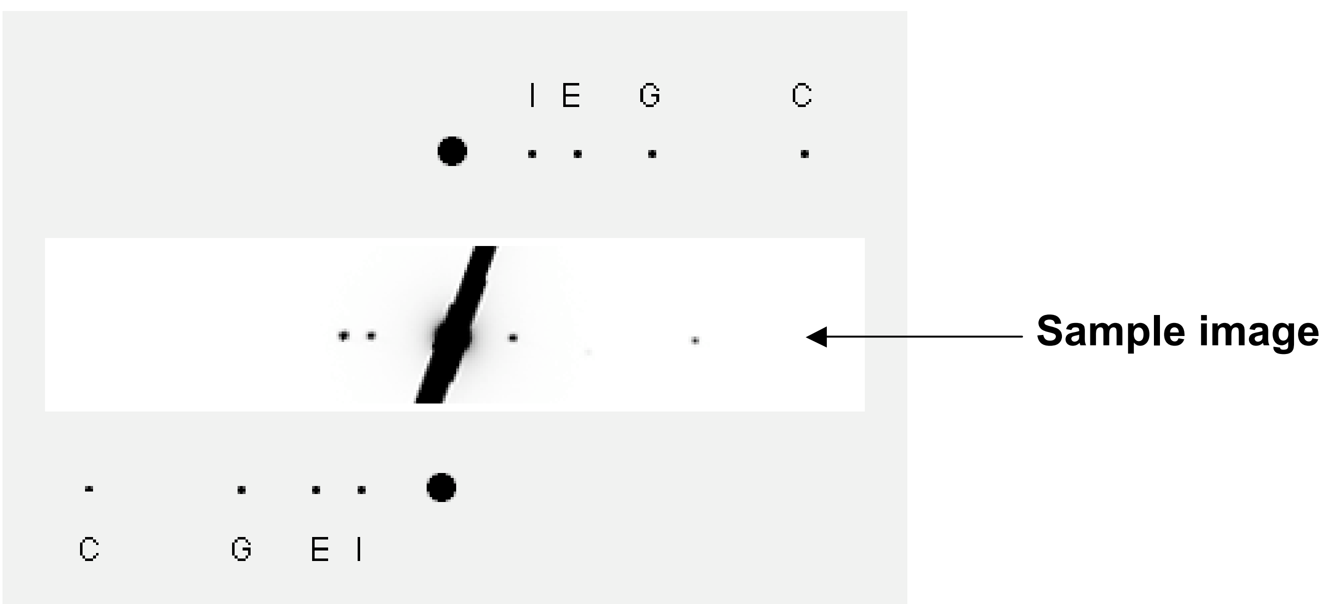
I can't see all four moons in my images. Why not? One or more moons may have passed behind Jupiter. The innermost moons should reappear in the next images.

When students have determined which moon is Europa, have them label the moon on their images, for future reference.

