MSE2150

Astronomy Laboratory – Planets

Lab Manual

Department of Astrophysics & Planetary Science
Villanova University

Fall 2025

Astronomy Laboratory – Planets
MSE2150
Fall 2025 Lab Schedule

Week 1: Introductory meeting
Lab A – Numbers, Graphs and *Excel*
Week 2: Lab B – Motions in the Sky
Week 3: Lab C – Lunar Eclipses & the Saros Cycle
Week 4: Lab D – The 2024 North American Total Solar Eclipse
Week 5: Lab E – Planetary Motion
Week 6: Lab F – Kepler's Determination of the Orbit of Mars
Week 7: Lab G – Gravity, Orbits, & Kepler's Laws
Week 8: Lab H – Measuring the Mass of Jupiter
Week 9: Lab I – Roemer's Measurement of the Speed of Light
Week 10: Lab J – Comets
Week 11: Lab K – Detecting Extrasolar Planets
Week 12: Lab L – Exploring Habitable Zones
Week 13: MAKEUP LAB

The "Observatory Lab" can be completed at any time during the semester.

Observatory Lab
The Villanova Public Observatory

PURPOSE:

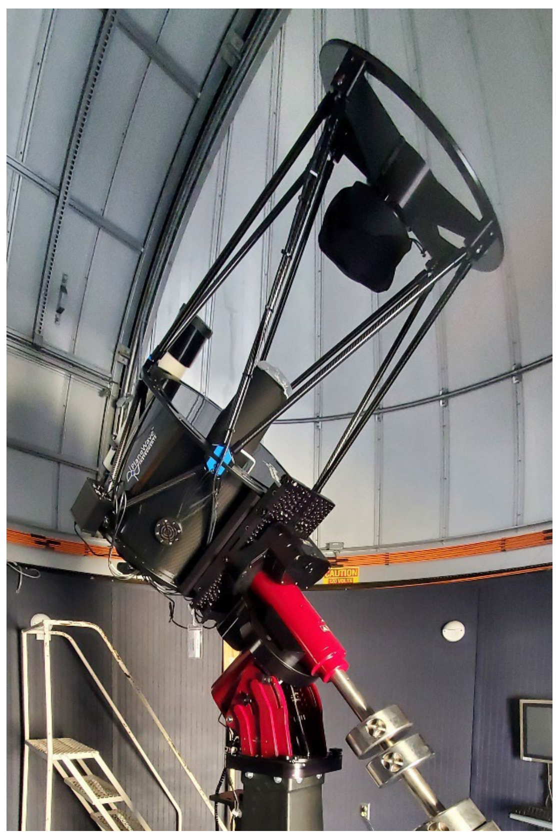
The science of astronomy began with the first humans who looked up into the nighttime sky and wondered "What's going on up there?" This semester, you will explore some of the answers to this question in your lecture course and in this lab course. Most of this exploration will happen in the classroom or in the lab room. This lab will give you the opportunity to go outside and actually look at the nighttime sky, using both the unaided eye and a powerful modern astronomical telescope.

EQUIPMENT:

The Villanova Public Observatory, accessible via the Department of Astrophysics & Planetary Science on the 4th floor of Mendel Science Center.

The Villanova Public Observatory

20" Planewave Telescope



Instructions

To complete this lab you must fulfill **4 requirements**:

1. At least once during the semester you must attend an evening observing session at the Villanova Public Observatory, which will be conducted by students from the Department of Astrophysics & Planetary Science. During this session, the students will take you on a tour of the most interesting objects visible in that night's sky.
2. Have one of the Observing Assistants sign and date the Cover Page of your lab report. The Cover Page is on page *Observatory-5* of this lab manual.
3. Sign that evening's Observatory Attendance Sheet. (If you can't find it, ask one of the Observing Assistants.)
4. Write a 2-page report (double spaced, 11- or 12- point font, normal margins) describing your visit to the Observatory. Include the sky conditions, describe the type of telescope you used, and the objects you viewed. If you have suggestions for improvements of the observing sessions, or any general comments about the experience, please feel free to include them in your report.

The observatory is accessed from the 4th floor of the Mendel Science Center through the Department of Astrophysics & Planetary Science. Once on the 4th floor, the Observing Assistants will direct you to the telescopes.

During the semester, and beginning Tuesday September 2, the Observatory will be open Monday thru Thursday evenings, initially from 8-10 PM and then, after Daylight Savings Time ends on November 2, from 7-9 PM. The Observatory will <u>not</u> be open during Fall Break or on any University holidays or Snow Days. The last possible night to complete this assignment is the last day of classes Thursday December 11. The Observatory will then be closed for the semester.

Lab reports can be handed in any time during the semester. The last day they will be accepted is the Reading Day, Friday December 12.

<u>**THERE IS NO MAKE-UP FOR THE OBSERVATORY LAB!**</u>

Since it is one of 13 graded lab assignments this semester, then 1/13 of your grade will be a zero if you don't get to the Observatory! There will be plenty of clear nights this semester, but don't wait til the end. It is entirely possible that the last week or so could be clouded out or rained out – it's happened before.

Frequently Asked Questions

What will I be looking at?

It depends on what is available in the sky. The Moon looks great through our telescopes and the best time to view it is a few days after the First Quarter phase. At this time, the Moon is high in the sky around the time of sunset and the side illumination creates very pronounced shadows on the lunar surface, allowing the rugged terrain to be seen clearly. During the Fall 2025 semester, First Quarter phases occur on **Aug 31**, **Sep 29**, **Oct 29**, and **Nov 28**.

Of the "naked-eye" planets, Saturn will be the most easily viewed this Fall. It will be visible with the telescope throughout the night for most of the semester. Jupiter will not make an appearance until late in the semester, rising late in the evening. Mars will be setting shortly after the Sun all semester and, therefore, will not be visible. Venus leads the Sun all semester and will only be visible as the "morning star" above the eastern horizon shortly before sunrise. On clear nights, both Neptune and Uranus may be observable with the telescope. If you'd like to keep track of the visibility of the planets throughout the year, check out: https://www.timeanddate.com/astronomy/night/

In addition to the Moon, Jupiter, and Saturn, there will be plenty of other objects available to keep the telescope busy, including star clusters, bright nebulae, and the Andromeda galaxy.

If you'd like to keep informed about upcoming celestial events in general, check out https://www.timeanddate.com/astronomy/sights-to-see.html

Is the Observatory Open tonight?

If "tonight" is a Monday thru Thursday and a regular class day, then the chances are good. It all depends on the weather. What is the best way to tell? Look up shortly after sunset. If you can see the stars, we're probably open. If you want a more high-tech solution, you can go to one of the many weather websites (or apps) available. Most of these show cloud cover and some will project the cloud cover a day or so in advance. One such site is http://www.weatherstreet.com/weather-forecast/Villanova-PA-19085.htm.

What if I don't fulfill all 4 of the requirements listed in the Instructions?

No credit will be issued for the Observatory lab. (I.e., you get a "0"!)

Lab Report Cover Page

Astronomy Laboratory - Planets
Mendel Science Experience 2150
Fall 2025

Observatory Lab
<u>The Villanova Public Observatory</u>

Name: ____

Lab Section: __________

Date: __________

Observatory Assistant
Name: ____
Signature: ____
Date: ____

Lab A
Working with Numbers, Graphs, and *Excel*

Adapted from: *Laboratory Experiments in Astronomy*, Johnson & Canterna

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PURPOSE:

To become acquainted with the *Excel* spreadsheet and to review some mathematical concepts that will be implemented in upcoming labs.

EQUIPMENT:

The computer and the *Excel* spreadsheet.

Introduction

By their nature, the sciences are quantitative. Science involves making measurements, analyzing quantitative relationships, and making predictions based on mathematical models. In this exercise we will review some of those mathematical fundamentals that will be used in subsequent exercises. This review will help you pinpoint any areas you might need to review in more depth. The magnitude scale, a strictly astronomical concept, will be introduced. This has been the shorthand notation used for centuries to describe the brightness of stars.

Lab Procedure

PART 1: SCIENTIFIC NOTATION

Astronomy is a science which deals with the very large and the very small. For example, the distance to the nearest star (beyond the Sun) is approximately 39,900,000,000,000 km, while the distance between the electron and proton in an atom of Hydrogen in interstellar space is about 0.00000000529 cm. It can be cumbersome to deal with such extreme numbers and a more compact way of dealing with them is to express them in **scientific notation**.

The number 13,700,000 is expressed in scientific notation as 1.37×10^7. "10^7" is shorthand for 1 followed by 7 zeros, $10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10$ (10 times itself 7 times), or 10,000,000. 1.37×10^7 equals 13,700,000 or 1.37×10 million. Any number can be expressed as a number between 1 and 10, times 10^n. Take 207,000 as an example. There are 5 decimal places to the right of the 2. Thus $207{,}000 = 2.07 \times 10^5$. Multiplication by 10 is equivalent to shifting the decimal point in a number one place to the right. Multiplication by 10^n is equivalent to shifting the decimal point n decimal places to the right, or to multiplying by 10 n times.

This technique is also useful for numbers smaller than 1. For example, 0.0012 can be represented as 1.2×10^{-3} (or 1.2 divided by 1000). A negative exponent indicates how many places the decimal is shifted to the left. 10^{-3} is equivalent to 0.001 or $1/10^3$. *Note:* A negative exponent does not mean that the number itself is negative; only that it is between 0 and 1.

EXERCISE 1-1: *Using Table 1 included on the last page of this lab, convert the numbers given in the first column ("Standard Notation") into scientific notation.* ***NOTE: Don't forget to hand in Table 1!***

EXERCISE 1-2: *Create a single-column Excel spreadsheet table using the "Standard Notation" numbers from Table 1. Label the top row of the column (you can call it "Standard Notation.") Your numbers should look exactly as they do in Table 1. You will need to adjust the number of decimal places displayed for each number. To do this, first highlight a cell, then right-click and select* ***Format Cells****. Select* ***Number*** *and type in the desired number of decimal places needed to match the format in the Table 1.*

EXERCISE 1-3: *On your Excel spreadsheet, copy your column of numbers and paste it into the adjacent column (i.e., column B). Now have Excel convert these numbers to scientific notation for you. To do this, highlight the cells, right-click, and select* ***Format Cells****. Then choose* ***Scientific Notation*** *and type in the desired number of decimal places (in this case, 2). Label this column "Scientific Notation."*

Notice that, in Excel, the format used for scientific notation is somewhat different from that described above. E.g., the quantity 2.07×10^{-5} is written by Excel as 2.07E-5, where the "E" stands for *"times 10 to the"*. This notation must be used to enter scientific notation into Excel.

Also notice that it is easier to keep track of **significant figures** in scientific notation. Simply, all the figures used in scientific notation are significant. Thus, the number 2.07E-5 is implied to have three significant figures and the number 2.070E-5 is implied to have 4 significant figures. In this last case, the trailing zero is significant and thus a result expressed as 2.070E-5 can be assumed to be more precise than a result expressed as 2.07E-5.

PART 2: LOGARITHMS

Another shorthand way of expressing very large or very small numbers is with **logarithms**. The **logarithm** or **"log"** of a number is simply the exponent to which 10 must be raised to equal that number:

$$x = 10^y \quad \Leftrightarrow \quad y = \log(x) \tag{1}$$

For example, the number one hundred million (100,000,000) can be written as 10^8 and, therefore, **log**(100,000,000) = 8.

Negative numbers do not have logarithms since there is no power to which 10 can be raised that will yield a negative number. However, the logarithm itself can be negative, and corresponds to a number greater than zero but less than one. The log of a number can also be a non-integer. Consider **log**(250). The number 250 is greater than 10^2 (i.e., 100) but less than 10^3 (i.e., 1000) and so we would expect its logarithm to be between 2 and 3. In fact, **log**(250) = 2.40.

EXERCISE 2-1: *In column C of your Excel spreadsheet, compute the logarithms of the numbers in the first column. For example, to compute the log of a number located in cell A2 of your spreadsheet (i.e., column A, row 2) and place the result in cell C2, simply type "=log(A2)" in cell C2. The log of the number in cell A2 will then appear in cell C2. Do this for all entries in column A. Be sure to label the column and adjust the number of decimal places in the displayed logarithms to preserve the number of significant figures in the original numbers.*

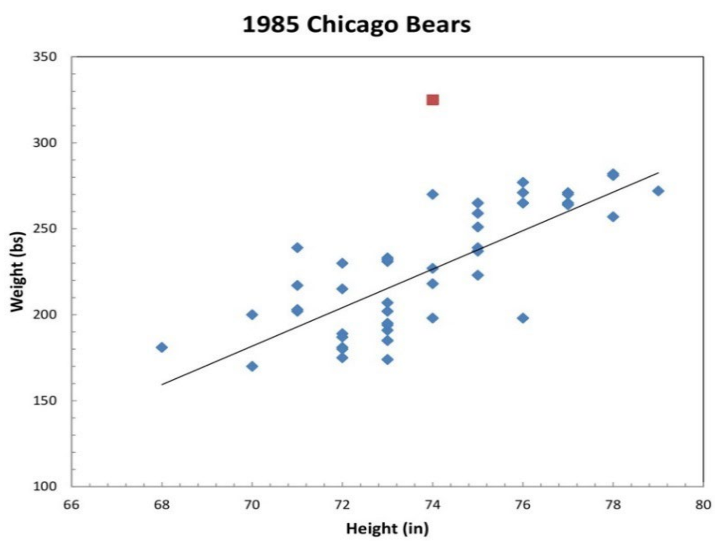
NOTE**:** Logarithms are never expressed in scientific notation. Always use standard notation.

NOTE**:** With logarithms, only the numbers to the right of the decimal point are significant digits. For example, the number 4,567,000,000 has 4 significant digits. It should be expressed in scientific notation as 4.567×10^9 (again, with 4 significant digits) and logarithmically as 9.6596. In his latter case, the integral portion of the logarithm, "9" actually refers to the power of 10 in the scientific notation form. The decimal portion ".6596" carries the information contained in the significant digits.

PART 3: LINEAR RELATIONSHIPS

In this exercise we will see how physical relationships may be examined graphically. In the figure below, we have plotted the weights (on the "y" axis) versus the heights (on the "x" axis) for the Super Bowl-winning 1985 Chicago Bears football team, using the small diamond symbols. It is clear from the plot that there is some general correlation between the heights and weights, i.e., "the taller, the heavier." We have drawn a straight line through the data to indicate a more specific *linear relationship* between the height and weight in this group. The line is intended to represent the **general trend** in the data, while ignoring specific deviations of individuals. In this case, the line appears to give a good fit to the general trend of the data and it is reasonable to conclude that height and weight are linearly-related for this dataset.

Note the outlying point far above the main relationship; these data correspond to William "the Fridge" Perry, one of the first 300 pounders in football and who clearly did not fit into the general height-weight relationship of his teammates!



In the Table below we have listed the heights and weights for a different team, namely, a selection of 15 typical college students.

Typical College Students			
Height (inches)	**Weight (pounds)**	**Height (inches)**	**Weight (pounds)**
60	95	69	150
70	173	64	115
67	125	62	112
75	180	64	127
61	105	68	155
73	200	72	160
67	140	65	127
71	150	…	…

EXERCISE 3-1: *Transfer these data to a new Excel spreadsheet. To open a new sheet, click* ***Sheet2*** *at the bottom of your current spreadsheet. (If there is no* ***Sheet2****, click the circled "+" sign to create one.) In your spreadsheet, use only two columns – height and weight. Label the columns appropriately. Be sure that the number format in your spreadsheet matches that of the table.*

EXERCISE 3-2: *Now create a graph of the college students' Weight vs. Height on your spreadsheet. Follow the instructions given in the "****Microsoft Excel Tutorial****" in Appendix I of this Lab Manual. Be sure that the data in the table are labeled and that the plot is properly scaled and annotated.*

Once again, you should observe a nearly linear relationship between the height and weight of people in the group, as you did for the football players in Problem 1. That is, the heights and weights should fall close to a straight line drawn through them.

EXERCISE 3-3: *Using the* ***trendline*** *feature of Excel, show the linear relationship that best fits the data. Make sure that the formula for the trendline is displayed clearly on the plot. (Right-click somewhere on the trendline, then click "Format Trendline…", then check "Display equation on chart.").*

Question 3-1: *Does a visual inspection of your plot confirm that the heights and weights for typical college students are linearly related? Discuss the possible causes of the observed relationship. Why might individuals deviate from this simple relationship?*

Question 3-2: *One of the most powerful uses of a graph is that of prediction. Say, for example, that you know the height of a college student but not his/her weight. We can make an "educated guess" and predict the weight of the student by using our graph and the trendline which represents the general relationship between height and weight. Suppose that this person is 6' 2-½" (i.e., 74.5") tall. What weight is predicted for a 74.5" tall college student? Use the formula for your trendline to make this determination. Show all the work* *in your calculation. Remember your significant digits!*

Question 3-3: *What differences do you find between the heights and weights of the groups shown in Figure 1 (the Chicago Bears) and on your graph (for college students)? What might be the causes of these differences? Do the lines drawn through the data in both graphs look like they are pieces of the same overall relationship? Explain.*

PART 4: NON-LINEAR RELATIONSHIPS

Not all physically interesting relationships are linear. For example, the table below shows the annual amount of U.S. Government expenditures from 1850 to 2010 versus year which, you will shortly see, reflects a very non-linear relationship.

