SIERRA COLLEGE OBSERVATIONAL ASTRONOMY LABORATORY EXERCISE
Lab N10: Jupiter and Saturn

NAME	GROUP

OBJECTIVE:
- Use apps to study the satellite systems of Jupiter and Saturn.
- Observe and measure the orbital behavior of its satellites.

INTRODUCTION:

The four largest planets in our solar system—Jupiter, Saturn, Uranus, and Neptune—are collectively known as the *Jovian planets*. One characteristic of the Jovian planets is that they have many moons, or *satellites*, in orbit around them. Jupiter alone has approximately 70 that we know of! The four largest satellites of Jupiter—Io, Europa, Ganymede, and Callisto—were first observed by Galileo.

In the 1600s, Johannes Kepler devised three somewhat mysterious laws of planetary motion. It was not until later that Isaac Newton was able to provide a physics explanation for these laws.

In this lab we will focus on *Kepler's Third Law*. In the simplest form, it can be written as $P^2=a^3$, where "P" is the period of an object orbiting around the Sun (given in years), and "a" is the average distance of the object from the Sun (given in *astronomical units, a.u.*—where 1 a.u. equals the average distance of the Earth to the Sun).

When Newton derived Kepler's Third Law, he solved it for the general case of any object orbiting any other object. In the simplified case where one object is much more massive than the orbiting object, Newton's version of Kepler's Third Law is still quite simple:

For the case of a satellite orbiting a planet, Kepler's Third Law becomes as in Equation 1. In this version of the law, κ is a constant, and the quantities "a" and "P" are as given before—but are now measured in km and seconds:

**Equation 1: Kepler's Third Law**

$M_{planet} = \kappa a^3/P^2$,

$\kappa = 5.9 \times 10^{11}$ kg s^2/m^3

When satellites are closely stacked, as they are in the Jovian systems, the satellites gravitationally interact with each other, creating *orbit-orbit resonances*. In such situations, the ratio of the orbital periods are given by perfect ratios of whole numbers, such as 2:1, 4:3, 5:7 etc.

PROCEDURE I: The orbits of the moons of Jupiter

1. Start the JupiterMoons app and select "Flip Horizontally" (so the text box is light gray). Set the time to NOW. Carefully sketch and label the positions of its four Galilean satellites in the frame below. If any are being occulted, note that in your sketch. (Do not be distracted by the occasional star, which might be labeled with its HD number.)

Figure 1: The Jupiter System
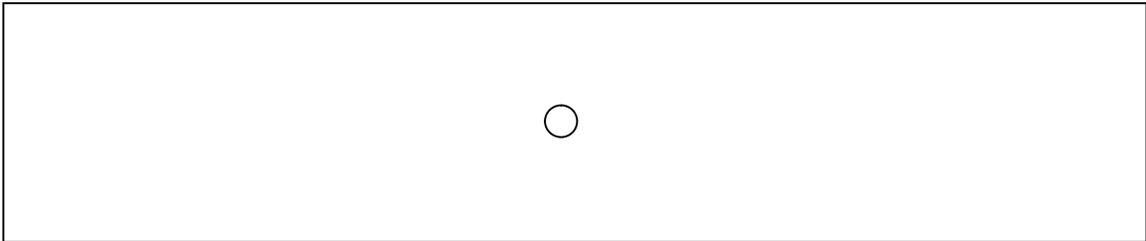
2. Set the time step to "10 Min" and press the Continuous-Advance button (▶). Watch the satellites orbit. While they orbit Jupiter in nearly perfect circles, we see the orbital system from the side. Notice that the satellites with smaller orbits orbit faster, with shorter periods. Write down the names of the satellites, in order of closest to furthest from Jupiter

(closest) _____   _____   _____   _____ (furthest)

3. Experiment with the Time-Step-Unit selections (1 Year, 1 Month, 1 Day, 1 Hour, 10 Min, 1 Min, 1 Sec), and the Backwards Time-Step button (◀|) and Forwards Time-Step button (|▶).

    Select the "1 Hour" Time-Step-Unit, and advance the time until the satellite Io is centered in front of (and not behind) Jupiter. Use the shorter Time-Step-Units to center Io in front of Jupiter exactly. Use the zoom view to refine your centering.

4. Return the Time-Step-Unit to "1 Hour." Then, making sure you do not lose count, click the Forwards Time-Step button (|▶) again and again until Io completes its orbit around Jupiter, returning to in front of Jupiter. Do not allow Io to go past the mid-point of Jupiter. Record the number to times you clicked the 1-Hour advance button in Table 1. Do this a second time, just to make sure you did not lose count.