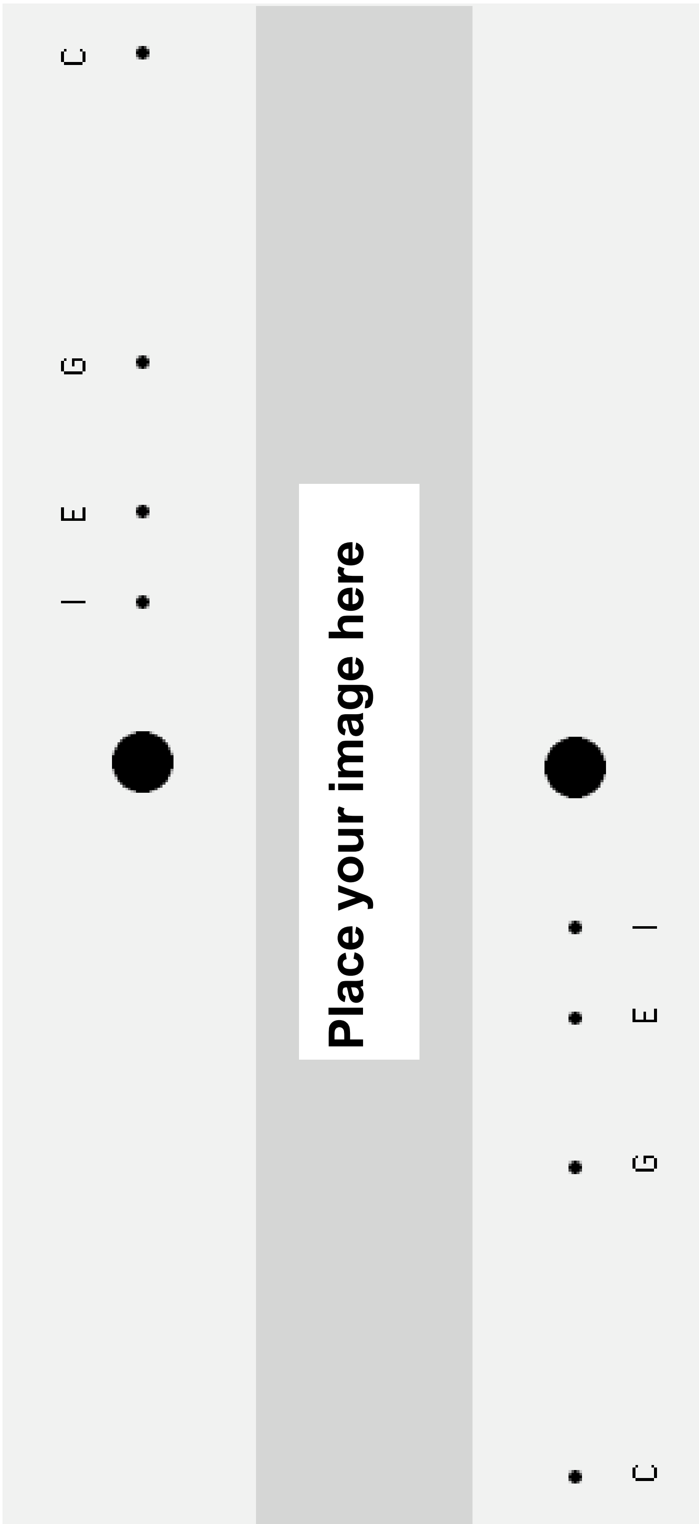
Turning-point guide for a zoomed-out image



Use this chart to help you figure out which moon is Europa. Cut out your image of Jupiter and its moons. Place it between the diagrams as shown. The two diagrams show the *farthest* from Jupiter that each of the moons can appear in your image. See the example below for help.



In the sample image, the moon at the right must be Callisto, because it appears farther from Jupiter than any of the other moons can go. The moon at the left could be Europa or Ganymede, but not Io. To determine which moon is definitely Europa, you'd need to examine the moons' motions through several images.



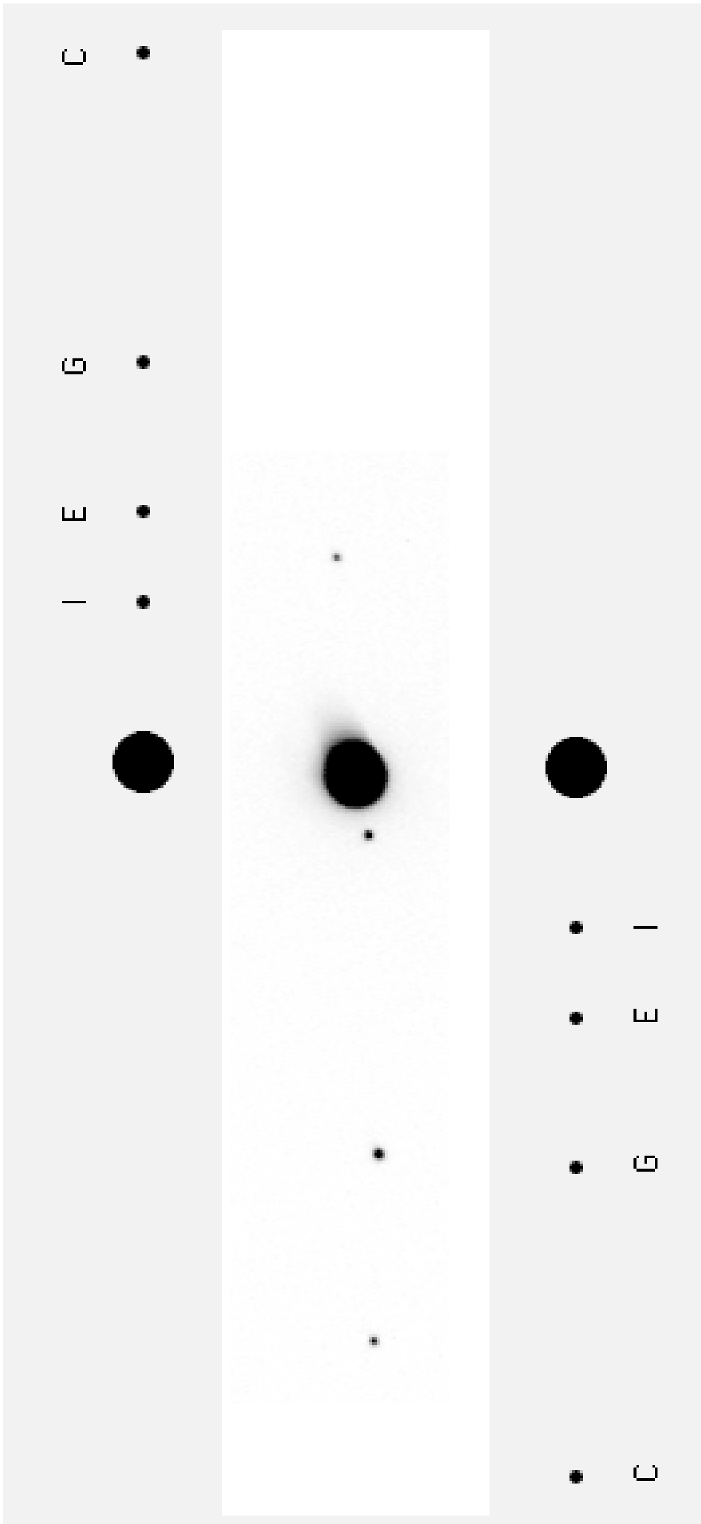
Turning-point guide for a zoomed-in image