U.S. Government Expenditures			
Year	**$**	**Year**	**$**
1850	29,000,000	**1960**	97,284,000,000
1860	78,000,000	**1980**	590,941,000,000
1880	304,000,000	**1990**	1,252,990,000,000
1900	629,000,000	**2000**	1,788,950,000,000
1920	6,785,000,000	**2010**	3,457,080,000,000
1940	10,061,000,000	…	…

EXERCISE 4-1: *Open a new Sheet in Excel by clicking the* ***Sheet3*** *tab and enter the data from the table above. (In your spreadsheet, use only two columns – year and expenditures.) Label the columns appropriately. If the width of the columns in your spreadsheet is too small, there might not be enough room for Excel to write in all the digits in the numbers and you will see "#########" instead. If you see this, simply drag the right edge of the column letter that represents the expenditure data to expand the width of these cells. Be sure to format the cells so that the numbers appear exactly as in the Table above.*

EXERCISE 4-2: *Now create a plot of expenditure (y-axis) versus year (x-axis). Don't forget to scale and label the plot axes appropriately. Find a trendline which seems to represent the data. Note that a linear trendline will definitely* <u>*not*</u> *work! Excel offers you several other options (e.g., "polynomial", "exponential", "power law", etc. Find the one which best represents the data and show it on your plot. Make sure to include the formula for the trendline on the plot. What kind of trendline did you use?*

(Hint: Maybe this gives meaning to the phrase:
"Our national debt is increasing at an exponential rate!")

EXERCISE 4-3: *In your Government Expenditures Excel spreadsheet, copy the contents of column B (Expenditures) to column C. Label this column "$ in Scientific Notation." Now use the* ***Format Cells*** *command to convert the expenditures in column C to scientific notation. Make sure to specify the correct number of significant digits by adjusting the numbers of decimal places displayed.*

EXERCISE 4-4: *In your Government Expenditures Excel spreadsheet, create a "Log $" column in column D to display the expenditures in logarithmic form. Again, be sure the correct number of significant digits is displayed.*

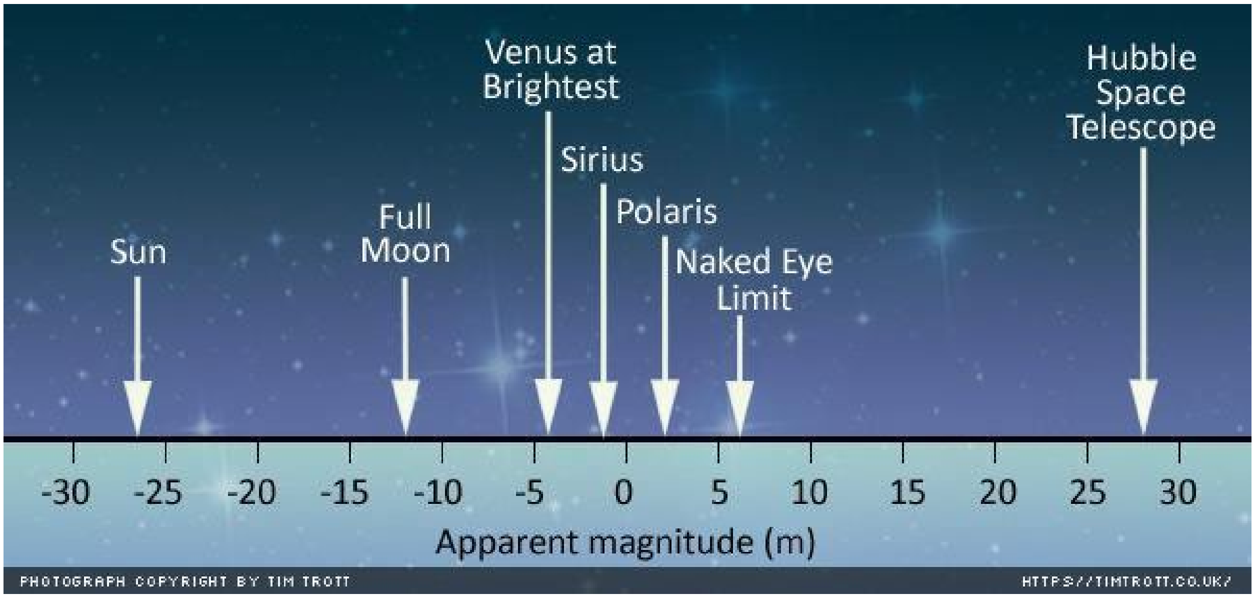
Your plot of Government Expenditures is interesting but notice how hard it is to distinguish among the values from earlier than about 1960. Also, you should see that it would be very difficult to use the graph to predict future spending with any confidence. Both problems might be reduced by looking at the logarithm of the expenses…

EXERCISE 4-5: *Now create a plot of the logarithm of the expenditures in dollars as a function of year. Adjust the scales to fill the plotting space (if necessary) and add labels and a title. Notice that the very non-linear relationship between Year and Expenditure seen in Exercise 4-2 has become much simpler looking. Because of this, we would say that expenditures and time have a* ***logarithmic relationship****. Create a linear trendline in your Year vs. Log($) plot. Does it fit the observed relationship? Don't forget to put the formula for the trendline on the plot.*

Question 4-1: *What does your plot from Exercise 4-5 suggest that the annual expenditure will be in the year 2020? Use the formula for the trendline you just created in Exercise 4-5 to make this prediction. Show all work in your calculation. Note that the formula will return the logarithm of the predicted expense. Record this and convert it to the expense itself using Equation 1. Express the result in both standard notation and scientific notation. Can we be confident in this prediction? Explain why or why not.*

PART 5: MAGNITUDES - AN ASTRONOMICAL EXAMPLE

Astronomers use a logarithmic scale, called the **Apparent Magnitude Scale**, to quantify the brightness of stars as seen from the Earth. These apparent brightnesses depend on both the intrinsic energy output of the stars and on their distances from the Earth. Over 2,000 years ago the Greek astronomer Hipparchus catalogued the positions and brightness values of approximately 6,000 stars visible to the naked eye. The apparent brightness was described by a unit called a **magnitude**, with first magnitude being the brightest visible stars and sixth magnitude corresponding to the faintest. Contrary to our intuition, the bigger (i.e., more positive) the apparent magnitude, the fainter the object. The brightest object in our sky – the Sun – has the most negative apparent magnitude. See the figure below.



In the following Table we have listed the apparent brightness relative to the star Mizar for the ten stars that are closest to the Sun. For example, the star Proxima Cen appears 2.54×10^{-4} times as bright as Mizar as seen from Earth. There is nothing particularly special about Mizar. It is just a convenient reference star, which appears in the handle of the Big Dipper.

Star	**Apparent Brightness relative to Mizar**
Proxima Cen	2.54×10^{-4}
Cen A	6.72
Cen B	1.96
Barnard's Star	1.02×10^{-3}
Wolf 359	2.58×10^{-5}
BD+36 2147	6.66×10^{-3}
L726-8 A	6.56×10^{-5}
UV Cet B	4.12×10^{-5}
Sirius A	2.55×10^{1}
Sirius B	2.20×10^{-4}

EXERCISE 5-1: *Open a new Sheet in Excel by clicking the* ***Sheet4*** *tab. Create an Excel spreadsheet with the Star names (column A) and apparent brightnesses (column B) from the table above. Be sure to use the correct form for scientific notation in Excel! Calculate the logarithm of the apparent brightness for each of the stars and place it in column C.*

The **apparent visual magnitude *m*** of a star is computed from its apparent brightness by the formula:

$$m = -2.5 \times \log(\text{apparent brightness}) + 2.06 \qquad (2)$$

where the constant 2.06 is needed to make these calculated magnitudes correspond to those derived by Hipparchus. The magnitude scale was not purposely designed by Hipparchus to be logarithmic; it just reflects the sensitivity of the human eye. The eye has evolved to be sensitive over a tremendous range of light levels, ranging from sunny days to a starlit night. To accomplish this remarkable feat it uses a shorthand of its own. Thus, a large range of sensitivity yields information that is compressed logarithmically and sent to our brains. Logarithmic scales are used in many other places, such as in describing sound levels (decibels) and earthquake vibration amplitudes (the Richter scale).

> ***EXERCISE 5-2:*** *Using your Excel spreadsheet, calculate the apparent magnitudes* ***m*** *for each of the stars using Equation 2 above and place the results in column D of your current spreadsheet.*

NOTE**:** Just like logarithms, astronomical magnitudes are never expressed in scientific notation. Always use standard notation. Also, just like logarithms, only the digits to the right of the decimal point are significant digits.

Lab Report Cover Page

Astronomy Laboratory - Planets
Mendel Science Experience 2150
Fall 2025

Lab A
<u>Working with Numbers, Graphs, and *Excel*</u>

Name: ____

Lab Section: __________

Date: __________

TABLE 1: EXERCISE 1-1

Convert the values given in the Standard Notation into Scientific Notation

Standard Notation	Scientific Notation
632,000,000,000	
632	
63.2	
632,000	
0.632	
0.000000632	
0.00632	
0.0000632	

Lab B
Motions in the Sky
(an Introduction to *Starry Night College)*

PURPOSE:

To introduce the planetarium program *Starry Night College*, which you will be using for several labs this semester, and to view the motions of the Sun and stars in the sky from a number of different times and places, including non-terrestrial locations!

EQUIPMENT:

Starry Night College computer program.

STARTING *STARRY NIGHT COLLEGE*:

Double-click the *Starry Night College* icon on your Desktop to start the program. When the program opens you will be presented with a panoramic view of the sky as seen from the top of the Mendel Science Center. This particular view was photographed during December 2018. There should be a cursor on the screen, shaped like a hand. Left-click on the cursor and drag it around to change the direction of the view. Go ahead and look around – you should see some familiar buildings. Note that the cardinal directions (North, East, South, West) are labeled near the horizon. (E.g., you should see an "S" near the base of one of the Chapel's steeples.) From Mendel Science Center, the Chapel is almost due south). You can also change direction by clicking **View, Face direction** and then **North, East , South, West,** or **Zenith** (straight up) on the top taskbar. Rotating the mouse wheel lets you zoom in or out.

If the cursor is not shaped like a hand, you can reset it by left-clicking the **Cursor Menu** on the upper left of the screen (it looks like the current cursor) and selecting **Adaptive**. See Figure 1 for a picture of the basic *Starry Night College* screen with all the various menus identified.

Daily Motion of the Sun and Stars

The Sun Today:

First, let's observe how the sky changes during the day. Left click the **Time Step Menu** and select a timestep of ***minutes***. Now, pressing the "Play" (▶) or "Rewind" (◀) buttons, will cause time to fly by, with minutes seeming like seconds. This will allow you to easily observe changes in the sky that actually occur over many hours. To return to the current time, left click the **Calendar Menu** (next to the **Cursor Menu**) and select ***Now.*** The single-step buttons,(▶| and |◀) let you jump forward or backwards in time by (in this case) exactly 1 minute.

***Exercise 1*:** Using the "Play" and "Rewind" buttons, watch the Sun move across the sky. (If this is a night lab and the Sun has already set, you'll have to rewind to get it back in your sky. In **Table 1**, (or in an Excel spreadsheet provided by your instructor) record the date of your observation, and the times of sunrise and sunset. Then calculate how many hours and minutes the Sun will be (was) above the horizon today. Also, record the direction towards the Sun at sunrise and sunset as well as its maximum height above the horizon. You can find this information by right-clicking on the Sun and selecting **Show Info…**. Then click **Position in Sky** in the **Sun Info** box that appears on the screen. The <u>*altitude*</u> gives the height of the Sun in angle above the horizon and the <u>*azimuth*</u> records the direction. An *azimuth* of 0° is directly North, while values of 90°, 180° and 270° refer to East, South and West, respectively. The maximum *altitude* occurs near noon, but the exact time depends on the locations of observers within their respective time zones and (whether they're in Daylight Savings Time). You'll have to hunt around a little to find the maximum. Record all this information in **Table 1** or in your Excel spreadsheet. The **Sun Info** box will remain on the screen until you dismiss it and updates the position of the Sun as it moves across the sky.

Table 1: The Motion of the Sun

	Today	**Winter Solstice**	**Summer Solstice**
	____________	12/21/2025	6/21/2026
Time of sunrise (hh:mm AM/PM):			
Time of sunset (hh:mm AM/PM):			
Duration of daylight (hh:mm):			
Azimuth of sunrise (°, `):			
Azimuth of sunset (°, `):			
Maximum altitude (°, `):			

<u>Seasonal Variations in the Sun's Daily Motion:</u>

You have probably noticed that the Sun does not travel the same path through the sky all year long. In this next exercise you will see exactly how different the Sun's paths can be, as seen from Villanova.

***Exercise 2*:** Change the date, using the fields to the right of the **Calendar Menu**, to December 21, 2025. This is the date of the next Winter Solstice, which, as you know, is the official "first day of Winter." Once again, observe the motion of the Sun across the sky. Record in the third column of **Table 1** the same information that you recently did for today's date.

***Exercise 3*:** Now change to June 21, 2026, which is the next Summer Solstice and the official "first day of Summer." Again, repeat the measurements and record your results in the last column of Table 1.

> ***Question 1A:*** *Comment on the differences between the Sun's motion in December and in June. How do the hours of daylight compare? The maximum height of the Sun above the horizon? Do your observations suggest why the days gets hotter in the summer than they do in winter? (Note: it's not because the Earth gets closer to the Sun in our summer – it doesn't.)*
>
> ***Question 1B:*** *We always say, "the Sun rises in the East and sets in the West." Is this true? (Note that due East corresponds to azimuth = 90° and due West to azimuth = 270°.)*

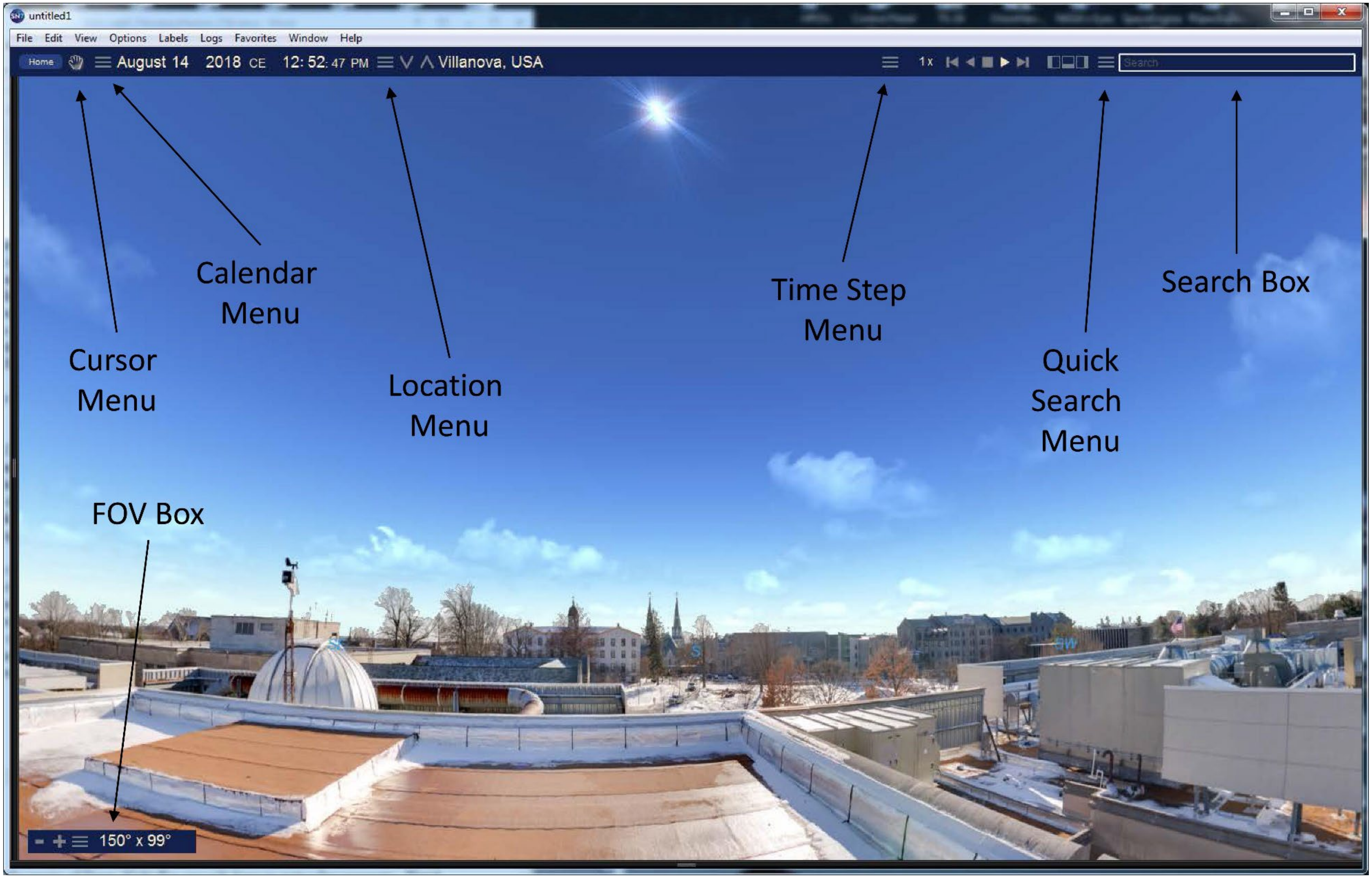


Figure 1: Starry Night College startup screen

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The Night Sky from Villanova:

Now let's look at today's nighttime sky, as seen from Villanova. Go back to the current time (click ***Now*** in the **Calendar Menu**) and then "Play" (▸) to get to midnight tonight (your timestep should still be set at ***minutes***). You could also just directly enter the time in the Taskbar next to the calendar date. You will now see the nighttime sky as it will appear from the roof of Mendel tonight, without having to worry about clouds or rain or bugs.

