Name: ____________________

Date: ____________________

Section: ____________________

Astron 104 Laboratory #6
The Speed of Light and the Moons of Jupiter
Section 1.2, 8.1

This lab is based on Project CLEA, `http://www3.gettysburg.edu/~marschal/clea/CLEAhome.html`.

You will use software to find eclipses of the moons of Jupiter, and by noting when these eclipses happen you can determine the speed of light.

Galileo discovered that Jupiter had four moons in 1610, which went around the planet with remarkable regularity. It didnt take long before astronomers had highly accurate measurements of the orbital period of these satellites. Io orbited in about 1.8 days (we will use the more exact number of 1.769861 days, and keep as many significant digits as possible in your calculations). Europa took 3.5 days. Ganymedes orbital period was just over 7 days. And Callisto, the most distant of the Galilean moons, went around Jupiter in 16.7 days.

The disappearance or reappearance of the moons at certain points in their orbit was the easiest position of the moons to time exactly. Astronomers, of course, noted that the moons disappeared when they went behind Jupiter. But it was even more common to see the moons disappearing before they actually passed behind the planet or reappear slightly after they came out from behind it. That is because the moons only shine because they reflect light. When the moons pass into Jupiter's shadow, they go dark. Jupiter's shadow is a cone of darkness that extends out from Jupiter into space in the direction opposite to the Sun. So the position of Jupiter's shadow depends on where Jupiter is in its orbit. Astronomers had to take this into account, as well as the orbital period of the moons, when they calculated a detailed prediction for eclipses of the moons. But once they had done these calculations, they could be used to forecast the times of future eclipses. In a sense, the moons were like the hands of a very precise celestial clock.

For example, imagine that you have an ephemeris of eclipses and know that Io will be eclipsed tonight at 22:31 your time. Later tonight when you observe Io disappear into Jupiter's shadow, you could be sure that the time was 22:31, even if you didn't have a wristwatch.

Useful Information

1. **Starting the Program**
   The *Jupiter's Moons and the Speed of Light* program is a standard program under MS-Windows. To run it, click on the CLEA icon labeled *Jupiter Moons & Speed of*

Light. Select **File→Login** from the menu bar, and type in your name when asked. If you then click "OK", you will see the title screen for the *Jupiter's Moons and the Speed of Light* exercise, and will be able activate the program from the menu bar using the **File→Run** menu option.

2. **Summary of the Activity**
The speed of light will be determined using a method developed in the 17th Century by Ole Roemer using data obtained by Giovanni Cassini.

In this activity, you will observe Jupiter using the CLEA simulation *Jupiter's Moons and the Speed of Light*.

The activity consists of observing the times of Io's eclipses when Jupiter is far from and near the Earth. You will find two dates when the distances between Jupiter and Earth are larger and smaller respectively. The greatest distance between the two occurs when Jupiter is at conjunction. Closest approach occurs at opposition.

Times for conjunction and opposition can be obtained in the CLEA exercise under:

File → Observation Date → Jupiter Phenomena

Distances between Jupiter and Earth are found by clicking "Record" on the bottom right of the main window.

In practice, dates about two months after conjunction and a month prior to opposition provide observing situations that allow Io's eclipses to be seen more easily.

3. **Overview of the Observing Procedure**
On the *far* date, observe and time an eclipse of Io. Then use the synodic period of Io to predict an eclipse several months later. Observe and time the predicted eclipse and compare the predicted time to the observed time.

Since the light from Io takes more time to travel the distance between Jupiter and Earth when they are far, and less when they are near, the *difference in time* (Δt) between predicted and observed time corresponds to the time light had to travel the *difference in distance* (ΔD).

Knowing the difference in distances between Jupiter and Earth on the two dates and the difference in time permits a straightforward calculation of the speed of light:

$$\text{Speed of Light} = c = \frac{\Delta D}{\Delta t}$$

4. **Become familiar with the CLEA simulation**
You should be able to:

Set dates and times: Select the **File→Observation Date→Set Date/Time** option from the menu bar.

Change the view magnification: Click the buttons at the bottom of the view screen to choose 100, 200, 300 or 400 times magnification. For most observations of Io, you will want to use the largest magnification possible in which the moon is visible.