Use this chart to help figure out which of the moons in your image is Europa.

Cut out the part of your image showing Jupiter and its moons. Place it between the two diagrams as shown.

The diagrams show the *farthest* that each moon can appear from Jupiter in your image.

The letters stand for the names of the moons: Io, Europa, Ganymede, and Callisto.



Turning point guide for a sample image

Can you tell which moon is which, for this sample image?

The diagrams show the *turning points* for Jupiter's four largest moons. These points are the farthest from Jupiter that each moon can appear in your image.

The first moon on the left must be Callisto, because it appears farther from Jupiter than the other moons can go. (Its orbit is beyond that of the other three moons.)

Can you figure out which moon is Europa?

Chart the motions of Jupiter's moons

	Distance (# of pixels) from center of Jupiter to...			
	1st moon (on left)	2nd moon	3rd moon	4th moon (on right)
Image 1 (earliest)				
Image 2				
Image 3				
Image 4				
Image 5				
Image 6 (latest)				
No. of pixels the moon has moved, from 1st to last image				

Instructions

1. Open your first Jupiter image using the MOImage program.
2. Make sure the line-measuring tool is clicked (arrow icon).
3. Click and drag the mouse to measure between two points.
4. Measure the distance from the center of Jupiter to each moon in your image.
5. Record the results in the chart above.
6. Do the same for each image.
7. Can you tell which moon has moved the most? Next most? Which moon do you think is Europa?

Part 3: What can I tell from my images?

Students have taken images of Jupiter and its moons and have identified the moon Europa. The next part of their challenge is to figure out what it would be like to land on Jupiter or Europa.

> If you could land on Jupiter, how much gravity would you find there? Could you stand up, or would you be too heavy?
>
> Is Jupiter dense enough to land on—or would you sink in?

Surprisingly, students can answer these questions on the basis of the data they have collected so far. To answer the questions, they will need to determine how large and how heavy Jupiter is, compared to Earth. They will Jupiter's size directly from their images. To determine how heavy (massive) Jupiter is, they will need to apply Kepler's relation. To use Kepler's relation, they will need to determine the period and radius of Europa's orbit, from their images.

How large is Jupiter?

Students now determine Jupiter's size compared to Earth, using measurements on their images. Students measure their images in one of two ways: using either their printed images, or *alternatively*, using images viewed on their computer monitors.

1. Remind students that they can tell how large something is if they know

   - how far away it is, and
   - its angular width in degrees.

The rule is: "An object that appears 1 degree wide, is 57 times farther away than it is wide. If the object appears narrower than 1 degree wide, it will be proportionally farther away." (See "A Wrangle with Angles.")

Students already know how far away Jupiter is. In this activity, they will measure how wide it is, in degrees, in their image. Then they will be able to figure out how large Jupiter is. Typical values are shown in the worked examples below, for a zoomed-in image.

Method A: Working with your printed image

If you are working from an image printed at normal size, use this method. If you are working from an image on the computer monitor, use Method B below.

1. Using a ruler, measure the diameter of Jupiter in your image in millimeters (preferably) or in inches. Record the result here:

Jupiter is ________________8.5 (typical)___________ (mm) wide.