***Exercise 4*:** Look towards the North and press the "Play" button. You'll now see the motions of the stars in the nighttime sky. Your view will be interrupted when the Sun rises, and the brightness of the daytime sky drowns out the light of the stars. To eliminate this inconvenience, press **View, Hide Daylight**. This wouldn't be so great in real life − since it would mean that there is no atmosphere to breathe − but in *Starry Night College* it's a big help. You can now watch the motions of the stars throughout their full 24-hour cycles, i.e., the "daily motion" of the stars. To identify any particular object in the sky, just press the "Pause" button (■) and hold the cursor over the object. If you want to see what constellations are in the sky at any time, select **View, Constellations, Labels**. (You can also select **Boundaries** and/or **Illustrations** to see more constellation information.

> ***Question 2:*** *Describe the motions of the stars as you look towards the North. What do they seem to be doing? Do all stars rise and set above and below the horizon? You should notice one star that is almost stationary while the others go through their daily motions. Place the cursor over this star to identify it. Which star is it? What are the altitude and azimuth of this star? Record them in* ***Table 2*** *or in the provided Excel spreadsheet.*

***Exercise 5*:** Observe the daily motions of the stars in other directions, particularly towards the East, South and West.

> ***Question 3:*** *Describe the motions of the stars as you look East and West. Do they rise and set straight up from the horizon? Or at an angle? How about towards the South?*

Table 2: Observations of the "North Star"

Observer's location	Observer's latitude (°,′)	Altitude of Polaris (°)	Azimuth of Polaris (°)
Villanova	40,02		
Godthab, Greenland	64,11		
Honolulu, Hawaii	21,21		

The Night Sky from Other Earthly Locations:

Freeze the motion of the stars in your *Starry Night College* simulation by pressing the "Pause" button. Return to the current time, but leave the daylight turned off. Now we'll take advantage of another useful property of *Starry Night College*; namely, the ability to view the sky from anywhere on Earth. Using this property, you will investigate how the daily motions of the stars vary, depending on the location of observers on Earth's surface. You will accomplish this magic by pressing **Options, Viewing Location…** on the Taskbar.

***Exercise 6*:** First let's head north. After pressing **Options, Viewing Location…**, type "Greenland" in the Viewing Location window that appears on the screen. There is only one preset viewing location from Greenland in the program's database and an entry for "Godthab (Nuuk), Greenland" should appear just below the search box. Left-click this entry to select it. (It should then appear highlighted in blue.) When you are ready to go to Godthab, press the **View From Selected Location** button at the bottom of the Viewing Location box and hold onto your hats. Once you've arrived, press the "Play" button and observe the daily motions of the stars.

> ***Question 4***: *Describe the motions of the stars. Are the motions similar to those seen from Villanova? How or how not? Do all the stars rise (above the horizon) and set (below the horizon)? Once again find the stationary star (toward the North). Identify it. Is it the same one as that seen from Villanova? Measure the altitude and azimuth of this star and record them in **Table 2**.*

***Exercise 7*:** Now we'll warm up by heading somewhere closer to the Equator. After pressing **Options, Viewing Location…**, type "Honolulu" in the Viewing Location box. Select the "Honolulu, Hawaii, United States" entry and press the **View From Selected Location** button when you're ready to head to Hawaii. Once there, press the "Play" button and observe the daily motions of the stars.

> ***Question 5:*** *Once again, describe the motions of the stars. Are the motions similar to those seen from Villanova and Greenland? How or how not? Do all stars rise and set? Once again, find the stationary star (toward the North). Identify it. Is it the same one as that seen from Villanova (and Greenland)? Measure the altitude and azimuth of this star and record them in **Table 2**.*

The Big Picture:

Using **Table 2**, compare the latitudes that you have been observing from with the altitudes of the fixed star (which by now you should realize is Polaris) above the horizon.

> ***Question 6:*** *Describe how altitude of Polaris compares with the latitude of from which the observation was made. compare. Describe how this relationship would have been of benefit to sailors in northern hemisphere in the days before GPS. What simple observation would have informed them of their latitude when they were out in the middle of the ocean, far from land? Why wouldn't this have helped sailors in the southern hemisphere? Is it reasonable that Polaris is called "the North Star"? (Hint: look at the azimuths). Based on your observations, where in the sky would you expect to find Polaris if you were at the North Pole? At the Equator? At the South Pole? If you want to check your answers, go to these places (via Starry Night College) and do some observing.*

As you know, the daily motion of the Sun and stars is caused by the rotation of the Earth on its axis, which just happens to be pointed nearly directly at Polaris. The apparent rotation of the sky is just an illusion, reflecting our own motion as the Earth rotates. If you want to explore and understand the rotating sky more thoroughly, take a look at the online simulation located at https://astro.unl.edu/naap/motion2/motion2.html.

The Sun's Yearly Motion

You have seen (**Table 1**) that the daily motion of the Sun in our sky is not the same every day and, in fact, varies on a yearly time scale. We'll now look at the more-difficult-to-see yearly path it makes through the stars, as a result of Earth's orbital motion. To begin, reset the program to its initial state by pressing **View, View from Villanova, USA (with Default Options)**. This returns the program to its initial state, when you first logged in, but with the current time. The next exercise will be done with the Sun high in the sky, so change the time to noon ("12:00:00 PM").

Exercise 8: Although the stars are always out there, we can't see them in the daytime due to the brightness of the sky. So, as you did before, select **View, Hide Daylight** to get rid of the that pesky atmosphere. To get a sense of the Sun's yearly motion through the sky, left click on the day number (next to the month) in the Taskbar. Then press the up-arrow (▲) on the keyboard to advance one day. Keep pressing this key (as fast as you want!) to get a good sense of the changes. Each time you click the button, time will move forward exactly 1 day.

> ***Question 7:*** *Describe how the Sun's position changes with respect to (1) the horizon and (2) the background stars over the course of one year. Remember, each observation is being done at 12 noon, so the Sun is near its highest point in the sky each day. Are these observations consistent with those you recorded in* ***Table 1****? Can you suggest why the Solstices were chosen in the first part of the lab to illustrate the Sun's varying path through the sky? Are the same stars in the daytime sky throughout the year? And, by extension, would the same stars be in the night sky all year? (If you're not sure, use Starry Night College to check.)*

Exercise 9: To put some context onto the sky, select **View, Constellations, Labels** and **View, Constellations, Boundaries.** You now have a roadmap of the sky. Once again, begin pressing the up arrow on the keyboard to advance day by day, observing the Sun's motion "through" the constellations.

> ***Question 8:*** *Is there anything familiar about the names of the constellations that the Sun passes through over the course of the year? Have you ever heard of the "Zodiac"? What do you know about it?*

Exercise 10: Now that you have the constellations labeled, let's test one of your answers to Question 7. Change the date and time to midnight on the next winter solstice (21 December 2025). In **Table 3**, write down the names of two prominent constellations in the winter sky. Now change the date to the next summer solstice (21 June 2026) and record the names of two prominent summer constellations in **Table 3**.

> ***Question 9:*** *Are the same stars visible in the nighttime sky at different times of the year? Can you suggest why this is so?*

Table 3: Summer and Winter Constellations

Summertime	
Wintertime	

The Big Picture:

The yearly motions you have just observed arise from two causes. First, the orbital motion of the Earth around the Sun causes the background pattern of the much more distant stars seen behind it to change as our position is space changes. This accounts for the yearly cycle of constellations visible in the nighttime sky. Second, the Earth's rotation axis is tilted with respect to its orbital axis, causing the Sun's height above our horizon to vary annually (and causing our seasons!). You can investigate both these phenomena using the online simulations located at https://astro.unl.edu/naap/motion3/zodiac.html and https://astro.unl.edu/naap/motion1/animations/seasons_ecliptic.html.

A View from the Moon

Starry Night College is not restricted to views of the sky from the surface of the Earth, and your last exercise will be to make observations from the Moon.

Exercise 11: Select **Options, Viewing Location…** from the taskbar. In the box that currently says "Earth," select "The Moon." Now begin to type "Tranquilitatis" in the search box. As soon as the entry "Mare Tranquilitatis (Sea)" appears, left click it and press the **View From Selected Location** button. You are now on your way to the Moon. When you arrive, you will be standing in the Sea of Tranquility, where the Apollo 11 astronauts first landed in 1969. Change the time to 20 July 1969, UT 20:00:00. You are now viewing the sky as it looked to Neil Armstrong and Edwin Aldrin during their first moon walk over 50 years ago. Look around and find the Earth in your sky. (Hint: look towards the west.) It should look similar to the photograph shown in **Figure 2**.

Now select timestep of 1 **hour** and press the "Play" button. You are now seeing a speeded up view of the lunar sky. Carefully observe the Earth in your sky.

Question 10: *Describe the changing appearance of the Earth in the sky. Does it rise and set (i.e., above and below the horizon)? Does Earth always look the same? If not, how does it change and about how long does it take to cycle through its changes.*

Question 11: *You should have noticed that the Earth is always high in the sky as seen from the Sea of Tranquility. About what is its altitude above the horizon? Why would this property have been useful to astronauts of Apollo 11 while they were on the surface?*

Question 12: *You should also have noticed that − unlike the Earth − the Sun (and stars) rise and set. Thus, there is a day/night cycle on the Moon. Approximately how long is the Moon's day/night cycle? Did the Apollo 11 astronauts land in lunar daytime or nighttime?*

When you are finished your observations, select **File, Exit** to close the program.

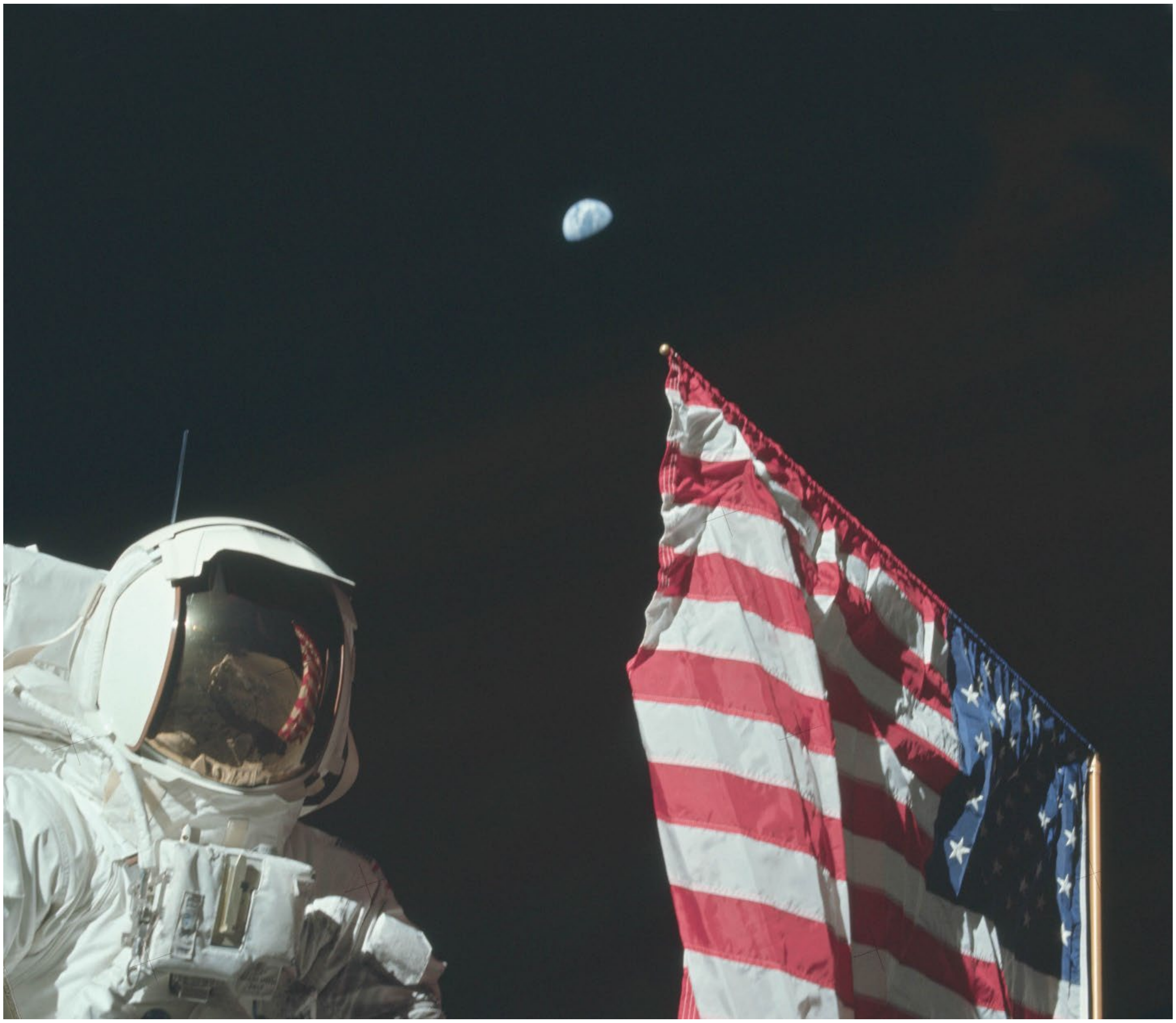


Figure 2: Astronaut Neil Armstrong on the surface of the Moon, 20 July 1969.

Astronomy Laboratory - Planets
Mendel Science Experience 2150
Fall 2025

Lab B
<u>Motions in the Sky</u>
(an Introduction to *Starry Night College*)

Name: ____

Lab Section: __________

Date: __________

Lab C
The 2024 North American Total Solar Eclipse

PURPOSE:

To understand the conditions necessary for an eclipse of the Sun ("solar eclipse") to occur; to observe the recent 2024 Total Solar Eclipses from positions on the Earth, Moon, and Sun.

EQUIPMENT:

Starry Night College computer program.

<u>Solar Eclipses</u>

In general, eclipses occur in the Solar System because the planets and moons are illuminated by light from the Sun and, as a result, cast shadows in space. An observer will see an eclipse if (1) he/she is viewing a planet or moon as it moves into the shadow of another object (in which case the planet or moon will darken because it is robbed of its source of illumination – the Sun) or (2) the shadow of a planet or moon falls on the observer (in which case the observer's environment will darken as it is robbed of its source of illumination – the Sun). On Earth, a ***solar eclipse*** is an example of the second case: The Moon moves directly between the Sun and the Earth, causing parts of the Earth's surface to temporarily darken as the Moon's shadow passes over them.

The geometry of a solar eclipse is shown in **Figure 1**. Note that the figure is not drawn to scale – the relative sizes and separations are not in their true proportions! Since the Moon's shadow trails away from the Moon opposite to the direction of the Sun, the shadow can only fall on the Earth when the Moon is

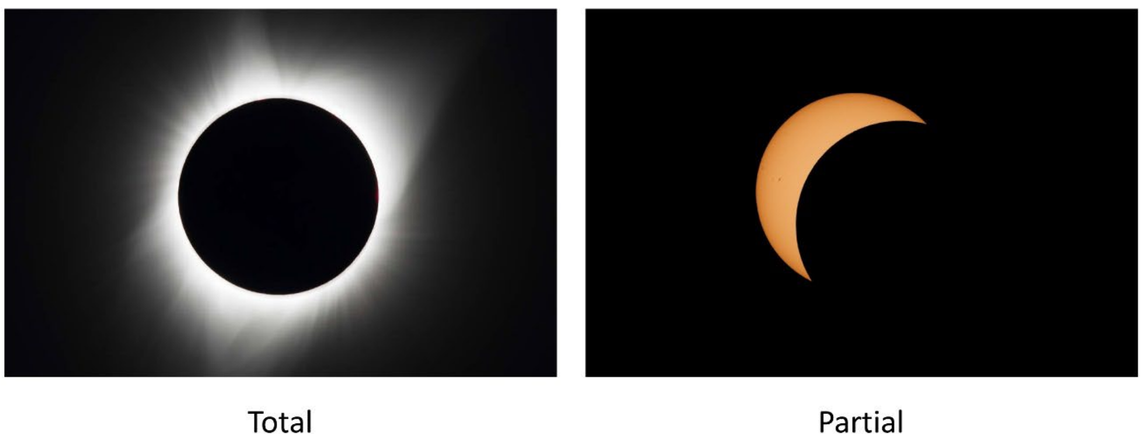


Figure 2: The Different Types of Solar Eclipses

directly between the Earth and Sun – which is when the New Moon phase occurs. *Thus, a solar eclipse can only occur during times when the Moon is "new."* Since the Moon's orbit and the Earth's orbit are not in the same plane, during most New Moons the shadow actually passes above or below the Earth, missing it entirely. On average, the conditions are right for a Solar Eclipse only ~3 times per year.

Because the Sun is not a point source, the Moon's shadow has two components. The inner shadow, called the *umbra,* is a narrowing cone. Study of **Figure 1** will show that, from a position within the umbra, the disk of the Sun is completely blocked by the Moon. The outer shadow, called the *penumbra* is a widening cone within which the Sun's disk is only partially obscured by the Moon. An observer on the small part of the Earth's surface falling in the umbra will see the face of the Sun completely blocked by the Moon. This produces a Total Solar Eclipse, as shown in the left panel of **Figure 2**. With the bright surface (or "photosphere") of the Sun completely blocked by the Moon, the daytime sky will actually darken and stars, planets and the Sun's corona will become visible. An observer within the region falling in the penumbra will see only a part of the Sun's surface blocked, yielding a Partial Solar Eclipse, also illustrated in **Figure 2**. The amount of blockage depends on how close the observer is to the umbra – the closer the observer, the more coverage. An observer outside the penumbra will see a completely unobscured Sun.

