Kepler's Laws and the Galilean Moons Lab

This is a two class lab. Work in groups of 2-3 and hand in one copy of the lab per group. All group members are expected to contribute equally.

Objective: Familiarize yourself with observations of orbital motion. Discover and apply Kepler's Laws and the Law of Gravity.

Materials: Rulers (1 per group member), colored pencils (5 colors), graph paper, data handout

Introduction

One of the great achievements of the astronomer Galileo Galilei was his identification of the four largest moons of Jupiter, now (appropriately) called the "Galilean moons" Io, Europa, Callisto and Ganymede. His observations were done with a small telescope and a great deal of patience. The observations that Galileo made of Jupiter, together with similar observations of Jupiter and the other planets in our solar system by Tycho Brahe, gave Brahe's apprentice Johannes Kepler the tools that he needed to develop the mathematical laws that we know today as Kepler's laws. You will find in this lab that you can use observations of Jupiter's moons to verify the basic principles described in Kepler's laws.

Procedure

You should have received a packet (one per group) with 50 images of Jupiter along with this lab. Each shows what you would see through a small telescope (today a "small telescope" still means bigger and of better optical quality than the one that Galileo himself used, which was essentially a sailor's spyglass!) if you were to have observed Jupiter in the night sky on the date and time indicated in the upper right of each image and from a special location on Earth, this is what you would have seen. **The images have been color reversed, so bright things are dark and dark things are bright.**

1. Label the Moons

If you examine them carefully, you will see that there are generally five objects in addition to Jupiter (the large, bright, banded object at the center) visible near it. Your first task is to go through each of the images and label these objects 1-5 in each image. **Note that all five will not always appear in every image and that some of them will trade places over the course of the 50 hours of data shown, so <u>look carefully</u>. If you called one object "object 2" in the first frame, you need to call it "object 2" throughout even when it switches places with other objects.**

As you go through the images, you should also place a dot at the center of Jupiter in each image using a ruler.

2. Measure

Now, go through and measure the distance to each moon in millimeters from the center of Jupiter that you marked in the last step. Record each value in the table at the end of this lab.

In cases where one (or more) of the five objects disappears, note that in the table by writing "gone" in the relevant box. There will be a couple of cases in which Jupiter itself is not visible in the image, in which case you should write "Jupiter gone" across the entire row of boxes. **Mark all distances where the object is to the right of Jupiter as positive and all where the object is to the left of Jupiter as negative.**

***note: The image pages are numbered. You should feel free to divvy up the pages between your group members and compile the data at the end, but make sure that you are all consistent about how you measure and how you mark the center of Jupiter. Calibrate yourselves first!*

3. Plot

Compile all of the data from Step 2 and use it to make a chart (one per group, but all group members need to assist and should not just be watching one person do all of the work!) of the location of each moon relative to Jupiter. Your graph should follow the following guidelines:

1. The x axis should show the distance from Jupiter in mm, and should include positive (to the right of Jupiter) and negative (to the left of Jupiter) values.
2. The y axis should be placed at the location of Jupiter (an x axis value of zero) and should show the time (from hour 1 to hour 50).
3. You should mark the location of each of the five objects at each hour (skip instances where it is "gone") with a small colored dot. Use five different colors for the five different objects and make a legend in one corner of your graph showing which is which.
4. Connect the path of each moon with a dashed line in that same color.
5. Follow the general guidelines for good graphs: **use your space wisely** (your chart should take up the whole page!), include a title and axis labels, etc.

4. Questions

Use the chart and the table that you made (as well as your instructor when you're stuck) to answer the following questions. Answer them on a separate sheet of paper. When you are finished, staple your table, chart, and answers to the questions and hand that in to your instructor with all group members' names on it. **For each of the following questions, use specific data from your chart and/or graph to support your answer. If you don't you WILL LOSE POINTS for completeness.**

1. One of these things is not like the others! You may have noticed that one of the five objects near Jupiter over this 50 hour time span follows a very different pattern of motion from the other four.
    a. Which object is it and how is it's motion different from the other four?
    b. Is this object in orbit around Jupiter? How can you tell?
    c. What might this object be? Make a guess and then design an experiment to test your hypothesis and describe it (hint: different types of objects in the sky move at different rates relative to one another. When would you come back to observe Jupiter again to verify or disprove your hypothesis?)
    d. When you have completed (c), see your instructor for a means of testing your hypothesis. When completed, describe the results of your experiment.