2. To determine how many degrees this is, you'll need to know the *scale of your image*, in degrees per inch, or degrees per millimeter:

   For a zoomed-out image:
   A *zoomed-out* image contains 720 pixels per degree.
   Standard sized printing is 72 pixels per inch, so
   1 inch = 0.1 degree
   1 millimeter = 0.004 degree

   For a zoomed-in image:
   A *zoomed-in* image contains 1440 pixels per degree.
   Standard sized printing is 72 pixels per inch, so
   1 inch = 0.05 degree
   1 millimeter = 0.002 degree

3. Using your measured width of Jupiter, in inches or millimeters, and the scale of your image, how wide in Jupiter in degrees?

Jupiter is ___8.5 mm x_0.002 degrees / mm = **0.017**__ degrees wide.

4. Skip Method B and go on to the next section.

Method B. Working with your image onscreen

If you are working with your image on a computer monitor, use this method. If you are working from a printed image, use Method A above.

1. Open your image in the MOImage processing program. Using the mouse, click and drag a line across a diameter (the widest part) of Jupiter. This width, in pixels, in displayed in the box above the image. Record the result here:

Jupiter is ______________24 (typical)____________ pixels wide.

2. To determine how many degrees this is, you'll need to know the *scale of your image*, in degrees per pixel:

   For a zoomed-out image:
   A *zoomed-out* image contains 720 pixels per degree.
   So 1 pixel spans 1/720 degree = 0.00139 degree.
   1 pixel = 0.00139 degree

   For a zoomed-in image:
   A *zoomed-in* image has 1440 pixels per degree.
   So 1 pixel spans 1/1440 degree = 0.000694 degree.
   1 pixel = 0.000694 degree

3. Using your measured width of Jupiter, in pixels, and the scale of your image, how wide in Jupiter in degrees?

Jupiter is__24 pixels x 0.000694 degrees/pixel = **0.17**_ degrees wide.

4. Go on to the next section.

Determining the size of Jupiter in miles

Now students know the angular width of Jupiter, in degrees, and its distance, in miles. Have students discuss with their team how they will use these to determine the diameter of Jupiter, in miles.

> In the example above, Jupiter was determined to be 0.017 degrees wide and was about 4.0 astronomical units, or 372,000,000 miles from Earth. So Jupiter's width in miles is
>
> width = (distance / 57) x number of degrees
> = (372,000,000 / 57) miles per degree x 0.017 degrees
> = 110,000 miles

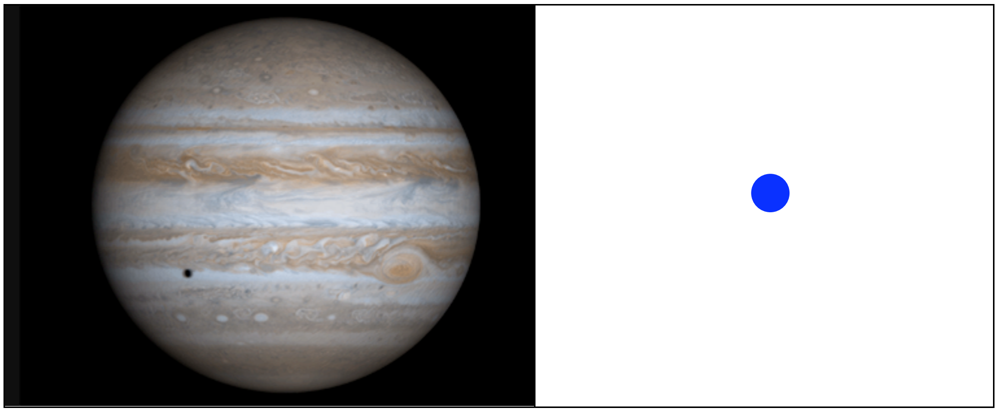
Diameter of Jupiter = __roughly__110,000_________ miles

How does Jupiter's size compare to Earth's? (Earth is about 8000 miles in diameter.)

This is more than ten times the diameter of Earth (which is about 8000 miles through the equator). Therefore more than 10 x 10 x 10 = 1000 Earths could fit inside Jupiter!

Jupiter is the largest planet in the solar system. In fact, if it were much larger—e.g. 20 times larger—it would collapse under its own weight to form a small star.

If Jupiter is this size...	Then draw Earth to the same scale:



Make sure that students record their results on their DATA PAGE for future use.

Students' results may vary by 20% or more from the currently accepted size of Jupiter. (Jupiter is 94,000 miles wide across its equator, which is 11.2 times wider than Earth. Jupiter's volume is 1321 times that of Earth; neither planet is a perfect sphere.) Possible sources of error include:

- Jupiter may be over- or under-exposed, and therefore will appear too large or too small, respectively;
- students' measurement of the diameter of Jupiter may not be accurate;
- the scale of the printed image (0.10 degree per inch, zoomed-out) is only approximate;
- the distance to Jupiter used in the calculation may not be precise.