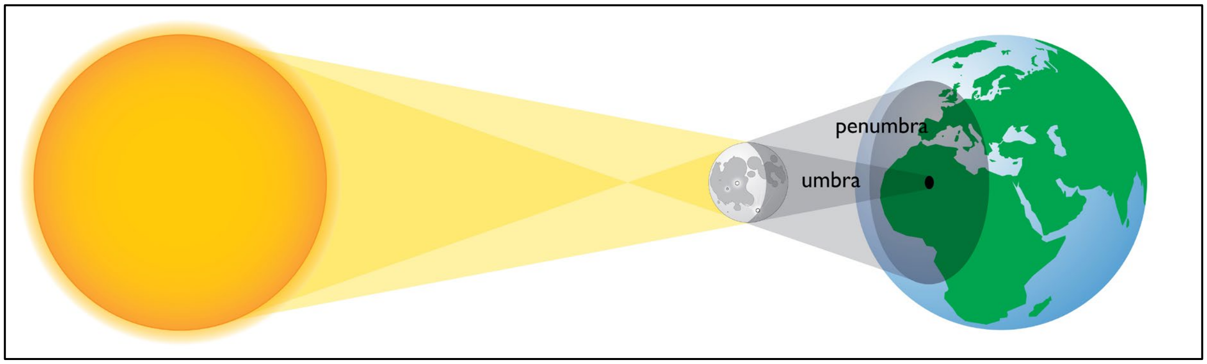


Figure 1: The geometry of a solar eclipse. The figure is NOT drawn to scale. Source: Megapixl.com

Because the umbra on Earth's surface is so small (typically less than ~100 miles in diameter) and because – due the combined effects of the Moon's motion in its orbit and Earth's rotation on its axis – it moves so quickly across the surface (typically ~1500 miles/hour), experiencing a Total Solar Eclipse truly requires being "in the right place at the right time."

The 2024 Total Solar Eclipse

The inhabitants of North America were fortunate on August 21, 2017 to have a Total Solar Eclipse pass directly across the continental U.S. This event, called my many "The Great American Eclipse," is estimated to have been viewed by well over 200 million people, either in person or via electronic devices. In fact, it proved so popular that Nature scheduled a repeat performance on April 8, 2024. In this lab you will use *Starry Night College* to examine this recent eclipse, and – in case you missed it – have the opportunity to view it from the surface of the Earth, the surface of the Moon, and the surface of the Sun.

To prepare for the eclipse, launch *Starry Night College* by double clicking the *SN7* icon on your Desktop. As you saw in the last lab, the program opens with a view of the current sky as seen from the roof of the Mendel Science Center.

THE VIEW FROM THE EARTH:

The "path of totality" of the 2024 eclipse, i.e., the path followed by the Moon's umbral shadow across North America, is shown in **Figure 3**. It entered the U.S. in Texas, traveled diagonally across the country, and exited in Maine. As you just learned above, viewing this eclipse required being in the right place at the right time. For the purpose of this lab, the "right place" is Niagara Falls and the "right time" is 8 April 2024 at about 2 PM. We chose Niagara Falls because it is relatively nearby (a 6 or 7-hour drive) and an interesting place.

To go to Niagara Falls, click **Favorites, MSE2150, Solar Eclipse Lab, Solar Eclipse from Niagara-1** on the *Starry Night College* taskbar. You will shortly find yourself standing on the Canadian side of the Falls, looking south, just before the eclipse reaches the Falls region. The Sun should appear almost directly south, near the top of the screen. If you can't see it, expand the Field of View (**+/-** buttons in the lower left of the screen) until you can.

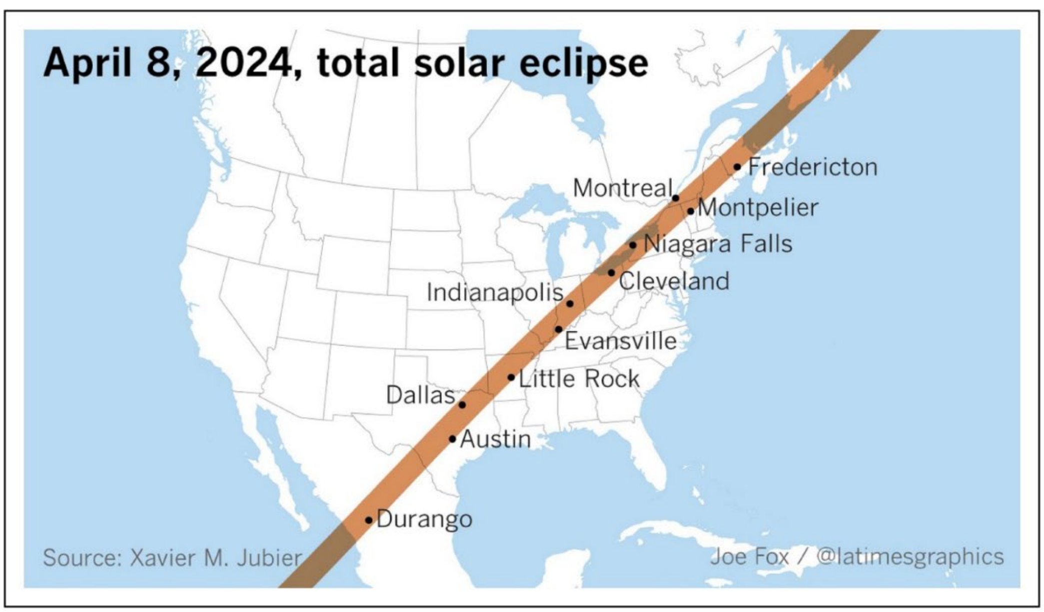


Figure 1: April 2024 Eclipse Path of Totality

To experience the eclipse, press the "Play" button (▸) in the toolbar. This will start the clock moving at several times normal speed. Watch the scene carefully. Be patient, it will take a few minutes for the whole story to play out. You can stop the simulation at any point using the "Pause" button (■) or reverse it using the "Rewind" button (◂).

> ***Question 1***: *What did you see? Describe the eclipse. What happened? What was the most striking event? When did it happen? How long did it last? Have you ever experienced this in "real life"? If so, where and when.*

Now let's zoom in and closely watch the Sun during the eclipse. Click **Favorites, MSE2150, Solar Eclipse Lab, Solar Eclipse from Niagara-2**. The time has been reset to shortly before the eclipse and you are now staring at the Sun, as if through a pair of binoculars or a small telescope (with a suitable solar filter installed!). Once again press the Play button and watch the eclipse.

> ***Question 2***: *What did you see? Describe how the appearance of the Sun changed throughout the eclipse. How does this relate to the explanation of solar eclipses given in the beginning of the lab (i.e., in the* ***Solar Eclipses*** *section)? What was the most striking phase of the eclipse? Exactly how long did this phase of the eclipse last? Be precise! (Rerun the simulation as many times as needed to do the timing.)*

> ***Question 3***: *If you had been viewing the eclipse from a position several hundred miles north or south of Niagara Falls, how different would the appearance of the Sun have been during the eclipse? What type of solar eclipse would you have seen?*

Test your answer to Question 3 taking a quick trip to Villanova to re-watch the eclipse. In the **Location Menu**, select **View from Villanova, USA** (the first entry). You will instantly be transported to the top of the Mendel Science Center. Find the Sun (it may be difficult!) and re-watch the eclipse.

> ***Question 4:*** *Did your observation of the eclipse from Villanova, which is about 290 miles SW of Niagara Falls, confirm your answer to Question 3? Describe how the eclipse looked to Villanovans in April 2024. Estimate how much of the Sun was blocked at the midpoint of the eclipse.*

THE VIEW FROM THE MOON:

Now we'll watch the eclipse from a position slightly farther away than Niagara Falls, namely, the surface of the Moon. To go to the Moon, click **Favorites, MSE2150, Solar Eclipse Lab, Solar Eclipse from Moon-1**. You are now standing on the Moon' surface (at roughly the center of the Moon's visible "nearside") and staring up at the Earth with a small telescope shortly before the eclipse. Start the simulation by clicking the Play button. You'll see the Earth slowly rotating, and the starry background slowly drifting by. You will also see something happening at the Earth's western (left) edge and slowly travel across the face of the Earth. Be patient! The whole story takes several hours to play out (several minutes in our simulation) and you should watch at least until the close in the simulation says 20:00 hours.

> ***Question 5***: *What did you see? Describe how the appearance of the Earth changed during the simulation. How does what you saw relate to the physical description of a solar eclipse as given earlier in the lab? From your position, standing on the Moon's surface, where is the Sun? Is it visible to you during the eclipse?*

To help clarify what you've just seen, we've placed some markers on the sky. To see them, click **Favorites,**

MSE2150, Solar Eclipse Lab, Solar Eclipse from Moon-2. The view is the same as above, except that the outline of the Moon's shadow at the position of the Earth is shown by the bullseye pattern. The smaller, inner circle shows the extent of the Moon's umbra, and the outer circle shows the extend of the penumbra. Start the simulation by pressing the Play button. Notice how small the umbra is compared to the penumbra. Clearly it is much easier to see Partial Eclipse than a total Eclipse.

> ***Question 6****: What is the total duration of the Total Eclipse (in decimal hours)? To make this measurement, you must determine how long the Moon's umbra falls upon the Earth. Record the time when the umbra first makes contact with the Earth and when it last makes contact with the Earth. The difference between these times is the eclipse length. Show all the work your calculation.*

> ***Question** 7: About how fast is the umbra moving across the Earth's surface (in miles/hour)? To crudely estimate this, assume that the shadow travels one Earth diameter (7917.5 miles) in the eclipse duration that you just measured. This gives you a speed of the shadow thru space. Notice, however, that the Earth's surface is rotating in roughly the same direction as the shadow is moving. The ground speed of the shadow is thus the space speed you just calculated **minus** the rotation speed of the surface. The rotation speed varies with latitude and is a maximum (at ~1000 miles per hour) at the Earth's equator. For your calculation, assume a speed of 800 miles per hour, which is appropriate for a latitude of 40°. Show all steps in your calculation. Given this speed, would it be possible jet airliner stay within the umbra and give its passengers a multi-hour view of the eclipse? (You'll have to look in the Internet to find out how fast commercial airliners can fly.)*

A more precise calculation would have to take into account the curved surface of the Earth and the precise path of the umbra. Your simple calculation should, however, justify the "ballpark" figure given in the ***Solar Eclipses*** section above for the speed of the umbral shadow. (If it doesn't, check your work!)

THE VIEW FROM THE SUN:

Finally, we'll watch the 2024 eclipse from a vantage point on the surface of the Sun. To go there, put on your SPF5000 sunblock and click **Favorites, MSE2150, Solar Eclipse Lab, Solar Eclipse from Sun.** You are now looking at the Earth through a powerful telescope shortly before the beginning of the eclipse. Start the simulation by clicking the Play button.

> ***Question 8****: Explain how the simulation you just watched is consistent with the geometry of a solar eclipse as explained in the* ***Solar Eclipses*** *section.*

Notice that – when viewed from the Sun − the Earth is never totally eclipsed by the Moon as it travels across its face. In astronomy, a ***transit*** occurs when a smaller celestial body passes in front of a larger body, obscuring a small part of it. And so, while the Earth enjoys the awesome spectacle of a total eclipse of the Sun, a solar viewer would merely note that the Moon is transiting the Earth. You will see other examples of transits in later labs. It is a complete coincidence that the apparent sizes of the Sun and Moon in our sky are so similar, leading to the truly spectacular appearance of the eclipsed Sun.

Lab Report Cover Page

Astronomy Laboratory - Planets
Mendel Science Experience 2150
Fall 2025

Lab C
The 2024 North American Total Solar Eclipse

Name: ____

Lab Section: __________

Date: __________

Lab D
Lunar Eclipses and the Saros Cycle

PURPOSE:

To understand the conditions necessary for an eclipse of the Moon ("lunar eclipse") to occur; to observe several eclipses and see that all eclipses are not alike; and to explore the eclipse repetition cycles, called "the Saros."

EQUIPMENT:

Starry Night College computer program.

Lunar Eclipses

In general, eclipses occur in the Solar System because the planets and moons are illuminated by light from the Sun and, as a result, cast shadows in space. An observer will see an eclipse if (1) he/she is viewing a planet or moon as it moves into the shadow of another object (in which case the planet or moon will darken because it is robbed of its source of illumination – the Sun) or (2) the shadow of a planet or moon falls on the observer (in which case the observer will darken as he/she is robbed of their source of illumination – the Sun). On Earth, a *lunar eclipse* is an example of the first case: the Moon moves into the Earth's shadow and darkens (from the point of view of an Earthly observer).

The geometry of a lunar eclipse is shown in **Figure 1**, from a point of view in the plane of the Moon's orbit about the Earth. Note that the figure is not drawn to scale – the relative sizes and separations are not in their true proportions! Since the Earth's shadow trails away from the Earth opposite to the direction of the Sun, the Moon can only move into the shadow when it is in the portion of its orbit that is on the opposite side of the Earth from the Sun – which is when the Full Moon phase occurs. *Thus, a lunar eclipse can only occur during times when the Moon is full.*

Because the Sun is a large object, the Earth's shadow has two components. The inner shadow, called the *umbra,* is a narrowing cone, tapering to a point over a million kilometers away in space. Study of Figure 1 will show that, from within the umbra, the disk of the Sun is completely blocked by the Earth. The outer shadow, called the *penumbra* is a widening cone within which the Sun's disk is partially obscured by the Earth.

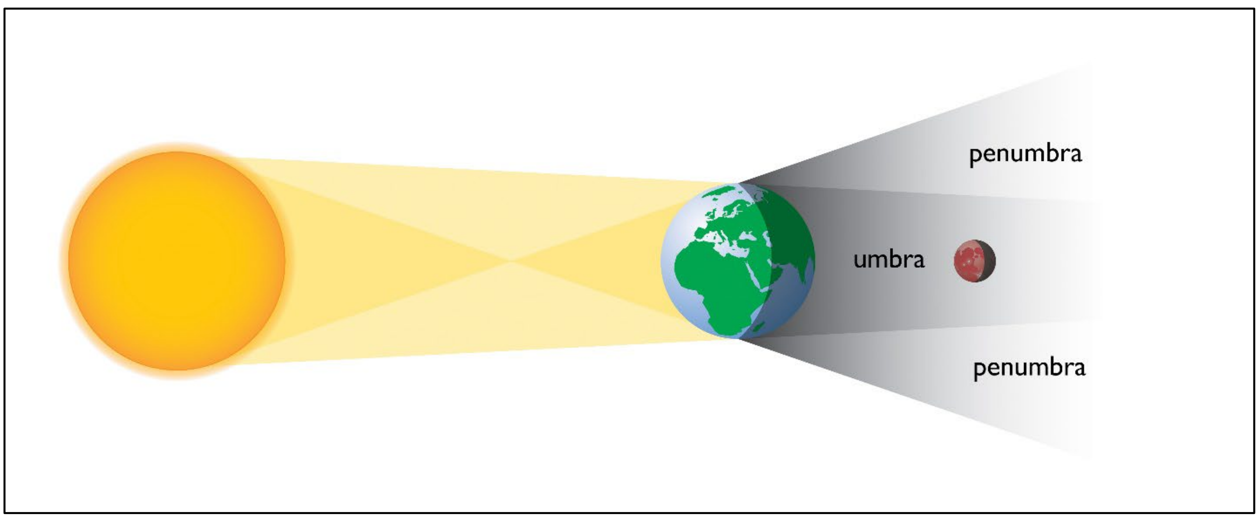


Figure 1: The geometry of a lunar eclipse. The figure is NOT drawn to scale. Source: Megapixl.com

If the Earth's shadow – at the distance of the Moon – could be seen in the nighttime sky it would appear as a small bullseye, several times larger than the diameter of the Moon. As the Moon's orbit takes it into the outer penumbra, the Moon would be seen to darken slightly; as it enters the umbra it would darken appreciably. Because the Moon's orbit is not in exactly the same plane as the Earth's orbit around the Sun, the Moon doesn't always enter the shadow in the same place (or at all!). This gives rise to several different "kinds" of lunar eclipses, which are illustrated in **Figure 2**. The dashed arrows in the figure show the path of the moon through the shadow and the position of the Moon is shown at the mid-eclipse point. During most Full Moons, the Moon actually passes completely above or below the penumbra, missing it completely and, on average, only one eclipse happens for every 8 Full Moons.

> ***Question 1**: Why isn't the Earth's shadow visible in the night sky? What must happen for us to know it is there?*

> ***Question 2**: Ancient astronomers noticed that the shape of the Earth's umbra, where it crossed the Moon's disk, was curved. What do you think this told them?*

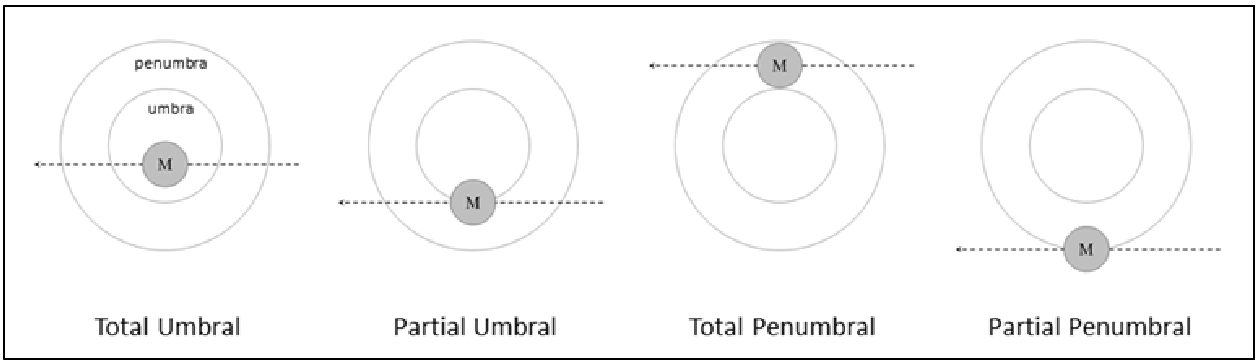


Figure 2: The different types of lunar eclipses

<u>Observing Eclipses with *Starry Night College*</u>

We will use the *Starry Night College* simulation program to observe the various types of lunar eclipses and explore the timescales associated with them. The program will show us an image of the Earth's shadow imposed on the sky, to allow us to examine the eclipses more closely – but remember that the true sky is not so accommodating!