Set the Observation Interval to various values (from several hours to 0.005 hours): This sets how much time elapses between each observation each time you press the *Next* button. Select the **File→Timing** option from the menu bar, and enter the desired interval in the blank marked *Observation Step*.

Set the ID Colors for the satellites and identify Io: Select **File→Features** from the menu bar and check the box marked *Use ID Colors*. The different moons will appear different colors. Which one is Io? You can find out by using the mouse to point the cursor at the moon and left clicking on it. The name of the moon will appear at the lower right of the view window, along with the x and y position of the moon with respect to Jupiter. If you don't immediately see the name of the moon, try moving the cursor—you need to be pointing right at it.

View the satellites from the overhead perspective: Select **File→Features** and check the box labeled *Show Top View*. This view makes it easy to sort out the moons Io, Europa, Ganymede, and Callisto on the telescopic view. The shadow of Jupiter is marked, too, by two green lines, so that you can see when a moon is about to enter Jupiter's shadow.

Determine when conjunction and opposition occur: Select **File→Observation Date→Jupiter Phenomena** from the Menu Bar. You will see a window that shows in the top two lines the exact date and time of the next oppositions and conjunctions.

Find the distance between Jupiter and Earth on any date: One way is to select **File→Observation Date→Jupiter Phenomena** at any time. The last line shown above is the Earth-Jupiter distance at the time you are observing (the time shown in the view of Jupiter's moons). Another way is to click the *Record* button on the telescope view window. A popup will open that will show you the Earth-Jupiter distance, and will also allow you to record the time of the eclipse in a data file for later manipulation.

View and print saved data: By selecting **File→Observation Date→View/Print Saved Events** you can see a record of timings and distances for eclipses, and print the records out. This is the data you will use in your determination of the speed of light.

5. **Dates and Times**
Time in the simulation is shown in two ways: standard format (Month-Day-Year, and UT as Hours-Minutes-Seconds) and Julian Day (JD). Universal Time is essentially the time at the Greenwich Meridian (6 hours ahead of Central Standard Time). Julian Day is just a running date that starts at noon Universal time and advances one unit every day. The fifth decimal place, 0.00001 JD, is about 0.8 seconds, or roughly 1 second.

Procedure: A Worked Example

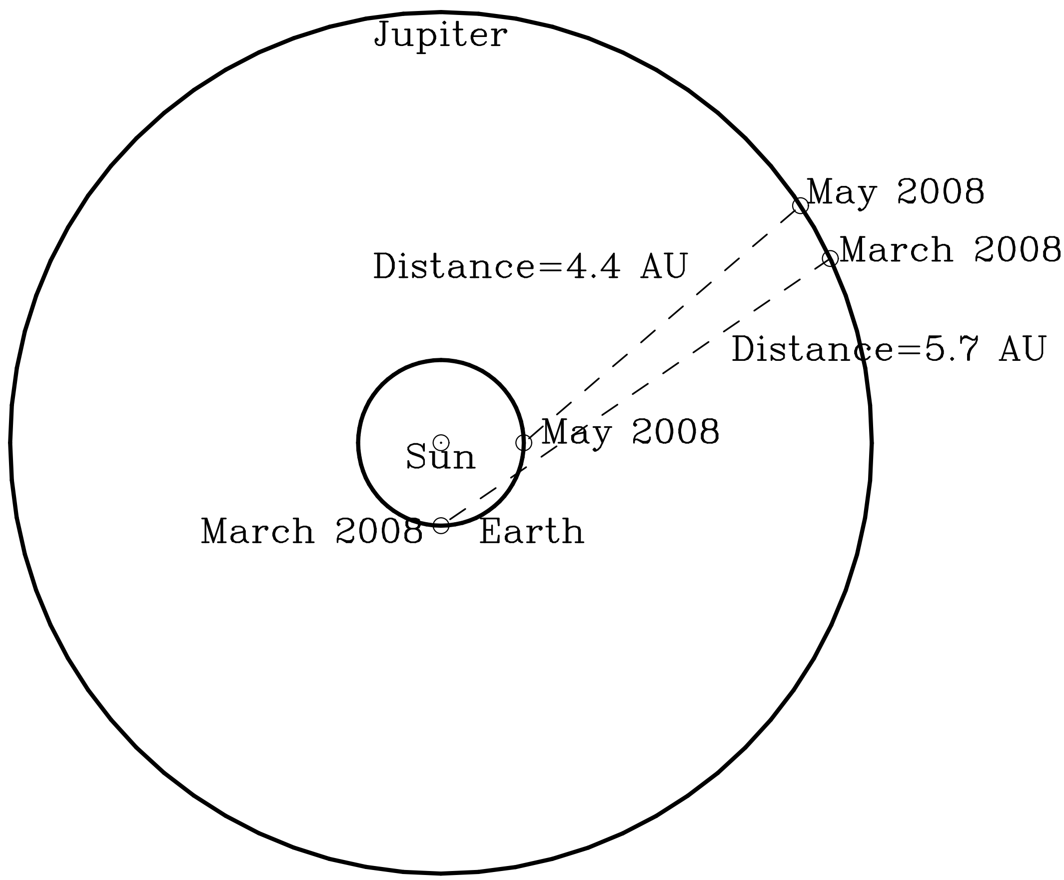
The following is an example that determines the speed of light from Jupiter's satellite Io. Work this example through using the program before trying your own determination on another set of dates. [*You may obtain data from the simulation that are close to but not exactly the same as what appears in the example. Differences of a few seconds to a minute are to be expected. This is due to the simulation and not necessarily a reflection of your observing technique.*]