For each of the following questions, use specific data from your chart and/or graph to support your answer. If you don't you WILL LOSE POINTS for completeness.

2. The other four objects are the four Galilean moons of Jupiter.
    a. Assign each of the objects that you've decided are moons a "Moon number" and record it as follows (on your separate sheet of paper)
        Moon 1 = Object ___
        Moon 2 = Object ___
        Moon 3 = Object ___
        Moon 4 = Object ___
    b. Do any of the four moons complete one full orbit of Jupiter over this time interval? If so, which? How can you tell?
    c. Make a small graph (on your sheet of answers and not on graph paper is ok) showing one full orbit of a moon around Jupiter (a generic moon, not one of the ones you've observed, so you don't need specific numbers on the x or y axes).
    d. On the same graph, sketch the path of a moon that is closer to Jupiter, and one that is farther from Jupiter and label all three.

3. The four moons of Jupiter show (or would show if we were to watch them for longer) the same general pattern of motion relative to Jupiter, but of course the four moons are also at different distances from Jupiter and therefore, according to Kepler's laws, orbit differently. One useful tool for judging their motions will be the speeds they are moving from your point of view, which are represented on the graph by the slope of the lines you plotted.
    a. Do the moons move by the same distance each hour? What is the range of speeds (mm/hr) for each of the moons?
       Ex: Moon 1: 1mm.hr at slowest and 5mm/hr at fastest
    b. For the moon(s) that complete a full orbit, where are they relative to Jupiter in the diagram when are they moving the fastest and where are they when are they moving the slowest?
    c. Are these "spots" related to the pattern of motion you described in 2? How?
    d. Approximately what percentage of a complete orbit have you observed for each moon? Justify your answer and explain how it is related to the range of speeds of each moon that you recorded in a.

4. The four moons that Galileo discovered in 1610 are named Io, Europa, Ganymede, and Callisto. This table below shows the period and orbital radius for each moon. The period is the time for one complete revolution around Jupiter.

Moon	Period (days)	Orbital Radius (km)
Io	1.8	421,600
Europa	3.5	670,900
Ganymede	7.2	1,070,000
Callisto	16.7	1,883,000

For each of the following questions, use specific data from your chart and/or graph to support your answer. If you don't you WILL LOSE POINTS for completeness.

a. Which of your moons 1-4 is which? Justify your answer for each.
b. How are the orbital radii of the moons related to how they moved over the course of your observation? Use Kepler's laws in your explanation.
c. How are the periods and orbital radii related to one another? Use both specific data from the table on the last page and Kepler's laws to justify your answer.

6. By analyzing images of Jupiter and its moons, you can determine values for the variables D and T in the equation below and solve for the mass of Jupiter, M_J.

$$M_J = \frac{4\pi^2 D^3}{GT^2}$$

In this equation, D is the radius of the orbit of one of Jupiter's moons and T is the time it takes the moon to complete one orbit (the orbital period). G, the constant of universal gravitation, and has a currently accepted value of: $G = 8.65 \times 10^{-13}$ $km^3/kg\text{-}hr^2$.
Note that this equation looks a lot like Kepler's Third Law, but is modified to incorporate Newton's universal gravitation constant, which makes it apply to <u>*any*</u> *central body that is being orbited by a much less massive object (not just the sun); e.g., The Hubble Space Telescope orbiting the Earth, a moon around a planet, one of the planets around the sun, or the sun around the center of our Milky Way galaxy. In all these cases the mass of the orbiting body is insignificant compared to the mass of the central body, and as you can see, its mass is not even included in the equation. If the mass of the orbiting body were significant, they would be orbiting around a common center, and a different equation would be needed.*