Launch *Starry Night College* by double-clicking the *SN7* icon that appears on your lab computer's Desktop. As you have seen in the previous labs, the program opens with a view of the sky as seen from the roof of the Mendel Science Center, facing towards the south. Remember that Figure 1 in Lab A identifies the various menus that are available for controlling *Starry Night College*.

<u>*Step 1: Getting Ready for the First Eclipse*</u>

We will begin this lab by examining a recent set of Lunar Eclipses. Click **Favorites, MSE 2150, Lunar Eclipse Lab, Eclipse Set A.** You should now see a nearly full Moon in the middle of the screen at 9 PM on 25 May 2021. The view is still from Villanova, but several adjustments have been made: (1) The Earth has become transparent so that we will be able to see the Moon whether or not it is above our horizon; (2) the daytime blue sky has been suppressed; and (3) the orientation has been adjusted so that Solar System motions run approximately horizontally on the screen. In addition, the Julian date is now displayed in the upper left part of the screen, along with the altitude of the Moon, i.e., its angle above the horizon. (A negative altitude means that the Moon is below the horizon.) To the left (eastward) of the Moon you should see a label saying "Earth shadow." This is the approximate location of Earth's shadow as projected on the sky. The shadow outline itself will not appear until it is close to the position of the Moon. You may have to adjust the size of the field-of-view (by using the "+/-" buttons in the **FOV Box**) to show both the Moon and the shadow target.

<u>*Step 2: Measuring the Contact Times*</u>

Now step ahead in time to determine the Contact Times for the eclipse. These are defined in **Figure 3**. CT_1 and CT_2 are the first moments that the Moon touches the penumbra and umbra, respectively. CT_3 and CT_4 are the last moments that the Moon touches the umbra and penumbra respectively. Try to determine these times to the nearest minute by suitably adjusting the time increments in the **Time Step Menu** and using the "Play" buttons (◂ ■ ▸). (The timestep should be set up initially as 1 minute.) Record the Julian Date (**to four decimal places**) and the altitude of the Moon (**rounded to the nearest degree**) at these moments in the "ECLIPSE A1" column of **Table 1** or in the Excel spreadsheet provided by your instructor. *Note that there will be no values for CT_2 and CT_3 unless the eclipse type is Partial Umbral or Total Umbral!*

NOTE: The moon should be stationary on your screen during these simulations, with the shadow and the background sky doing the moving.
If the Moon moves, right click on it and select "Center"

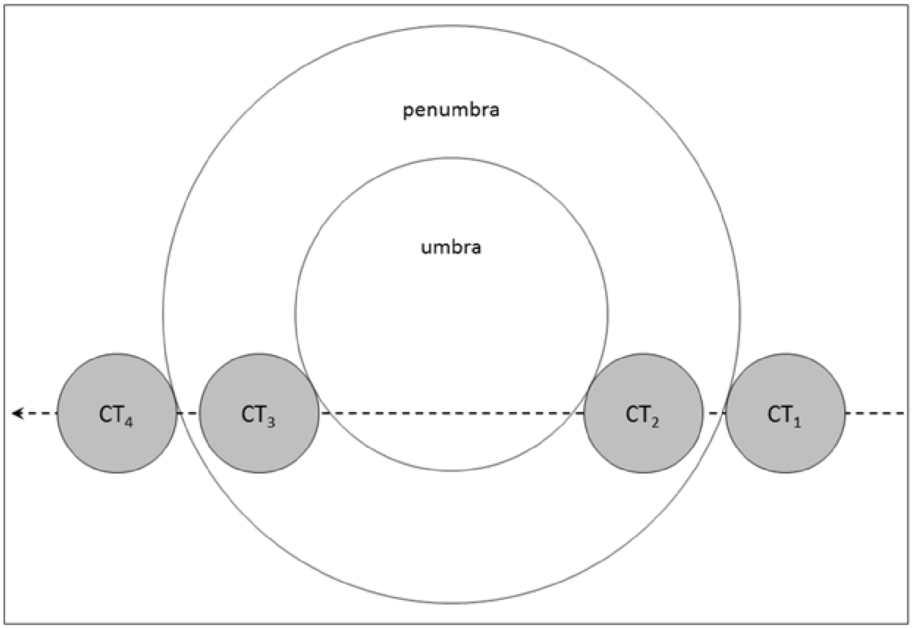


Figure 3: Eclipse Contact Times

Step 3: Looking at two more eclipses

Early astronomers noted that eclipses seem to occur about every six "lunar months," where a lunar month is the period of the Moon's phases and lasts for 29.5 days. Six lunar months is 6 x 29.5 days = 177 days, which is a little less than half of a calendar year.

Use the **Time Step Menu** to set the timestep to 1 lunar month, then press the single-step button (▶|) six times to jump ahead six lunar months. (The new date should be about six months later than for ECLIPSE A1.) Widen your field of view if necessary and you should see the Earth's shadow nearby. Now adjust the time steps suitably and measure the Contact Times for this eclipse. Record these values in the column labeled "ECLIPSE A2" in **Table** 1 or the Excel spreadsheet.

Now let's do one more eclipse. Once again, jump ahead by six lunar months, find the shadow target and measure the eclipse times. Record all the data in the "ECLIPSE A3" column of **Table 1** or the spreadsheet.

You should now have Contact Time data for three eclipses in **Table 1**.

Step 4: Characterizing the Eclipses

Compute the duration of ECLIPSE A1 (**in units of hours**) and enter in the appropriate place in **Table 1**. The duration is given by $CT_4 - CT_1$, i.e., the time interval between the beginning and end of the eclipse. Next compute the Julian Date of the midpoint of the eclipse and enter in **Table 1**. The midpoint of an eclipse is simply the average of the 4 contact times. To express this time in calendar date and local time, click the **Set Julian Day…** option in the **Calendar Menu** and enter the desired Julian date. When finished, click **Set Julian Day** and the corresponding calendar date and time will appear in the information bar. Record this information in **Table 1**. Look at the position of the Moon at this midpoint date. If you have done your calculations correctly, the Moon should be halfway through the eclipse. What kind of eclipse was ECLIPSE A1? Determine the type by comparing the midpoint view of ECLIPSE A1 with **Figure 2**. Record the eclipse type in **Table 1**. On **Figure X** ("Eclipse Set A"), draw an image of the Moon showing its location within the umbra or penumbra at the midpoint of ECLIPSE A1. Also, draw an arrow showing the path of the Moon across the shadow. Label the arrow "A1" to identify the eclipse. **Make your drawing carefully and accurately. Draw the Moon in the correct scale relative to the shadow**. (It should be about the size of a Quarter.) Your drawing should look something like one of the panels in **Figure 2**.

Repeat the above procedure for ECLIPSE A2 and ECLIPSE A3.

> ***Question 3**: From an examination of the altitudes you recorded for your 3 eclipses, were any of them be visible from Villanova? If so, how much of the eclipse was be visible? (Remember, a negative altitude means the Moon is below the horizon!)*

The Saros Cycle

It should be very clear to you at this point that, although eclipses can occur every six months or so, the individual eclipses are not identical. Early civilizations, notably the Babylonians and Chinese, kept careful records of eclipses, just as you have done thus far. By comparing eclipse data over many centuries, they were able to predict the appearance of eclipses. They also noticed that nearly identical eclipses seem to recur after a time of about 18 years, known as the "Saros Cycle". In this part of the lab, we are going to test this and determine a precise value for the Saros Cycle.

Step 1: Jumping to the next Saros Cycle

To jump ahead in time by approximately one Saros cycle, select **Favorites, MSE 2150, Lunar Eclipse Lab, Lunar Eclipse Set B.** The date should now be 6 June 2039, about 18 years after ECLIPSE A1.

Step 2: Characterizing the Three Eclipses

Now repeat the measurements you made above. I.e., determine the contact times for this eclipse and record these data in the column labeled "ECLIPSE B1 " in Table 2 or in your Excel spreadsheet.

Now jump ahead 6 lunar months, find the next eclipse, and repeat your measurements. Record in **Table 2** ("ECLIPSE B2").

Finally, jump ahead another 6 lunar months and repeat the measurements, again recording the data in **Table 2** ("ECLIPSE B3").

Now compute the durations and midpoints and identify the eclipse types as you did for eclipse set A. Using **Figure Y**, sketch the location of the moon at each eclipse midpoint and the path followed by the moon. Be sure to label each eclipse.

When you are finished, you should have data for three eclipses recorded in **Table 2** and three eclipses paths and midpoints sketched in **Figure Y**.

> ***Question 4**: Carefully examine Tables 1 and 2 and Figures X and Y. Comment on the eclipses you've observed. Are all lunar eclipses alike? Does the moon always trace the same path through Earth's shadow? Do all the eclipses have the same duration? Now compare the sequence of eclipses in Set A and the sequence in Set B. Does it appear that the sequence in Set B is a repetition of that for Set*

A? Are the durations of the corresponding eclipses the same (i.e., A1 vs. B1, A2 vs. B2,…)? Are there any systematic differences between the eclipses in Figure X and those in Figure Y? Do eclipses really seem to repeat with a cycle of about 18 years?

Step 3: Computing the Saros Cycle

You **should** have seen that the pattern of eclipses does indeed repeat with a period of about 18 years. Let's now make a more precise calculation of this period. Fill in the first three rows of **Table 3** by differencing the midpoint times of the eclipse pairs A1 and B1, A2 and B2, A3 and B3. Then compute the average of these times (which will be in units of days) and enter it into the 4th row of the table. This is your estimate of the Saros Cycle.

Step 4: Checking Your Results

Use a web browser to find out the accepted value for the Saros cycle. (I.e., type "Saros" into your favorite search engine.) Make sure you find a source that quotes the Saros period to at least 2 decimal places (when expressed in days).

> ***Question 5****: What is the accepted value for the Saros Cycle? What source did you use? How different is the accepted value from your value?*

Now you know the Saros Cycle! Next time you see a really great eclipse – whether it is a lunar or a solar eclipse – all you have to do is wait around for one Saros cycle and it will happen again!

Table 1: Data for Eclipse Set A

	ECLIPSE A1	ECLIPSE A2	ECLIPSE A3
	time (JD)	time (JD)	time (JD)
	altitude (°)	altitude (°)	altitude(°)
CT_1			
CT_2			
CT_3			
CT_4			
Duration (Hours)			
Mid-Eclipse (JD)			
Mid-Eclipse (Calendar and Time)			
Eclipse Type			

Table 2: Data for Eclipse Set B

	ECLIPSE B1	ECLIPSE B2	ECLIPSE B3
	time (JD)	time (JD)	time (JD)
	altitude (°)	altitude (°)	altitude (°)
CT_1			
CT_2			
CT_3			
CT_4			
Duration (Hours)			
Mid-Eclipse (JD)			
Mid-Eclipse (Calendar & Time)			
Eclipse Type			

Table 3: Determination of the Saros Cycle

Midpoint(B1) – Midpoint (A1)	
Midpoint(B2) – Midpoint (A2)	
Midpoint(B3) – Midpoint (A3)	
Average Saros Period (days)	

Figure X: Eclipse Set A

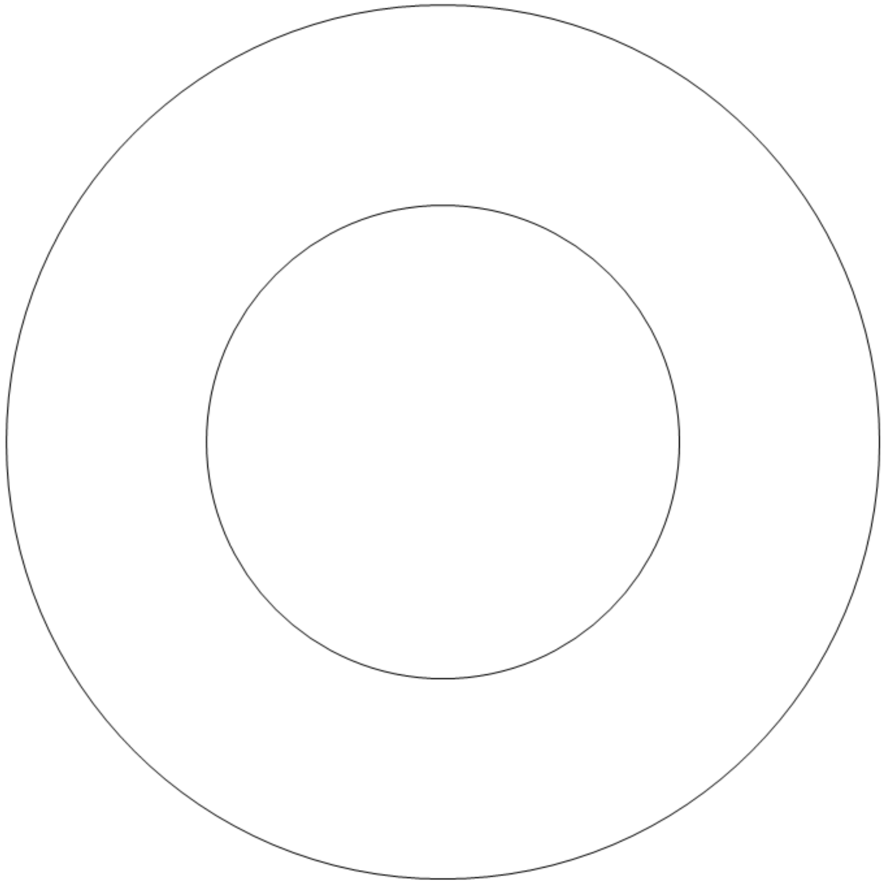
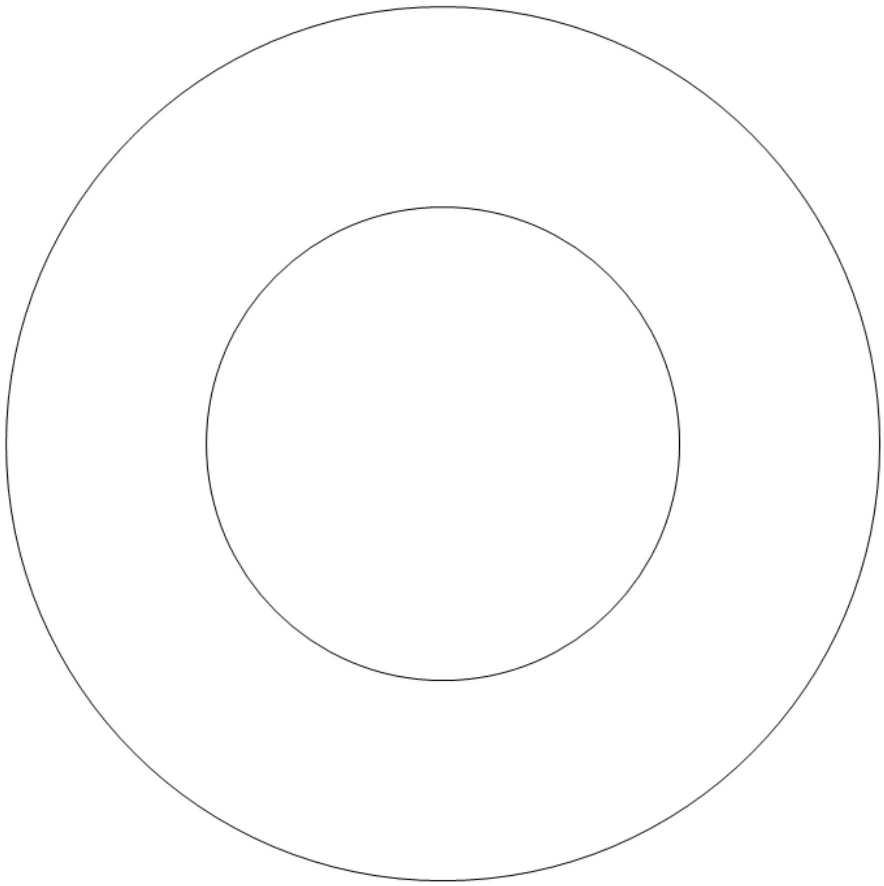


Figure Y: Eclipse Set B



Lab Report Cover Page

Astronomy Laboratory - Planets
Mendel Science Experience 2150
Fall 2025

Lab D
Lunar Eclipses and the Saros Cycle

Name: ____

Lab Section: __________

Date: __________

Lab E
<u>Planetary Motion</u>

PURPOSE:

To observe the motions of the planets across the sky.

EQUIPMENT:

Starry Night College computer program, calculator or Excel spreadsheet

<u>The "Inferior" Planets</u>

Ancient observers noticed that two of the five "naked eye" planets, Mercury and Venus, always appear near the Sun in the sky. They were called the "inferior" planets since they seemed to be subservient to the Sun and were forced to tag along with it as it moved through the sky. The times when these planets achieve their greatest apparent separations from the Sun are called Greatest Eastern Elongation (GEE), when the planets are East of the Sun, and Greatest Western Elongation (GWE), when the planets are West of the Sun. GEE and GWE are the best times for viewing these planets because they will be visible in a darkened western sky in the evening after the Sun sets (at GEE) or in a darkened eastern sky early in the morning before the Sun rises (at GWE).

Launch *Starry Night College* as you did in the previous labs, by double-clicking the *SN7* icon on your desktop.

Now set up the program for this lab by clicking **Favorites, MSE 2150, Planetary Motion Lab**. You are now looking in the direction of the Sun on 1 June 2022 at 11 in the morning. As in the last lab, we have made the Earth transparent (so you can see the Sun even at night), eliminated the bright sky, and oriented our view so that Solar System motions run approximately horizontally on the screen. Note that east is to the left on the screen and west to the right and the field of view covers about one-half of the sky in the east-west direction. Venus and Mercury should be clearly visible on the screen (as well as some of the other planets).