Have the teams discuss the question,

> *Does the size of Jupiter alone tell you how strong the gravity will be at Jupiter's surface? What other information will you need?*

Jupiter's size alone does not tell us how strong its surface gravity will be. We also need to know its *mass*. Students will be able to estimate Jupiter's mass after they collect additional information about the motions of its moons.

How far is Europa from Jupiter?

The distance from Jupiter to its moon Europa cannot be determined directly from a single image. The reason is that we see the moon's orbit edge-on, so Europa appears to move back and forth on a straight line that passes through Jupiter. We would have to image Europa *just* at the "turning point" of its motion, that is, its point of maximum apparent distance from Jupiter.

Although students could in principle take an extended sequence of images and find this turning point, it saves time to just use the diagram provided. The diagram shows the position of each of Jupiter's moons at the *turning point* of its apparent motion. The distance between Europa and Jupiter in this diagram corresponds to the radius of Europa's orbit.

1. Have students measure, on the diagram provided, the distance from the center of Jupiter to the moon Europa, in inches.

2. Then have them use the scale of their image that they determined previously to convert this measure into miles.

   For example, in the zoomed-in diagram, Europa's turning point is 1- 5/16 inches (= about 1.3 inches) from Jupiter's center. This is about 4 times the size measured for Jupiter's diameter, so the estimated distance from Jupiter to Europa is about 4 x 110,000 miles = **440,000 miles**.

3. Have students record their answers to the questions in their journal.

   How does this distance compare to the distance between Earth and our own Moon?

   Considering the comparison above, how do you expect the ***period*** *of Europa to compare with the* ***period*** *of Earth's Moon (which is about a month)?*

The distance from Jupiter to its moon Europa—about 440,000 miles—is twice the distance from Earth to its Moon. According to

The best current value for the distance between Europa and Jupiter is 442,000 miles (670,000 kilometers).

Kepler's relation, the farther a moon is from its planet, the longer should be its period. However, the *mass* of the planet *also* affects the moon's period. Until we know how Jupiter's mass compares to Earth's, we can't predict how Europa's period compares to Earth's.

How long does it take Europa to orbit Jupiter?

In this activity, students estimate the period of Europa, using their images. The period is the time that it takes Europa to orbit Jupiter once. For Earth's Moon, the period is about one month.

The word "month" comes from the word "moon."

The Moon's period is about 27 days. The time between full Moons is a few days longer than one period, due to the Earth's motion as the Moon orbits. The Moon has to play "catch up" as the Earth moves around the Sun.

It would take too long for students to follow the motion of Europa for an entire orbit. In the procedure we'll use, students determine what fraction of an orbit Europa completes during the period of their observations; then they estimate how long Europa would take for an entire orbit.

Procedure

1. Students work with two of their images: the *earliest* and the *latest* images they took. These are the two images that span the interval of observation.

2. Have students record in their journals *the number of hours that elapsed* between this earliest and latest image. (The time when each image was taken can be found in two ways: It is listed in the Image Info file on the Website; and it is part of the FITS version of the image, which can be read using the MOImage program.)

3. Have students use the handy measuring guide in their student journals, labeled "How to estimate the period of Europa's orbit." Be sure to use the guide that corresponds to the scale of the image—either zoomed-in or zoomed-out; the guides are marked correspondingly.

   This guide helps students map their edge-on view of Jupiter and its moons, onto a top-view diagram of Europa's orbit.

This makes it easier for students to estimate how far Europa has progressed in its orbit.

4. Have students examine the example guide first.

5. Students work with two of their images: the *earliest* and the *latest* images they took. These are the two images that span the interval of observation. For each image, they carefully cut out a strip showing Jupiter and its moons, as shown in the example.

6. Place the images so that the center of Jupiter in each images lines up with the drawings of Jupiter (small black circle) in the diagrams.

7. For each image, *carefully* draw a straight line from Europa to the diagrams. Make sure the lines are parallel. (See example guide.)

   The lines will map the edge-on view onto a top view of Europa's orbit.

8. Have students estimate *what fraction of its entire orbit has Europa moved* during the period of observation?

9. Finally, have students estimate how long it would take Europa to orbit Jupiter once. For example, if Europa completed 1/12 th of its orbit in 6 hours, then it would complete a whole orbit in 72 hours.