    If you click too rapidly for the App, you will get an incorrect count. If you miss the Forwards Time-Step button with one of your taps, you will change the zoom factor or time-step—either way, you will get a faulty result. So be deliberate, careful, not too fast, and not sloppy.

5. Set the Time-Step-Unit to "10 Min." Then, making sure you do not lose count, click the Forwards Time-Step button (|►) enough times to bring Io to exactly in front of Jupiter, as it was at the end of Procedure step 3. Record the number to times you clicked the 10-Min advance button in Table 1.

6. Repeat Procedure steps 3-5, but this time for Europa. Record your data in Table 1. Clicking the button repeatedly is tedious, but if you do it carefully it should be easy, and when you repeat your count you should get the same value.

7. Now center Ganymede carefully in front of Jupiter, and then zoom out so you can see the entire Jovian system. Set the Time-Step-Unit to "1 Day." Click the Forwards Time-Step button one time, and observe Ganymede's new location. Repeat this process, counting your clicks, until Ganymede almost completes one full orbit. As needed, switch to 1-Hour or 10-Min time steps, and click the forwards button to make Ganymede complete 1 full orbit. Record your data in Table 1. Repeat this step, to make sure you did not make any counting errors.

8. Repeat this for Callisto, and record your data in Table 1. Repeat this step, to make sure you did not make any counting errors.

9. In Table 1, convert your orbit measurements for the satellites to the format hh:mm. Record your results. Then convert your time to decimal format hours, also recording your results. Refer to the boxed calculations #1, #2 (next page) if you need help.

Table 1: Orbital Periods I

	Days	1 Hour	10-min	hhh:mm	Decimal hrs
Io					
Europa					
Ganymede					
Callisto					

10. Further analyze the decimal hour orbital periods you calculated Table 1. Divide the orbital periods of Callisto, Ganymede, and Europa, by the orbital period of Io. Round your values to the nearest tenth. Also, convert the orbital periods of all the satellites into seconds. Use correct units throughout.

Table 2: Orbital Periods II

	Orbital Period ÷ Io Orbital Period	Orbital Period (seconds)
Io		
Europa		
Ganymede		
Callisto		

Sample calculation #1—hhh:mm format

Io or Europa

Suppose for Io you clicked the 1-Hour advance button 17 times, and the 10-Min advance button 5 times. Then

  Orbital time (hhh:mm) = 17 h + (5 x 10 min) = 17 h 50 min = 17:50

Ganymede or Callisto

Suppose for Ganymede you clicked the 1-Day advance button 8 times, the 1-Hour advance button 9 times, and the 10-Min advance button 2 times. Then

  Orbital time = (8 x 24 h) + 9 h + (2 x 10 min) = 192 h + 9 h + 20 min = 201:20

Sample calculation #2—decimal hours format

Suppose you have a time interval in the hhh:mm format of 98:50. Convert this into decimal hours format.

  Orbital time (decimal hours) = 98 h +50 min x (1 hr/60 min) = 98.83 h

11. Zoom out on the app display. Using the time advance buttons, adjust the time so that Io swings as far as possible either to the left or right of Jupiter. Measure the distance from Io to Jupiter's center, in mm. Repeat for all the satellites. Record your data in Table 3. If Callisto disappears out of the field of view, try moving it to the other side of its orbit.

Table 3: Orbital Distances

	Scale mm	True m
Io		
Europa		
Ganymede		1.07×10^9 meters
Callisto		

12. Ganymede's orbital distance is 1.07×10^9 meters. Divide this distance by the scaled distance you measured on the app, to obtain the image scale for the app display, in meters/mm. Record that value below, with proper units. Multiply this image scale by the distances you measured on the display, to calculate the orbital distances of the satellites for Table 3.

Image scale: _____

PROCEDURE II: The orbits of the moons of Saturn

13. Start the SaturnMoons app, selecting "Flip Horizontally." Set the year/month/day to 2021/06/18, and the time to 14:00:00. Zoom in so that Titan is still barely visible at lower right. Sketch (ONLY) the locations of Rhea, Tethys, and Titan. Also, sketch the location of Dione, but in a different pencil color. Label them. These are the satellites that are easiest to see. Add the rings to Saturn.

    Also label the location of the extremely faint satellite Enceladus, using the same color as you did for Dione.