Let time run freely forward by clicking the "Play" button (▶). The Time Step should be set to 6 hours and so time should be passing rapidly. In this simulation your gaze is fixed in the same direction in space (toward the constellation Orion. Do you see it?) and so the stars appear motionless. Watch carefully as the Sun disappears off the screen on the left and then reappears a little while later on the right. Watch at least until the Sun returns to about the middle of the screen. The Sun takes a year to repeat its original position among the stars (and return to the center of the screen), but through the magic of *Starry Night College*, we only need to wait a few moments. In general, you should have of noticed several things:

1. The Sun's smooth motion "thru" the background pattern of stars, taking about 1 year to reappear in the same place.
2. The Moon's more rapid and apparently "wobbly" motion through the stars, taking about 1 month to reappear.
3. The general eastward (toward the left) motion of the other Solar System objects on the screen.

After observing these motions, restart the simulation (**Favorites, MSE 2150, Planetary Motion Lab**) and press the play button. Now**,** focus your attention on the motions of the Sun and the two inferior planets Venus and Mercury. They will all soon drift off the screen on the left (east) side. Be patient! They will eventually reappear on the right. (If you are not a patient person, you can follow the Sun by using the hand cursor to drag the screen around.) Watch the motions of the Sun, Mercury, and Venus for several minutes and then answer the following questions.

> ***Question 1:*** *Describe the motion of the Sun through the sky: In which direction does it move relative to the stars? Is the motion steady or does the Sun stop and start? Does the Sun follow the same path over and over? Or does the path vary? Is the set of constellations that the Sun seems to pass through familiar to you? (To see the constellation names, click* ***Labels, Constellations****.) Where have you heard of them before? Why does the Sun seem to move through the background pattern of stars?*

Question 2: *Describe the motions of Venus and Mercury relative to the Sun. Were the ancients reasonable in thinking that these planets seemed to be "subservient" to the Sun?*

Stop the simulation (click on ■) and rewind it to the beginning by clicking **Favorites, MSE2150, Planetary Motion Lab** again. Lock the Sun in the center of the screen by right clicking on it and then selecting **Center**. Then use the FOV Box to change the width of the view to ~100°**.** Now step forward slowly in time to determine the next occurrence of GEE for Mercury, i.e., when Mercury achieves its greatest separation from the Sun on the eastern (left) side. Adjust the Time Step to whatever value allows you to make the best estimate of this time. When you find the next GEE, enter the date and angular separation in **Table 1**. To measure the separation, click on the Cursor Menu and select **Angular Separation**. Drag a line between the Sun and Mercury and the angular separation will be displayed on the screen. (Note: do not record the "position angle," which will also be shown on the screen). Step forward in time again, until Mercury reaches GWE. Record the time and the angular separation (to the nearest 0.1°) in **Table 1**.

NOTE! Starry Night College records the angular separation in units of degrees (°), arc-minutes (') and arc-seconds ("). You will have to convert this measurement into decimal degrees by recalling that there are 60 arc-minutes per degree and 60 arc-seconds per arc-minute.

Return to the beginning of the simulation again and repeat the above procedure for Venus, entering the results in **Table 2**.

Question 3: *Imagine that Venus and Mercury are both at their respective GEE's. The Sun has just set, i.e., it is just below the horizon and the sky is getting dark.* ***Figure 1*** *shows how this would look for the planet Venus. How much time will you have to observe Venus and Mercury before they set? Remember that the Sun moves completely around the sky (e.g., from sunset to sunset) over the course of one day. That's an "angular speed" of 360° per 24 hours, or 15°/hour. Use this speed and your angular separations in* ***Tables 1*** *and* ***2*** *to answer the question. Explain what you did to get your answer.*

Modern astronomers know that the inferior planets appear "attached" to the Sun as it travels though the stars because their orbital radii are smaller than Earth's. As can be seen in **Figure 2**, when viewed from the Earth, the line-of-sight towards an inferior planet (in any part of its orbit) is never far from the line-of-sight towards the Sun. Besides affecting our ability to observe these worlds, this also gives us the

Figure 1: Venus at sunset, at GEE

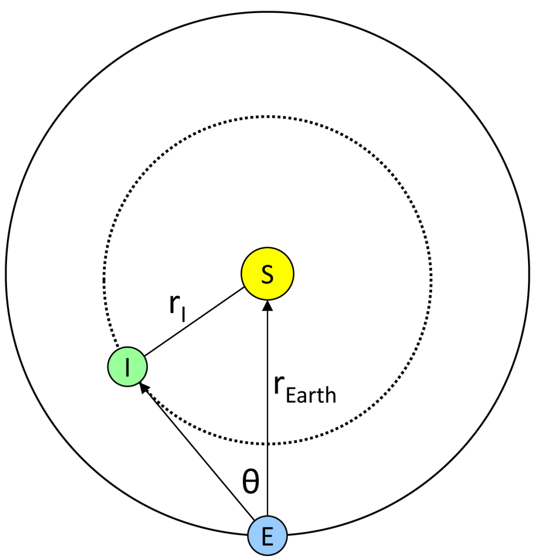


Figure 2: Relative positions of the Sun (S), Earth (E), and an Inferior planet (I) at GEE.

opportunity to measure their orbital radii with simple naked-eye observations. The positions of the Earth and the inferior planet in **Figure 2** are such that the planet appears at GEE, i.e., its farthest angular distance eastward of the Sun. At this time, the line-of-sight towards the planet is tangent to the planet's orbit (i.e., the Sun-planet-Earth angle is 90°). In this case, simple trigonometry yields

$$r_I = r_{Earth} \sin\theta \tag{1}$$

Where r_I and r_{Earth} are the radii of the planet's and Earth's orbits, respectively, and θ is the GEE separation angle. If we call Earth's orbital radius 1 Astronomical Unit (AU), then r_I in **Equation (1)** is determined in units of AU. Note that the same measurement and calculation could be made with the planet at GWE.

Question 4: *What are the orbital radii of Mercury and Venus? Use the separation angles you measured in* ***Tables 1*** *and* ***2*** *to compute orbital radii at both GEE and GWE. Enter the results in* ***Table 3****. Did GEE and GWE yield the same result for each planet? If the orbits of the planets were perfect circles centered on the Sun (as in* ***Figure 2****), then all GEE and GWE measurements should yield the same result – to within the uncertainty of the observations, which we might consider to be about ± 1°. Are your results consistent with circular orbits? In a later lab, we will see that planetary orbits are not necessarily circular but are more often elliptical in shape. Do you suspect that either or both of Venus and Mercury have elliptical orbits? Show all calculations.*

NOTE! Microsoft Excel assumes that all angles are in units of radians. If you are using Excel to compute the orbital radii of Venus and Mercury, you must first convert your measured angles (in degrees) into radians before computing the sine.

The "Superior" Planets

Early observers also noted that the other three "naked-eye" planets – Mars, Jupiter, and Saturn – did not seem tied to the Sun and could, for instance, appear high in the nighttime sky at midnight. These were called the "superior" planets. The ancients also noticed that, at this time, the planets appeared to reverse their normal slow eastward motion through the stars, and for a short time, move backwards (westward). This phenomenon is known as *retrograde motion*.

Return to the beginning of the simulation again by clicking **Favorites, MSE2150, Planetary Motion Lab** again. Once again let the time run freely forward (click on " ▶ "), this time focusing on Mars, which – initially – is on the right side of the screen You will see it drifting steadily eastward through the stars, which are locked in place. You will also see the Sun and the other Solar System objects moving generally eastward. Keep watching Mars until you observe a retrograde motion event. This may take a year or two, so be patient! If Mars disappears off the left side of the screen, just wait until it reappears on the right. (Note: you may observe retrograde motion in other planets during this time.)

After you have seen what Mars' retrograde motion looks like, stop the simulation (click on " ■ "). Carefully step back in time to determine exactly when the retrograde event you just witnessed began and when it ended. The "beginning" of retrograde is when the planet stops its normal ("prograde") eastward motion and the "end" of retrograde is when it resumes moving eastward. Zoom in and adjust the Time Step as necessary to make the most accurate measurements of these times. Record the dates and times in **Table 4**. Use two decimal places in the Julian Date, which is shown in the upper left corner of the *Starry Night College* window. It may help if you have *Starry Night College* draw Mars' path through the heavens as it moves. To do this, right click on Mars and select **Celestial Path**.

Compute the midpoint of the retrograde event (i.e., the average of the start and stop times). Record this in **Table 4**.

We could repeat this experiment with other superior planets (as well as Uranus, Neptune, and Pluto) and we would find that they, too, experience periods of retrograde motion.

Checking Your Work

Retrograde motion was a puzzle to ancient astronomers who believed that the Earth was the center of the Solar System and that all celestial objects orbited around it. This was the *geocentric* (Earth-centered) model. Retrograde motion would seem to require that the planets stop their orbital motions, go backwards for a time, and then resume their normal motion. This was not considered to be reasonable behavior for a celestial object!

The *heliocentric* (Sun-centered) model of the Solar System, in which the Sun was seen as the center of the Solar System and only the Moon actually orbited around the Earth, provided a natural explanation for retrograde motion. The heliocentric model showed that retrograde motion is only an apparent motion of the planet, which occurs when the Earth "passes" another planet whose orbit is larger than the Earth's. In this case, neither object has to actually stop and back up. The moment of Opposition, i.e., when the planet and the Sun are exactly opposite in the sky (separated by 180°), should occur right at the midpoint of retrograde motion. This would explain why retrograde motion occurs when the superior planets are most easily viewed - it happens when the planets are high in the dark midnight sky and at the time when the planets are closest to the Earth.

Let's check this for Mars.

In the *Starry Night College* tool bar, select **Favorites, MSE2150, Inner Solar System**. Our perspective is now hovering about 4 A.U. above the plane of the Earth's orbit, in the direction of the North Celestial Pole. Set the time and date to that which you recorded for the midpoint of the retrograde event you just observed. Now move forward or backwards in time to determine the exact moment of the Opposition which occurs closest to this time (i.e., when Mars and the Sun are in exactly opposite directions in the sky). Adjust the time step as needed to get the most accurate measurement Record this in **Table 5**, keeping 2 decimal places in the Julian Date.

> ***Question 5:*** *Given your results, is it reasonable to consider that retrograde motion occurs near the time of Opposition? How big a difference was there between your measurement of Opposition and of the retrograde midpoint (be exact). Could this difference be caused by measurement uncertainty? It was easy to measure the time of Opposition looking down on the Solar System from "above" with Starry Night College. But how easy was it to measure the midpoint of retrograde motion?*

> ***Question 6:*** *While you are viewing the inner Solar System, take a look at Mercury's orbit. Does the orbit look circular? Is the Sun exactly in the center of the orbit? If it is not, then Mercury's distance from the Sun varies throughout its orbit and the orbit is not circular. Is this consistent with what you found in earlier in this lab? Is this result consistent with your conclusion in Question 4? What about Venus?*

Table 1: Mercury's Greatest Elongations

	Calendar Date (mm/dd/yy)	**Angular Separation** (°)
Greatest Eastern Elongation (GEE)		
Greatest Western Elongation (GWE)		

Table 2: Venus' Greatest Elongations

	Calendar Date (mm/dd/yy)	**Angular Separation** (°)
Greatest Eastern Elongation (GEE)		
Greatest Western Elongation (GWE)		

Table 3: Orbital Radii of Venus and Mercury

	Mercury	**Venus**
Orbital Radius at GEE (AU)		
Orbital Radius at GWE (AU)		

Table 4: Mars' Retrograde Motion

	Calendar Date (mm/dd/yy)	**Local Time** (hh:mm:ss)	**Julian Date** (days)
Retrograde Motion Begins			
Retrograde Motion Ends			
Midpoint of Retrograde Motion			

Table 5: Mars' Opposition

Calendar Date (mm/dd/yy)	**Universal Time** (hh:mm:ss)	**Julian Date** (days)

Lab Report Cover Page

Astronomy Laboratory – Planets
Mendel Science Experience 2150
Fall 2025

Lab E
<u>Planetary Motion</u>

Name: ____

Lab Section: __________

Date: __________

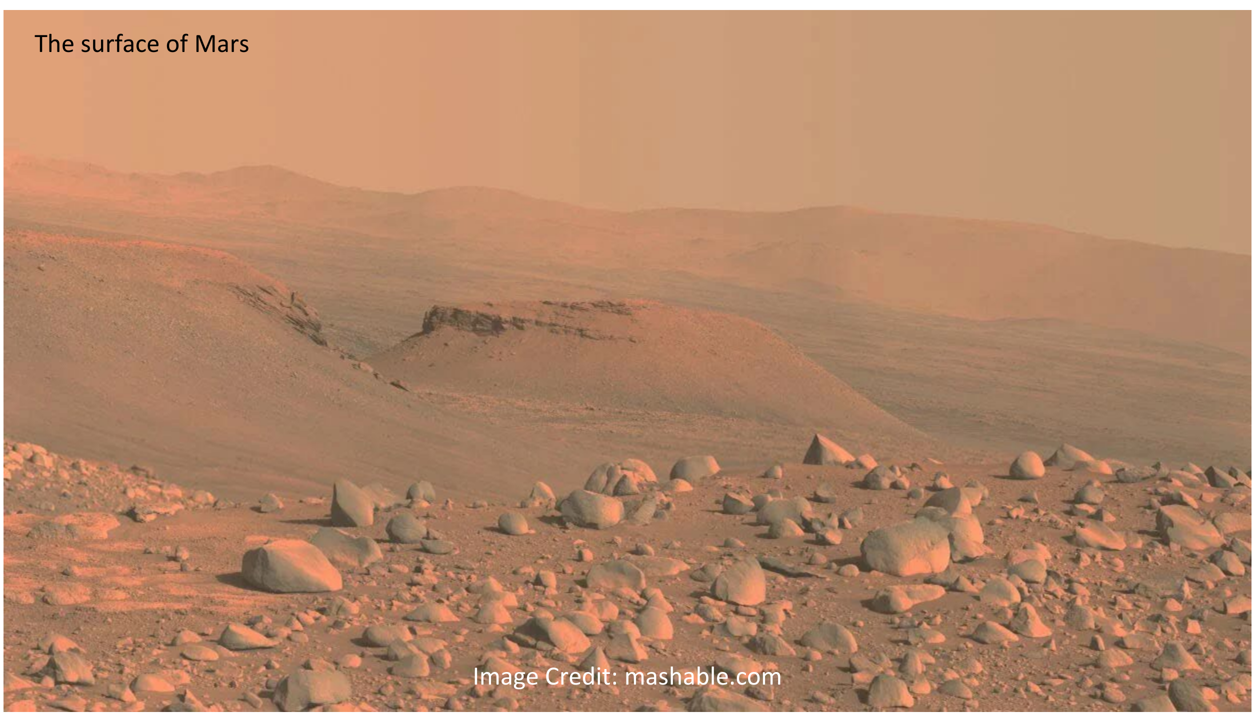
Lab F
Kepler's Determination of the Orbit of Mars

PURPOSE:

To recreate the method that Johannes Kepler used to triangulate the distance to Mars and determine the shape of its orbit using only naked-eye observations.

EQUIPMENT:

Starry Night College computer program, calculator or Excel spreadsheet, ruler, protractor



The surface of Mars

<u>Kepler's Method</u>

In the early 1600's, the German mathematician and astronomer Johannes Kepler (1571-1630 AD) developed a clever technique for measuring the distance between the Mars and the Sun at specific points along Mars' orbit, requiring only measurements of the relative positions of Mars and the Sun at specific times. **This was one of the crucial first steps along the path to measuring the size of the Universe itself**! Kepler utilized tables of observations obtained by the great "naked-eye" observer Tycho Brahe (1546-1601 AD) but, in the story below, we'll pretend Kepler was doing the observing himself.

The technique begins on a date at which Mars is in opposition to the Sun (which you now know occurs at the mid-point of its retrograde motion). We can visualize this alignment as shown in **Figure 1A**. Kepler then waited a specific number of days (say, a month) past opposition. The planets were then aligned as shown in **Figure 1B** and he measured the angle between the Sun and Mars on the sky. Finally, Kepler waited 687 more days, which he had previously determined to be the true orbital period of Mars, and then once again measured the angle between the positions of Mars and the Sun on the sky. At this time, Mars had completed one full orbit and returned to the same position in its orbit, but Earth had moved less than two full years and was in a different position in its orbit, as seen in **Figure 1C**.

Given this set of measurements, the situation now looks like **Figure 2.** The positions of the Sun, Earth, and Mars form a quadrilateral. Kepler has now measured the angles $\beta 1$ and $\beta 2$ and knows angle α because of the known number of days it took the Earth to move from position 1 to position 2. If the distance between the Earth and the Sun, D_{Earth}, is known then − with a little trigonometry − the quadrilateral can be completely specified, including the separation of Mars and the Sun, D_{Mars}, at this particular place in Mars' orbit. Kepler didn't know how far the Earth was from the Sun, but he could nevertheless express the distance of Mars in terms of the Earth-Sun distance, which we now call the Astronomical Unit (AU).

Alternatively, the Mars-Sun distance can be determined graphically, as we will do in this lab. By carefully drawing the relative positions of the Sun and Earth, the intersection of the two arrows in **Figure 2** (which are determined by the measured angles $\beta 1$ and $\beta 2$) defines the location of Mars. Its distance from the Sun can be measured with a ruler and then scaled by the Earth-Sun distance to yield a distance in AU.

The beauty of this technique is that it requires only a careful measurement of the angle on the sky between the Sun and Mars on two carefully chosen dates.