10. Make sure that students record their estimate for Europa's period on the DATA PAGE in their journal.

11. Have students record their responses to the questions in their science journal.

    How does the period of Europa's orbit compare with the time it takes our own Moon to go around the Earth?

    Why do you think that Europa orbits Jupiter so much faster than our own Moon orbits Earth—given that the two moons are at roughly the same distance from their planets?

If you were exploring Europa, how long would you have before you were plunged into night, as Europa passes into Jupiter's shadow? How often would you be out of sight of Earth?

Europa orbits Jupiter once every 3.55 days (= 85 hours). Students' results may be considerable longer than this.

Europa's period is much faster than our Moon's period of about 27 days, even though Europa is farther from its planet than is our Moon. This is an indication that Jupiter must be significantly more massive than Earth.

Once during each 3.55 day orbit, Europa will pass behind Jupiter and be plunged into darkness. It will also be out of sight of Earth once during each orbit. From any given spot on Europa, you will be in sunlight during only half of the moon's orbital period. That's because Europe rotates on its axis at exactly the same rate as it orbits Jupiter. As a result, the same side of Europa always faces Jupiter—just as Earth's moon does. And just as (almost) any point on the Moon's surface is dark during half of its period, so will any point on Europa be dark for half the time.

Go Figure!

How much does Jupiter "weigh"?

Students are now ready to determine Jupiter's mass compared to Earth's, using their results from the previous activities.

1. Have students discuss with their teams:

   What information about the moons will you need to determine the mass of Jupiter? Why?

2. Then have students do the calculation and record their results on their DATA PAGE.

From Kepler's relation, we can find the mass of Jupiter, compared to Earth's, if we know the distance and period of one of Jupiter's moons—in this case, Europa—*and* we can compare it with the distance and period of the Earth's Moon. Our Moon is *about* 230,000 miles from Earth; the Moon's period is about 27.3 days.

Use the relationship:

$$M \sim \mathbf{d^3 / T^2}$$

M is mass of the planet
d is distance from planet to moon
T is the time for one orbit (the "period")

If we put in Europa's distance *compared* to the Moon's distance, and Europa's period *compared* to the Moon's period, then we can calculate from the Kepler's relation Jupiter's mass *compared* to Earth's mass.

This is equivalent to writing the relation as the equation

$$\mathbf{M = d^3 / T^2}$$

M is mass, in units where Earth's mass = 1
d is distance, where Earth-Moon distance = 1
T is the period, where period of Earth's Moon = 1

where we are allowed to choose the units so that Earth's mass = 1, the Earth-Moon distance = 1, and the period of Earth's Moon = 1.

As an example, say that students have estimated the distance to Europa as 450,000 miles, and estimated the period to be 4 days.

Then in Kepler's relation we can input:

d = distance to Europa, *compared to* Earth-Moon distance
= (450,000 miles / 230,000 miles) = 2.0

T = period of Europa *compared to* period of Earth's Moon
= (4 days / 27.3 days) = 0.15

We calculate:

M = mass of Jupiter *compared to* Earth

$$\frac{\mathbf{M}_{\text{Jupiter}}}{\mathbf{M}_{\text{Earth}}} = \text{mass of Jupiter } \textit{compared to} \text{ Earth}$$

$$= \frac{(\mathbf{d}_{\text{Europa}} / \mathbf{d}_{\text{Moon}})^3}{(\mathbf{T}_{\text{Europa}} / \mathbf{T}_{\text{Moon}})^2}$$

$$= (2.0)^3 \ / \ (0.15)^2 = 8 \ / \ .025$$

$=$ 320 times more massive than Earth.

The best current value: Jupiter is 317.8 times more massive than Earth.

In this example, students have found that Jupiter is more than 300 times more massive than Earth. Students have arrived at this number by using Kepler's relation and applying their measurements for the distance and period of one of Jupiter's moons.

How dense is Jupiter?

Discuss with students that, according to their results, Jupiter is more than 1000 times as large as Earth, yet weighs only about 300 times more. What could account for this? One conclusion is that Jupiter is not as *dense* as Earth; for example, it may not be composed of rocks. This idea will be examined in the next calculation.

Discuss with students:

> What information will you need to determine Jupiter's density? Looking back on your results so far, do you have that information?

The *density* of an object is its *mass per unit volume*. Students have found both the mass and volume of Jupiter, compared to Earth, so they can compare its density to Earth.

> How does the density of Jupiter compare to Earth density, which is about 5.5 grams/ cubic centimeter? Could Jupiter be solid rock?