1. **Find two dates when Jupiter and Earth are far and near**
   Preferably these dates should be about a month before Jupiter is at opposition and about 2–3 months after Jupiter is at conjunction. This ensures that Jupiter's shadow is to the East of the planet so that eclipses are easily seen.

   Far Date = March 1, 2008 (about 3 months after conjunction)

   Near Date = May 31, 2008 (about a month before opposition)

   On these dates the orbital geometry allows Jupiter to be easily observed from earth. In March, the local time for observing Jupiter would be a few hours before dawn. In May observing would be around midnight. In addition, these dates put Jupiters shadow on the east side of the planet so that it is possible to observe moons moving into the shadow. The relative geometry is shown below.



2. **Observe and time an eclipse of Io on the Far Date**
The eclipse happens at the moment Io moves into Jupiter's shadow. If there is no eclipse on your Far Date, there will be one the next day – observe that one. The time of the far date eclipse is:

$$\text{Standard Format} = \text{March 1, 2008 18h 07m 18s}$$

$$\text{Julian Day} = 2454527.255069$$

Observing tips:

- Set the magnification view to 400× and use the ID Colors to identify Io.
- Turn on the "Top View" to see where Io is with respect to the position of Jupiter's shadow.
- When Io is *MORE than one Jupiter disk* away from the planet's edge, set the Observing Interval to 0.5 hour.
- Use the Next button to advance the observations.
- When Io is *one Jupiter disk* away from the planet's edge, set the Observing Interval to 0.01 hour. Advance a few steps. . .
- When Io is about *one quarter of a Jupiter disk* away from the planet's edge, set the observing interval to 0.005 hours.
- Gradually advance time, step by step, until the moon just disappears—this is the start of the eclipse.

3. **Estimate how many orbits Io will make from the Far Date to the Near Date:**

$$\begin{aligned}
\text{Number of Orbits} &= \frac{\text{Far Date} - \text{Near Date}}{\text{Period of IO}} \\
\text{Number of Orbits} &= \frac{\text{May 31, 2008} - \text{March 1, 2008}}{1.769861\,\text{days}} \\
\text{Number of Orbits} &= \frac{91\,\text{days}}{1.769861\,\text{days}} = 51.42\,\text{orbits} \\
\text{Number of Orbits} &= 51\,\text{wholeorbits}
\end{aligned}$$

Note that you should *round down* to get the number of whole orbits.

4. **Calculate the time interval from the first eclipse to the predicted eclipse on the Near Date:**

$$\begin{aligned}
\text{Time to Predicted Eclipse} &= \text{Number of Orbits} \times \text{Period of Io} \\
\text{Time to Predicted Eclipse} &= 51\,\text{orbits} \times 1.769861\,\text{daysperorbit} \\
&= 90.262904\,\text{days}
\end{aligned}$$

5. **Calculate the JD of the predicted eclipse at the Near Date:**

$$\begin{aligned}
\text{Predicted Eclipse Time} &= \text{Far Eclipse Time (JD)} + \text{Time to Predicted Eclipse} \\
\text{Predicted Eclipse Time} &= 2454527.255069 + 90.262904 \\
&= 2454617.517973
\end{aligned}$$