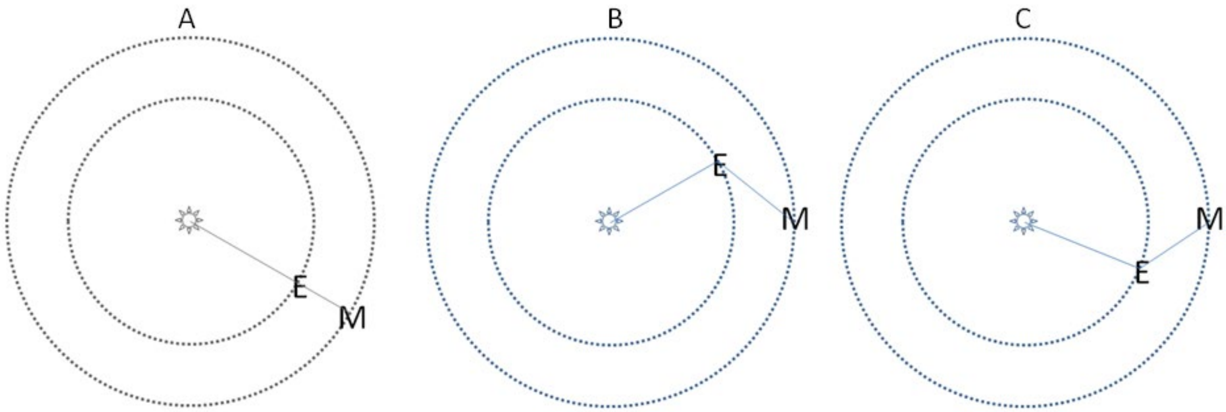


Figure 1: The relative positions of the Sun, Earth, and Mars in Kepler's Method

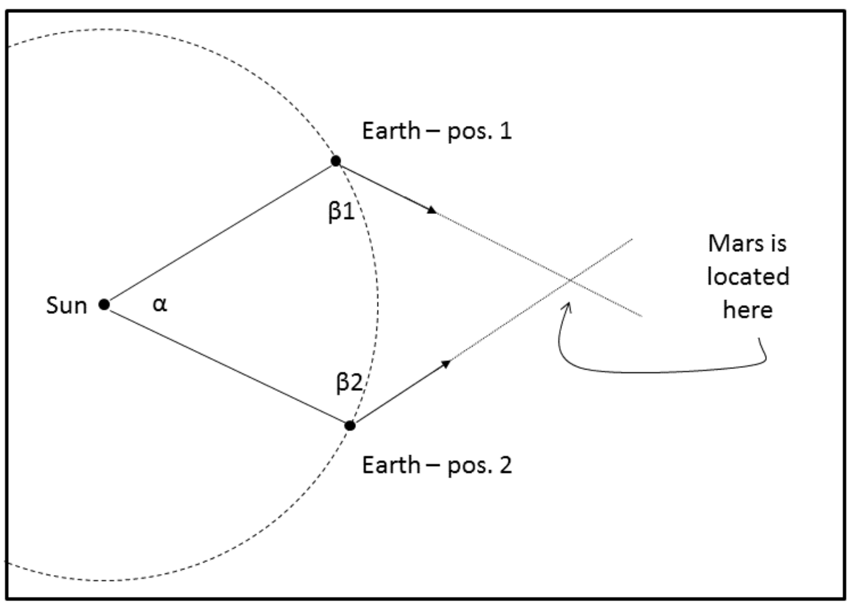


Figure 2: A graphical solution to the distance of Mars

The Distance to Mars with *Starry Night College*

We will now use *Starry Night College* to repeat Kepler's measurements (using data from Kepler's time) and determine Mars' distance from the Sun at one particular spot on its orbit. First, we'll identify a time when Mars was in opposition to the Sun. Then we'll jump ahead 46 days (position 1) and then 687 days (position 2), measuring the angle between the Sun and Mars on the sky each time.

Step 1: Find the Opposition of Mars

Launch *Starry Night College* and then setup the simulation by clicking **Favorites, MSE2150, Mars Distance Lab**. You are now looking in the general direction of the planet Mars at noon on 20 June 1595. This is around the time when some of the observations Kepler used may actually have been made. To make our observations easier, we have once again stopped the Earth's rotation and made the Earth transparent.

Now step ahead in time until you notice Mars beginning its retrograde (westward) motion. *Remember! Eastward motion is to the left on your screen and westward motion is to the right!* Start with a time step of several hours. Zoom in as closely to Mars as possible and determine this time as precisely as you can. Record it in the first row of **Table 1**, keeping two decimal places in the Julian Date column.

Now move ahead in time until Mars finishes its retrograde motion and once again begins to move Eastward. Determine this time as precisely as possible and record it in the second row of **Table 1**.

Determine the date of the mid-point of the retrograde motion by averaging the two Julian dates. This is the moment of Opposition, when Mars is directly opposite the Sun from our vantage point on Earth, as shown in **Figure 1A** above. Record this time, in calendar form and Julian Date, in the third row of **Table 1**.

Step 2: Measure the Mars-Earth-Sun Angles

Set the date and time in *Starry Night College* to the moment of Opposition, which you just determined. Now step ahead 46 days in time from this date. This 46-day jump moves Earth and Mars to the positions indicated in Figure 1B, and you are now ready to measure the first Mars-Sun separation angle

Change to the Local observing perspective (**Options**, **Orientation**, **Local**). Make sure the horizon is on (**View**, **Show Horizon**). Mars and the Sun are widely separated on the sky. In order to see them both, set the field of view to 180°. Make sure you are facing towards the south. It may be that both Mars and the Sun don't happen to be above your horizon at this exact moment. If so, move ahead or back in time by a few hours until they are both visible from your location on the Earth's surface. Set the time step to 1 hour and step forward or backwards in 1-hour increments until both Mars and the Sun are visible in the sky. **You should not have to move more than +/–12 hours.** Now we're ready to measure their separation. If we were doing this outside you might imagine we'd use an instrument resembling a giant protractor, as in **Figure 3**. We'd sight along the protractor to both Mars and the Sun and then determine the angle between the 2 directions. *Starry Night College* makes this process even easier. Click on the Cursor Menu and choose **Angular Separation**. Now drag a line between Mars and the Sun. Their angular separation β will be displayed on the screen. Record the date and the β angle – in decimal degrees – for "Position 1" in **Table 2**. (Note: do not record the "position angle," which will also be shown on the screen.)

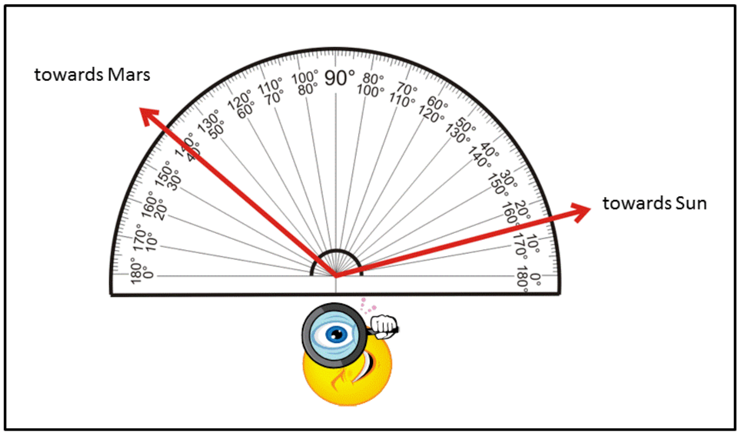


Figure 3: Measuring the Mars-Earth-Sun separation angle on the sky

Next, step ahead 687 days. This returns Mars to the same place in its orbit and the Earth moves to the position indicated in Figure 1C. Once again, adjust the time by 1-hour increments so that both Mars and the Sun are in the sky and measure the angle between them as you did above. Record the date and the angle, for "Position 2," in **Table 2**.

(*Note! We could have jumped ahead almost any number of days past Opposition; the particular use of 46 days will result in angles β1 and β2 being nearly equal. The important thing is that two sets of measurements that are made are spaced 687 days apart so that Mars is in the same place in its orbit.)*

Step 3: Compute the Angle α

Finally, we need to determine the angle α, as shown in **Figure 2**. Since the time elapsed from position 1 to position 2 was 687 days, the Earth moved through 1.881 complete revolutions around the Sun, which is 677°. This is 43° less than two full revolutions (720°) and so the angle α is

$$\alpha = 720° - 677° = 43°$$

Step 4: Determine the Mars-Sun Distance

The distance between Mars and the Sun can now be determined using the Earth-Sun distance as our "yardstick." As noted above, this could be done trigonometrically, but we will use a graphical technique and simple triangulation, which better illustrates the underlying concept of Kepler's scheme.

First, on the scale drawing given on page 9 of the lab, mark the locations of the Earth on its orbit at positions 1 and 2 and draw lines connecting the Earth and Sun. The Earth's orbit is represented by the large circle on the drawing. You can place position 1 anywhere along the orbit you like. Once you've done that, use your protractor to determine the location of position 2, such that the two positions form an angle α, whose vertex is at the center of the Sun. Label the Earth at positions 1 and 2 by "E1" and "E2", respectively.

Now, lay out the angle *β1*, whose vertex is at E1. Draw a line extending away from Earth at E1 toward Mars. Next, lay out the angle *β2*, whose vertex is at E2. Draw a line extending away from the Earth at E2 toward Mars.

MAKE THESE DRAWINGS AS CAREFULLY AS YOU CAN!!!!
MAKE SURE YOUR PENCIL IS SHARP!!!!

Notice that the intersection of these two lines determines the location of Mars at the time of the two observations! To determine its distance from the Sun, simply use your ruler to measure the Mars-Sun distance and then scale it by the size of the Earth's orbit. To do this, first measure the Mars-Sun distance in mm and enter it in the first row of **Table 3**. Be as precise as possible! Measure the Earth-Sun distance in mm and enter it in the second row of **Table 3**. (You can measure the Earth-Sun distance from any point on Earth's orbit since the orbit is represented in the figure as a circle with the Sun at the center.) Divide the Mars-Sun distance (in mm) by the Earth-Sun distance (in mm) and you now have your determination of the distance of Mars from the Sun in units of the Earth-Sun distance (i.e., Astronomical Units, or AU) at the time of the observations at position 1 and 2. Enter this result in the last row of **Table 3**.

YOUR DRAWING SHOULD BE FULLY LABELED AND SHOW THE DISTANCE MEASUREMENTS AND THE VALUES OF THE THREE ANGLES USED TO DETERMINE THE DISTANCE.

Checking Your Work

How well did you measure Mars' distance from the Sun? Unlike poor Kepler, you can use *Starry Night College* to find out. Let's move to a position about 4 AU above the Solar System, looking "down" on the Sun and its innermost family… Select **Favorites, MSE2150, Inner Solar System.** Now set the time to the date of Opposition you determined above.

> ***Question 1:*** *Is Mars close to Opposition? I.e., do the relative positions of the Sun, Earth, and Mars resemble those in Figure 1A? Sketch the relative positions of the Sun, Mars, and Earth as they appear on your screen. Connect Sun-Earth-Mars with a dashed line. (Make your sketch in the form of Figure 1A. Use the space provided on the last page of the lab.) Use Starry Night College to determine the exact time of Opposition. How different is it from the time you estimated from retrograde motion?*

Now jump ahead to position 1.

> ***Question 2:*** *Do the relative positions of the Sun, Earth, and Mars resemble those in Figure 1B? Sketch the new positions of the Sun, Mars, and Earth as you did in Question 1. Connect them with a dashed line*

Finally, jump ahead to position 2

> ***Question 3:*** *Do the relative positions of the Sun, Earth, and Mars resemble those in Figure 1C? After this 687-day jump, did Mars return to the same place in its orbit as in Question 2? Sketch the new positions of the Sun, Mars, and Earth as you did above. Connect them with a dashed line.*

We're now ready to check your Mars distance. With the date set to that at position 2, click on the Cursor Menu and select **Angular Separation**. **Now drag a line between Mars and the Sun and their current separation will be displayed in units of AU.** Enter this result in Table 4.

> ***Question 4****: How well did you do? Comment on the consistency of your measurement using triangulation* with *the distance given by Starry Night Pro above. Did you get the same answer?*

To answer this question, you must have some idea of the uncertainty in your results. To get a handle on this, change one of the β angles by, say + or - 2° and redraw one of the lines in your picture (add a dotted line to your figure to show this). Re-measure the resultant position of Mars. How does a small change on the measured angle affect your resultant Mars-Sun distance? (NOTE! If your measurement differs from the actual value by more than can be accounted for by a small error in the angles, there is something wrong with your measurements, check them!)

Finally, if you look closely at Mars' orbit on the screen, you'll notice something that Kepler discovered; namely, that Mars' orbit is not a circle and its distance from the Sun is not constant. We'll explore this further in a future lab, but for now determine the minimum and maximum distances of Mars from the Sun, by moving Mars to various points in its orbit and repeating the distance measurement you did with the Angular Separation cursor. Record these minimum and maximum differences in **Table 5**. Compute the percentage change in Mars' distance from the Sun and enter that in **Table 5.**

The Earth's orbit is much more circular than Mars'. The difference between its minimum distance from the Sun (which occurs in January) and its maximum distance (which occurs in July) is only about 1.4%.

Question 5*: If Earth's orbit were as noncircular as Mars' orbit – but had the same size it does now and, thus, the same orbital period − would we notice any differences? Explain*

Table 1: Determination of the Time of Martian Opposition

	Calendar Date (mm/dd/yyyy)	Local Time (hh:mm:ss)	Julian Date (days)
Beginning of Retrograde Motion			
End of Retrograde Motion			
Time of Opposition (retrograde midpoint)			

Table 2: Mars-Earth-Sun Angles

	Calendar Date (mm/dd/yyyy)	Julian Date (days)	β (°)
Position 1			
Position 2			

Table 3: Graphical Determination of the Mars-Sun Distance

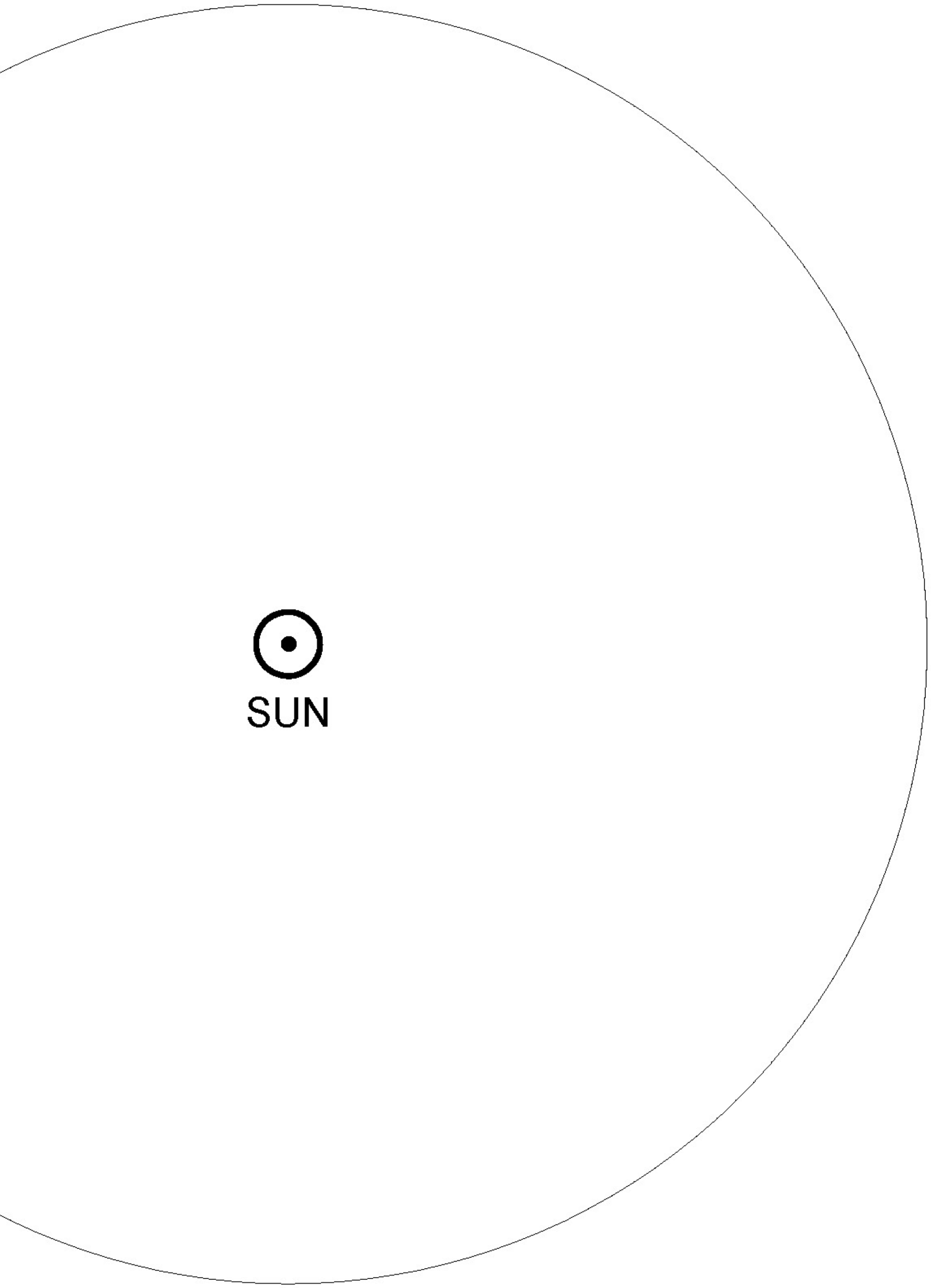
Mars-Sun distance (mm)	
Earth-Sun distance (mm)	
Mars-Sun distance (AU)	