Students have found that Jupiter is about 320 times more massive than Earth, but has about 1200 times the volume of Earth. Therefore Jupiter's density, compared to Earth's density is about

> 320 / 1200 = 0.27 times Earth's density

The average density of Earth is about 5.5 grams per cubic centimeter. Jupiter's average density is only 0.27 times this

> 0.27 x 5.5 = 1.47 grams per cubic centimeter.

The table shows densities of various substances, at atmospheric pressure. Jupiter is clearly less dense than rock. Its density if much closer to liquified natural gas, or water (ice). It is possible that Jupiter has a small, rocky interior, but clearly the bulk of the planet must not be made of rock.

Liquefied natural gas:	1 gram/ cubic centimeter
Water:	1 gram/ cubic centimeter
Rock:	3 gram/ cubic centimeter
Iron:	5 gram/ cubic centimeter

Have students discuss with their teams:

> *In your judgment, is it safe or unsafe to attempt to land on Jupiter?*

Since Jupiter is less dense than solid rock, we had probably better not try to land on the planet.

In reality, Jupiter is known to consist largely of liquefied gases, and does not have a surface. If you tried to land on Jupiter, you would sink deep into the interior of the planet and be crushed by the enormous pressure of the liquified gas above you!

How much would you weigh on Jupiter?

How much stronger is Jupiter's gravity than Earth's (at the surface of each planet)?

Have students discuss with their team what factors influence the gravitational pull you feel from a planet.

> *What equation describing the relationship between these factors will you need? Which of your previous results will you need?*
>
> *How much would you weigh at the surface of Jupiter?*
>
> *If Jupiter is so much more massive than Earth, why isn't your weight proportionately that much more?*

The gravity you feel is determined by only two factors: the **mass** of the planet pulling you down, and your **distance** to the center of the planet. So to find the force of gravity on Jupiter compared to Earth, you'll need to know the mass of Jupiter compared to Earth, and the size of Jupiter compared to Earth. (Your mass is the *same* on both planets!)

This is summarized in Newton's law of gravity:

$$F \sim mM / r^2$$

$$\text{Force of gravity at surface} \sim \frac{(\text{your mass}) \times (\text{mass of planet})}{(\text{radius of planet})^2}$$

$$\text{Surface gravity compared to Earth} \sim \frac{(\text{mass of planet compared to Earth})}{(\text{radius of planet compared to Earth})^2}$$

$$= \frac{(320)}{(11)^2}$$

Teachable moment: Your mass doesn't change on Jupiter, but your weight does. Why is that?

So Jupiter's gravity is 320 / 121 = 2.6 times as strong as Earth's. If you weigh 100 pounds on Earth, you would weigh 260 pounds on Jupiter's surface (if it had a solid surface!).

Note that although Jupiter is 320 times as massive as Earth, you wouldn't weigh 320 times as much on Jupiter. That's because the gravity you feel also depends on your distance from the center of mass of the planet, which is also its center of gravity. Jupiter is much larger than Earth, so on Jupiter's surface you would be much farther from the center of the planet than you would be on Earth.

What is the surface of Europa like?

Have each team examine and discuss the images of Europa in their journals.

> What do you think the bright spot and dot are in the lower right portion of this image of Europa?
>
> How does this image compare to Earth's Moon? What might account for the lack of many craters?
>
> What might the dark, reddish-brown material be? What are possible sources of this material? What evidence would you need to support your hypotheses?
>
> The surface of Europa is very bright. What might this indicate?
>
> What might the cracks on the surface indicate? Where are on Earth might you see cracks like this?

The bright spot at the lower right of the Europa image looks a lot like one of the craters of our Moon. Note the circular crater and what look like faint "rays" of material spreading out from the crater.

Earth's Moon has many more craters than just this one on Europa, or the few found on Earth. We think that most of the worlds in the solar system were bombarded by asteroids early in their history. Therefore, something must have erased the many craters that must have been formed by asteroid impact. On Earth, we know that wind and water erode the Earth's surface features over time. On Europa, we think that surface ice must move and change with time. Thus evidence of old craters would have been erased as new ice formed at the surface.

The bright surface and the long, straight cracks, indicate that the surface might be ice. The view is very similar to aerial photos of the ice in Antarctica or on large frozen lakes. No one knows for sure what the reddish-brown material is made of. It is thought to be made of salts that ooze up from beneath the ice on Europa.

Assessing student work

Were students able to take 3 successful images of Jupiter and its moons? Were they able to create a digital movie of the motion?

Did they correctly identify Europa?