a. As a practice problem, use the equation above to find the mass of the Earth given the following observational data: The period of the Moon around the Earth is 655 hr and the mean radius of its orbit is 384,000 km. Once you have an answer, look up the real value or ask your instructor to verify that you are doing the calculation correctly. Make sure that you also attach a unit to the mass. Use the information you were given above to explain why that unit is valid.
b. Use your plot to estimate the "turn-around" point (the maximum distance from Jupiter) for each of the moons, in mm, from Jupiter.
c. In order to convert this "turnaround distance" to a real physical distance, you need a reference object. Luckily, Jupiter is the perfect candidate. It has a real diameter of 1.43×10^5km. Measure its diameter on your images and use it to estimate how much "real" distance 1mm on your images represents.
Hint: This is a "conversion factor", which we will talk about in more detail later in the class. For now, all you need to know is that when you have something of the form A mm (in the image)= B km (in real life), you can also say that 1 mm = B/A km. In other words, B/A km is the real distance represented by 1mm in your images. Multiply all of your distances in mm by this conversion factor to get the real number of km between the objects

For each of the following questions, use specific data from your chart and/or graph to support your answer. If you don't you WILL LOSE POINTS for completeness.

d. Make a table listing each moon, your estimate for its turnaround distance in your images (in mm) and it's real distance from Jupiter (in km) according to your conversion calculation (use the conversion factor you calculated in c). Save room for three additional columns in your table.

e. Again using **your data only**, estimate the period for each of the moons in hours. Your answer to 3d will help. Add this to the table you made in c (but don't forget to explain using data how you arrived at this conclusion).

f. You now have the period and radius for each of the moons. For each moon, plug these values as well as the constants into the equation for the mass of Jupiter and fill in that mass in the last column of your table.

g. Calculate the average of your four independent estimates for the mass of Jupiter.

h. The currently accepted value for the mass of Jupiter is 1.90×10^{27}kg. Determine the percent difference between this accepted value and your calculated (experimental) values using the following equation:

$$\% \text{ Difference } = \frac{\text{accepted value - calculated value}}{\text{accepted value}}$$

Do it for each moon individually and for the average of all four.

i. Which of your estimates for the mass of Jupiter is the closet to the real vale? Why? Be specific, using the data from your table and from the table in #4.

5. Wrap Up

a. What is the "big picture" of the chart that you made? Write a one sentence explanation describing what it shows.

b. How far apart are the two instances where Jupiter itself (and all of it's moons) are "gone" in your table/images?

c. Develop a hypothesis to explain this. See your instructor for a means to test your hypothesis and then describe the result here.

d. When you interacted with your instructor, you should have noticed that the motion of Jupiter (and every other object in the sky) over this time interval is peculiar compared to what you're used to. Describe the motion of objects in the sky from the location we are simulating with these observations.

e. What location on Earth were the simulated observations "taken" from? What is special about day/night in this place?

f. Why did we have to go to this location to complete these observations of Jupiter (*Hint: think about the time interval over which these observations were taken and whether you could do this from Tucson).*

g. Galileo lived in Florence, Italy, where the sky moves nightly in the same way it does from Tucson. Describe how they would have been different and what he would have had to do to overcome any obstacles created by his observing location.

	Object 1	Object 2	Object 3	Object 4	Object 5
Hour 1					
Hour 2					
Hour 3					
Hour 4					
Hour 5					
Hour 6					
Hour 7					
Hour 8					
Hour 9					
Hour 10					
Hour 11					
Hour 12					
Hour 13					
Hour 14					
Hour 15					
Hour 16					
Hour 17					
Hour 18					
Hour 19					
Hour 20					
Hour 21					

	Object 1	Object 2	Object 3	Object 4	Object 5
Hour 22					
Hour 23					
Hour 24					
Hour 14					
Hour 25					
Hour 26					
Hour 27					
Hour 28					
Hour 29					
Hour 30					
Hour 31					
Hour 32					
Hour 33					
Hour 34					
Hour 35					
Hour 36					
Hour 37					
Hour 38					
Hour 39					
Hour 40					
Hour 41					

	Object 1	Object 2	Object 3	Object 4	Object 5
Hour 42					
Hour 43					
Hour 44					
Hour 45					
Hour 46					
Hour 47					
Hour 48					
Hour 49					
Hour 50					