Figure 2: Saturn and Rhea, Dione, Tethys, Titan, and Enceladus
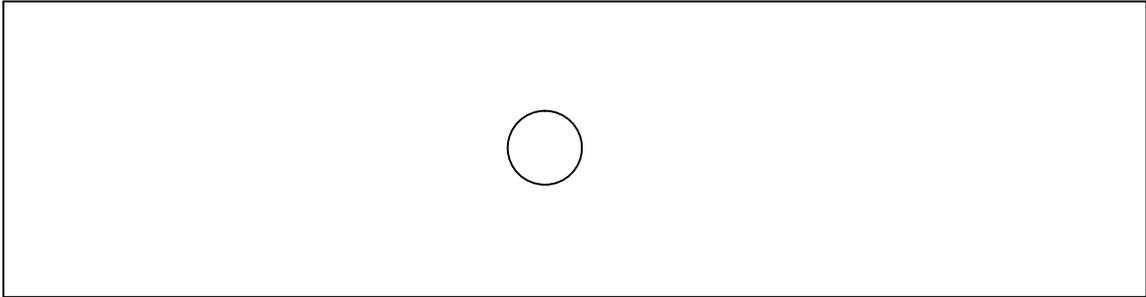
14. Using a Time-Step-Unit of "1 Hour," step forwards in time, watching Dione. Skip forwards until 2021/06/21 at 08:00:00. Notice Dione has completed one full orbit, and has returned to where you sketched it in Figure 2. Have any other satellites returned, more or less, to their starting locations? Write their names below.

_____ _____ _____ _____

PROCEDURE III: The mass of Jupiter

15. In Table 4, the four satellites are just indicated by their first letter. Transfer your values for orbital distance (a) for the satellites, in meters, from Table 3 to Table 4. Also transfer your values for orbital period (P) for the satellites, in seconds, from Table 2 to the appropriate column below.

Table 4: Preparing for Keplerian calculations.

	Orbital distance (a) (meters)	a^3 (meters^3)	Orbital period (P) (sec)	P^2 (sec^2)
I				
E				
G				
C				

16. Cube the values of the orbital distance (a) for the satellites, to obtain values of a^3 for Table 4. Also calculate values for P^2. Use correct units throughout.

17. Use Kepler's Third Law (Equation 1), and the orbital values of a^3 and P^2 from Table 4 for Io, to calculate the mass of Jupiter for Table 5. Repeat for the other satellites. Refer to the boxed calculation #3 if you need help.

Table 5: Estimates for the mass of Jupiter

	Mass
Io	
Europa	
Ganymede	
Callisto	
Average	

18. Average your four estimates of the mass of Jupiter for the last line in Table 5.

Sample calculation #3—Using Kepler's Third Law

Suppose the lab analysis indicated that

$a^3 = 1.90 \times 10^{27}$ m^3 and $P^2 = 4.35 \times 10^{11}$ sec^2

Kepler's Third Law is:

$M_{system} = \kappa a^3 / P^2$ where $\kappa = 5.9 \times 10^{11}$ kg s^2/m^3

So…

$M_{system} = \kappa a^3 / P^2 = (5.9 \times 10^{11}$ kg s^2/m$^3) \times (1.90 \times 10^{27}$ m$^3) / (4.35 \times 10^{11}$ sec$^2)$

$= 2.58 \times 10^{27}$ kg

VOCABULARY:
Jovian Planet
Satellite
Kepler's Third Law
Astronomical unit
Orbit-orbit resonances

QUESTIONS/ANALYSIS:

1. Of the four large satellites of Jupiter, one is not synchronously locked in an orbit-orbit resonance with the others. Which is it?
    (Hint: Refer to Table 2.)

    Satellite = _____

2. The actual mass of Jupiter is 1.898×10^{27} kg. Use the discrepancy formula to calculate the % difference between your average value from Table 5, and the actual value.

    Discrepancy = _____

3. In Procedure steps 14-15, you observed that during the time interval 2021/06/18 at 14:00:00, to 2021/06/21 at 08:00:00, Dione completes one full orbit. How many hours, and how many seconds, is this orbital period?

Orbit time (h) = _____   Orbit time (s) = _____

4. Dione's orbital distance from Saturn is 3.77×10^8 m. Based upon this and its orbital period, what is the mass of Saturn? Use correct units.

    Saturn's mass = _____

5. A physicist would point out that our version of Kepler's Third Law is a slight approximation, and is using the assumption that Jupiter (or Saturn) is much more massive than the satellite orbiting it. Table 6 below gives the approximate masses of solar system objects. Calculate the ratio of the planet mass to its satellite mass to show that our assumption is correct.

Table 6: Checking our assumptions

	Planet Mass	Satellite Mass	Planet Mass/ Satellite Mass
Io	1.90×10^{27} kg	8.93×10^{22} kg	
Europa	1.90×10^{27} kg	4.80×10^{22} kg	
Ganymede	1.90×10^{27} kg	1.48×10^{23} kg	
Callisto	1.90×10^{27} kg	1.08×10^{23} kg	
Dione	5.68×10^{26} kg	1.1×10^{21} kg	

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