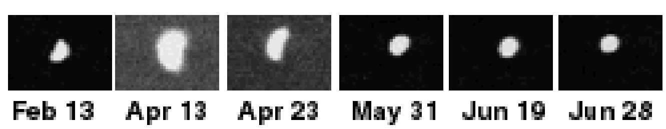
Did they use their images to present evidence for the physical properties of Jupiter?

Did they identify potential sources of error in their work? Identifying these errors is more important than comparing their results for the mass, density, or surface gravity of Jupiter with textbook values.

Student projects

Can you prove that the planet Venus orbits the Sun?

This project is especially effective if students first predict what they expect to observe as Venus orbits the Sun. In the sequence shown here, taken over 5 months, notice that Venus gets much larger when it is on the same side of the Sun as Earth, and then much smaller as it moves to the far side of its orbit. Make sure that students use a variety exposure times, because the crescent shape will be lost if the image is overexposed.



The planet Venus goes through phases over the course of five months. Note that its size also changes. **Images by Anita Honkonin's students at Lincoln-Sudbury HS, Sudbury, MA.**

Observations of the phases of Venus were presented by Galileo and others as evidence that the planets revolve around the Sun.

Weigh a black hole at the center of our galaxy

This project shows how powerful the laws of motion are: Students can use the same procedure to weigh a black hole as they use to weigh Jupiter. Three terms will be unfamiliar to students:

Our Milky Way galaxy is the giant, spiral collection of billions of stars, of which are own Sun is one. (See Exploration 5.)

A black hole is the amazing object formed when large stars collapse under their own weight, at the end of their lifetimes. The gravity near a black hole is so strong that nothing that falls in can escape.

A light-day is the distance that light travels in one day. This is 186,000 miles per second x 86,400 seconds in a day. For comparison, the Earth is 8 light-minutes from the Sun.

In weighing the black hole at the center of our Galaxy, students should find approximately the following:

The radius of the star's orbit is roughly 5 light-days—that is, the star is roughly 5 light-days from the presumed black hole at the center. This is about 900 times farther than the distance between Earth and Sun.

The period of one orbit is roughly 15 years, based on the time-markings on the animation.

So using Kepler's relation, the mass of the black hole is:

$$\mathbf{M = d^3 / T^2}$$

mass is in units of the mass of the Sun,
distance is in units of the Earth-Sun distance, and
time is in units of one Earth period (one year)

This is

$$\mathbf{M} = (900)^{3} / (15)^{2}$$

$$= 729{,}000{,}000 \; / \; 225$$
$$= 3.2 \text{ million times the mass of the Sun}$$

So the mysterious object at the center of our Milky Way galaxy weighs more than 3 million Suns. Astronomers believe that a mass this large, contained in a region so small, must be a black hole.

	Distance (# of pixels) from center of Jupiter to...			
	1st moon (on left)	**2nd moon**	**3rd moon**	**4th moon (on right)**
Image 1 (earliest)				
Image 2				
Image 3				
Image 4				
Image 5				
Image 6 (latest)				
No. of pixels the moon has moved, from 1st to last image				

Approximate times when Jupiter is visible

This is for the first of the month. Estimate rising time for your date.
For Boston, subtract 25 minutes
For Tucson, add 20 minutes
1 a.u. = 1 astronomical unit = Sun-Earth distance ~ 93 million mi

Date	Jupiter rises...	Jupiter highest	Jupiter sets...	Distance from Earth
2003				
Dec	12 23a	6 43a	1 03p	5.5 a.u.
2004				
Jan	10 25p	4 47a	11 07a	4.8 a.u.
Feb	8 17p	2 41a	9 02a	4.5
Mar	6 05p	12 35a	7 00a	4.4
Apr	3 45p	10 16p	4 48a	4.5
May	1 39p	8 12p	2 46a	4.9
Jun	11 44a	6 14p	12 48a	5.4
Jul	10 03a	4 28p	10 54p	5.8
2005				
Jan	12 45a	6 29a	12 14p	5.4 a.u.
Feb	10 47p	4 33a	10 16a	5.0
Mar	8 50p	2 39a	8 23a	4.6
Apr	6 31p	12 25a	6 13a	4.5
May	4 16p	10 10p	4 06a	4.6
Jun	2 05p	8 01p	1 59a	4.9
Jul	12 13p	6 07p	12 04a	5.3
2006				
Jan	2 51a	8 09a	1 24p	5.9 a.u.
Feb	1 11a	6 23a	11 35a	5.4
Mar	11 25p	4 38a	9 49a	5.0
Apr	9 17p	2 32a	7 43a	4.6
May	7 03p	12 22a	5 36a	4.4
Jun	4 43p	10 01p	3 23a	4.5
Jul	2 30p	7 57p	1 19a	4.8