6. **Observe the eclipse on the Near Date, and record the JD:**
Advance the simulation to a few hours before the Near Date eclipse. Starting your observations before the predicted eclipse is a key part of getting good data. The reason for this is that you expect the near eclipse to occur several minutes before the predicted time, and you dont want to miss it. If you miss it, and observe the next eclipse, several days later, you wont get the right speed of light. So, just to be on the safe side, *let's start our observations 0.1 JD, or 2.4 hours, before the predicted eclipse time. In other words, since the predicted eclipse time is Julian Day 2454617.517973, we start our observations on Julian Day2454617.417973.* Then slowly advance the time to catch the predicted eclipse a few minutes before your predicted time.

   Observe and time the eclipse of Io that happens on this Near Date

$$\text{Observed Eclipse Time (JD)} = 2454617.508208$$

7. **Find the difference between the times of the predicted eclipse and the observed eclipse, Δt:**

$$\begin{aligned}
\text{Time Difference} &= \text{Observed Eclipse Time (JD)} - \text{Predicted Eclipse Time (JD)} \\
\text{Time Difference} &= 2454617.5082082454617.517973 \\
&= -0.009765\,\text{days} \\
\Delta T &= -14.1\,\text{min}
\end{aligned}$$

   The negative value indicates that the eclipse occurred before the predicted time.

8. **Find the change in distance between Jupiter and Earth from the Far Date**

to the Near Date, ΔD:

$$\begin{aligned}
\text{Distance of Jupiter from Earth (March 1)} &= 5.71785\,\text{AU} \\
\text{Distance of Jupiter from Earth (May 31)} &= 4.39149\,\text{AU} \\
\text{Change in Distance } (\Delta D) &= \text{March 1 distance} - \text{May 31 distance} \\
\Delta D &= 5.71785\,\text{AU} - 4.39149\,\text{AU} \\
&= 1.32636\,\text{AU}
\end{aligned}$$

9. **Calculate the Speed of Light:**

$$\begin{aligned}
\text{Speed of Light} &= \frac{\Delta D}{\Delta T} \\
&= \frac{1.32636\,\text{AU}}{14.1\,\text{min}} \\
&= 0.094327\,\text{AU/min} \\
&= 2.34 \times 10^8\,\text{m/s}
\end{aligned}$$

10. **Compare your value to the correct value,** 3×10^8 **m/s**
Find the Percent Difference between *your calculated value* of the Speed of Light and the accepted value, $c = 3.00 \times 10^8$ m/s.

$$\begin{aligned}
\text{Percent difference} &= 100 \times \frac{\text{your value} - c}{c} \\
&= 100 \times \frac{2.34 \times 10^8\,\text{m/s} - 3.00 \times 10^8\,\text{m/s}}{3.00 \times 10^8\,\text{m/s}} \\
&= 100 \times \frac{-0.64 \times 10^8\,\text{m/s}}{3.00 \times 10^8\,\text{m/s}} \\
&= -21\%
\end{aligned}$$

Procedure

1. **Find two dates when Jupiter and Earth are far and near**
   Preferably these dates should be about a month before Jupiter is at opposition and about 2–3 months after Jupiter is at conjunction. This ensures that Jupiter's shadow is to the East of the planet so that eclipses are easily seen.

   Far Date = ____________________

   Near Date = ____________________

2. **Observe and time an eclipse of Io on the Far Date**
   The eclipse happens at the moment Io moves into Jupiter's shadow. If there is no eclipse on your Far Date, there will be one the next day – observe that one. The time of the far date eclipse is:

   Standard Format = ____________________

   Julian Day = ____________________

3. **Estimate how many orbits Io will make from the Far Date to the Near Date:**

4. **Calculate the time interval from the first eclipse to the predicted eclipse on the Near Date:**

5. **Calculate the JD of the predicted eclipse at the Near Date:**

6. **Observe the eclipse on the Near Date, and record the JD:**

7. **Find the difference between the times of the predicted eclipse and the observed eclipse, Δt:**

8. **Find the change in distance between Jupiter and Earth from the Far Date to the Near Date, ΔD:**

9. **Calculate the Speed of Light:**

10. **Compare your value to the correct value, 3×10^8 m/s**