Table 4: *Starry Night College* Measurement of the Mars-Sun Distance

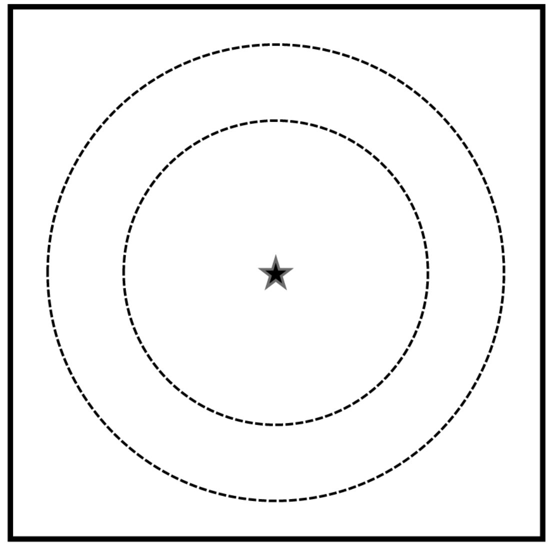
Calendar Date (mm/dd/yyyy)	
Mars-Sun distance (AU)	

Table 5: *Starry Night College* Determination of Mars' Orbital Extremes

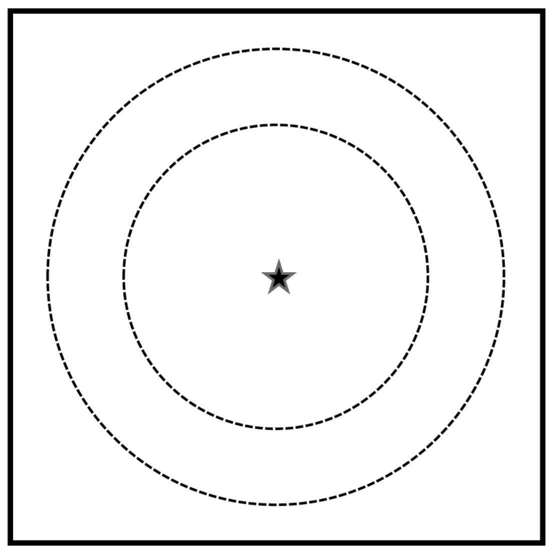
Minimum Mars-Sun distance (AU)	
Maximum Mars-Sun distance (AU)	
Percentage Change (Max-Min)/Average*100%	


SUN

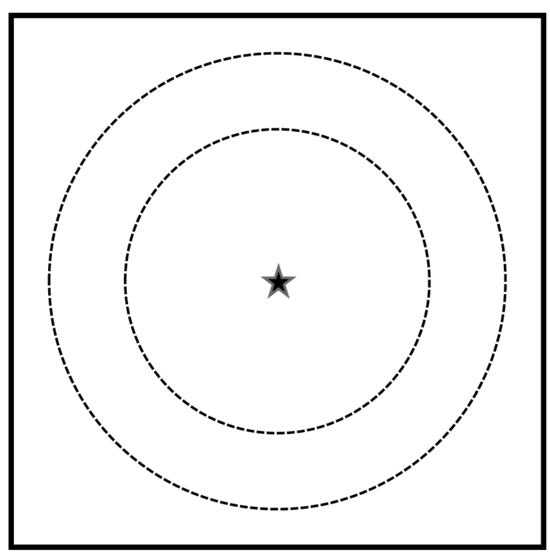
Question 1 Sketch:



Question 2 Sketch:



Question 3 Sketch:



Lab Report Cover Page

Astronomy Laboratory - Planets
Mendel Science Experience 2150
Fall 2025

Lab F
<u>Kepler's Determination of the Orbit of Mars</u>

Name: ____

Lab Section: __________

Date: __________

Lab G
Gravity, Orbits, and Kepler's Laws[1]

PURPOSE:

To study the motions of objects under the influence of gravity.

EQUIPMENT:

PhET interactive simulation program *Gravity*; EXCEL spreadsheet

[1] Adapted from the Phet lab material: http://phet.colorado.edu/en/

Introduction

Gravity is one of the four fundamental forces in nature. It is the weakest of the natural forces, yet it affects all matter across the extent of the entire universe and holds planets and binary stars in their orbits. What causes gravity is still not completely known but its effect on matter can be easily observed and measured. Systematic studies of gravity were carried out by Galileo and Newton in the 15^{th} and 16^{th} centuries and the fundamental laws they uncovered are, essentially, what modern astronomers use in the study of the universe today.

Because gravity is always attractive and pervades the universe, it is not possible for two bodies to remain at rest in empty space. There will always be a calculable attractive force between them. In this lab we will make observations and measurements to study the motion of bodies under the influence of gravity and verify the Three Laws of Orbital Motion discovered by Johannes Kepler.

Experimenting With Gravity

Open the program *Gravity.jar*[2] on your computer. Check that the following options are set or checked:

- Check box for System Centered
- Check box for Show Traces
- Check box for Show Grid
- Slider set to "Accurate"
- Number of bodies set to 2

PART A: BODIES OF EQUAL MASS

Set up the simulation as follows:

- Mass of both bodies = 200
- Position of body 1: X= -200, Y=0
- Position of body 2: X= +200, Y=0
- Velocities for both bodies: X=0, Y=0

The objects are now sitting at rest with respect to each other and the simulation will show us how the combined gravitational attraction that the two objects feel for each other affects their motions. Start the simulation by pressing the green START button. ***Carefully observe the motions of the two bodies.*** Note that there is a clock in the lower right of the simulation to allow you to time the various motions. When the action stops, you can hit the red STOP button to freeze the clock. The red RESET button will return the simulation to its starting conditions. Repeat this several times and then run the simulation several times with both masses set to 100, then with both masses set to 50, and then with both masses set to 25.

> ***Question 1:*** *How would you describe what you have just observed? You must address the following questions: In which direction do the two bodies move? How does their speed vary during the simulation? Do they speed up (accelerate)? Or slow down (decelerate)? Or move at constant velocity? How do the speeds of the two bodies compare to each other? Is one faster than the other? Where is their "meeting point" with respect to their original positions? How did the*

[2] Available from PhET website: http://phet.colorado.edu/en/simulation/my-solar-system

simulation change when you decreased the masses? Did the bodies move faster or slower? How did the time required for them to "meet" change when you change the mass? Does the strength of the gravitational attraction between the bodies appear to depend on their masses?

PART B: BODIES OF UNEQUAL MASS

Set up the simulation as follows:

- Mass of body 1 = 200
- Mass of body 2 = 100
- Position of body 1: X= -200, Y=0
- Position of body 2: X= +200, Y=0
- Velocities for both bodies: X=0, Y=0

Run the simulation several times, carefully observing the motions of the two bodies. Next, rerun the simulation several times with the mass of body 2 set to 50, then set to 25, and finally set to 1.

Question 2: *How has the simulation changed from the case of equal masses? You must address the following questions: Does each object still move in the same sense as you observed above (i.e., speed up, slow down, or move at constant velocity)? Do the bodies still move at equal speeds? If not, which one accelerates faster? Do they still meet in the middle? If not, which one has to move the farthest? Overall, does the combined gravitational attraction of the two objects for each other have a bigger effect on the motion of the more massive object or the less massive object?*

Question 3: *Imagine an extreme case, where the mass of body 1 is, say, 50,000 times greater than that of body 2. What do you think would happen if we ran such a simulation?*

If you think about it, you have probably already performed the above simulation many times in real life: we call this "dropping" something.

Set the simulation up as follows:

- Mass of body 1 = 500 (Earth)
- Mass of body 2 = 0.01 (the thing you're dropping)
- Position of body 1: X= -200, Y=0
- Position of body 2: X= +200, Y=0
- Velocities for both bodies: X=0, Y=0

You can use the mouse to click and drag the ball around the grid. Try a few experiments placing the ball at different locations on the grid and releasing it by pressing START.

Question 4: *Based on your experiments, what direction does something fall when we "drop" it? In other words, how does gravity influence what we mean by the word "down"?*

Experimenting With Orbits

We've seen that the force of gravity acts to draw two bodies together. Yet we've also seen, from everyday experience, that this fate can somehow be averted. For example, the Earth and Sun are gravitationally attracted to each other, but the much-less-massive Earth has not fallen into the much-more-massive Sun. Likewise, with the Moon and the Earth, etc.

We could imagine a situation where the two bodies are a star and a planet. Typically, the mass of the star is much larger, so set the simulation as follows:

- Mass of body 1 (star) = 200
- Mass of body 2 (planet) = 1
- Position of body 1: X = 0, Y=0
- Position of body 2: X=100, Y=0
- Velocity of body 1: X=0, Y=0

Clearly from your earlier experiments, a motionless planet will fall toward a star. But what if the planet is in motion? Will it still fall into the star? Try adding a positive X-velocity to the planet, say 150 units, and press Start. Try different values of the X-velocity, both larger and smaller than 150 units.

> ***Question 5:*** *How does the planet move when you give it an initial positive X-velocity (i.e., a motion directly away from its star? Will adding enough X-velocity eventually prevent the planet from falling into the star? If so, can this explain how the Earth avoids falling into the Sun?*

There is another, more interesting, way for a planet to avoid falling into its star. Namely, by establishing an "orbit." In this case, the planet has an initial velocity which is perpendicular to the direction to the star. Set the planet's velocity to X=0 and Y=10. Start the simulation and observe what happens. Now increase the Y velocity, until the planet just misses the star. **Now you have an orbit!** (Notice that, in the simulation, the orbit may pass inside the body of the star. That's because the calculations assume that the star and planet are point masses with all of their mass concentrated at the center.)

> ***Question 6:*** *How does the planet move when you give it an initial Y-velocity? How does this motion change as you increase the Y-velocity? What is the* <u>*precise*</u> *minimum Y-velocity you need for the planet to avoid hitting the star as it falls towards it**? (I.e., the planet must pass just above the surface of the star.)*** *Describe the shape of the path that the planet follows at this minimum initial velocity. Does it matter if the planet's initial Y-velocity is pointed up or down (i.e., positive or negative)? If so, what effect does the direction have?*

Now let's see what happens if the planet is moving faster than the minimum orbital velocity. Keep increasing the Y-velocity of the planet (by, say, 10 units at a time) and observe the changing shape of the orbit. It should eventually become circular

> ***Question 7:*** *How does the shape of the orbit change as you increase the planet's initial Y-velocity? At* <u>*precisely*</u> *what Y-velocity does the orbit look circular? (You can tell from the grid – the planet should pass through the point [X, Y]= [-100, 0] on the other side of the star when the orbit is a circle.) Describe the shape of the orbit if you make the initial velocity* <u>*larger*</u> *than the circular velocity? (Try several values.) How do the points of minimum separation and maximum separation change when the velocity goes from less than the circular speed to greater than the circular speed?*

Kepler's First Law

The orbits of the planets are ellipses, with the Sun at one focus

In the 1600's, the German astronomer/mathematician Johannes Kepler first observed that the orbits of the planets are not, in general, circles. As you just observed above, a circular orbit requires a very specific initial Y-velocity. At larger and smaller values than this, the orbit will be oval-shaped. More precisely, and as first discovered by Kepler, the planetary orbits are *ellipses*. An ellipse is a very specific type of oval. We don't need to worry about the mathematics here, but we can how a simple method to draw an ellipse.

As shown in Figure 1[3], we stick two pins through a piece of foam board and place a loop of string around them, leaving some slack in the string. Next use the pencil tip to pull the string taut. Move the pencil to trace out a curve on the paper, keeping the string taut. The shape traced out is an ellipse. The location of each pushpin is called a *focus* (plural: *foci*) of the ellipse. Half of the longest distance on the ellipse is called the semi major axis and is designated by the letter '*a*'. The letter '*b*' is used to designate the semi minor axis. The minor axis is located at right angles to the major axis, and passes through the center of the ellipse.

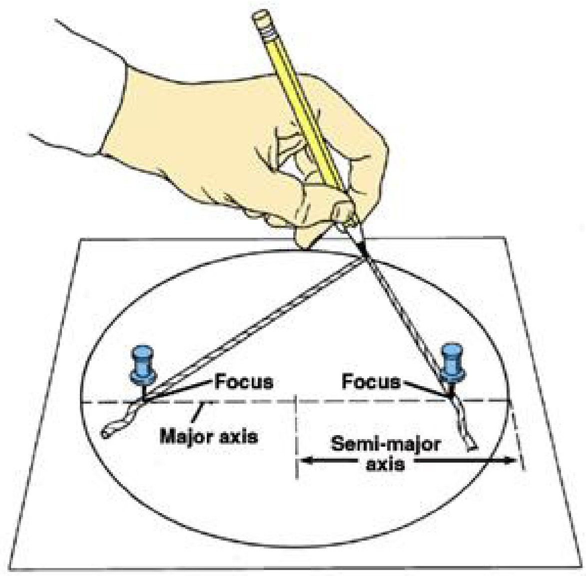


Figure 1

In your simulations above, the "star" was always located at one focus of the elliptical orbits traced out by the "planet." There is no object located at the other focus. The point at which a planet passes nearest its star is called *periapse* and the point at which it is farthest is called *apoapse*. (If the star is the Sun, these points are called *perihelion* and *aphelion*).

> ***Question 8:*** *What would happen to the* <u>*shape*</u> *(not the size) of the ellipse in Figure 1 if the length of the strings were kept the same but the distance between the two foci (i.e. the pushpins) were increased? Decreased? What shape would you get if the two pushpins were in the same place, i.e., at the center of the ellipse?*

[3] http://mail.colonial.net/~hkaiter/Gravity_Inertia.html

Kepler's Second Law:

A planet's speed varies during an orbit

From careful observations of the motions of the planets in the night sky, Kepler also discovered that the orbital speeds of the planets vary in a very regular and predictable way. We can observe this, in speeded-up form, with the gravity simulator.

Change the parameters of the simulator as follows:

- Mass of body 1 (star) = 200
- Mass of body 2 (planet) = 1
- Position of body 1: X = 0, Y=0
- Position of body 2: X=100, Y=0
- Velocity of body 1: X=0, Y=0
- Velocity of body 2: X=0, Y~35-40 units larger than the circular orbit velocity you found above

Start the simulation and carefully observe the motion of the planet.

Question 9: *How does the speed of the planet vary as it travels around its star? Where is the planet when it is moving fastest? Where is it when it is moving slowest? Where does the planet spend more time – at periapse or apoapse?*

<u>Kepler's Third Law:</u>

Orbit speed vs. orbit size

Kepler's third major discovery was a precise relationship between the size of a planet's orbit, and its orbital period (i.e., how long it takes to complete one full orbit.)

Set the parameters of the simulator as follows:

- Mass of body 1 (star) = 200
- Mass of body 2 (planet) = 1
- Position of body 1: X=0, Y=0
- Velocity of body 1: X=0, Y=0

To begin the simulation, set the (X, Y) position of the planet (body 2) to (50, 0). For those values and each of the other X positions in the table below, determine the <u>precise</u> Y-velocity for a <u>circular orbit</u> and measure the time for one orbit. (For each X value, a circular orbit will cut the grid the same distance to the left and right of the star. You can use the *Tape Measure* feature of the program to measure the distance to the orbit from the star on each side of the star.) Note that, since we are looking at circular orbits, the starting X position of the planet is the same as its orbital radius (or semi-major axis), and the starting Y-velocity is the orbital velocity.

Orbital Radius (starting X-position)	Orbital Velocity (starting Y-velocity)	Orbital Period
50		
100		
150		
200		
250		

Transfer these values to an Excel spreadsheet, labeling each column.

Now make a plot of Orbital Velocity (y-axis) vs. Orbital radius (x-axis). Be sure to scale and label your plot appropriately. Fit a trend line to the data points and determine which type of line best fits your data. This is most easily done by checking the boxes for "Display Equation on Chart" and "Show R-squared Value on Chart". The R-squared value is a "goodness of fit" parameter and should be as close to 1.000 as possible. Try the different trendline options, finding the one for which R-squared is closest to 1.0. Ultimately, you should find that a power law – labeled "Power" in Excel – gives the best fit to the data, without systematic deviations. **Use the power law for your final fit to the data**.

Do the same as above for Orbital Period (y-axis) vs. Orbital Radius (x-axis). Find the best-fitting trendline and print the Equation and R-squared value on the graph. Once again, you should see that a power-law provides the best fit to the data. **Use the power law for your final fit to the data**.

Your two graphs should show you that orbital speeds and periods are very strong and well-determined functions of the orbit size. This was first discovered by Kepler and has become known as Kepler's Third Law, or Kepler's Harmonic Law. More specifically, Kepler discovered that:

$$Orbital\ Period^2 = C \times Orbital\ Radius^3 \quad (1)$$

which can be simplified to:

$$Orbital\ Period = K \times Orbital\ Radius^{1.5} \quad (2)$$

where C and K are constants, whose precise values depend on the masses of the star and its planets.

> ***Question 10:*** *Is Kepler's Third Law consistent with your results from the gravity simulation? I.e., are Orbital Period and Radius related as predicted in the equations above? How do you know this? (Note that the values of C or K are not important for this comparison.) Include your Excel table and graphs in your lab writeup)*

> ***Question 11:*** *In our own Solar System, the dwarf planet Pluto, which has just been visited for the first time by a spacecraft, has an orbital radius about 40 times larger than the Earth's orbit. Using the Harmonic Law, approximately what is the orbital period of Pluto* ***? (Note: if you use units of years and Astronomical Units, then the values of C and K in Equations (1) and (2) become 1.)*** *How many times has Pluto gone around the Sun since Kepler died in 1630? (Show all work.)*

Lab Report Cover Page

Astronomy Laboratory – Planets
Mendel Science Experience 2150
Fall 2025

Lab G
<u>Gravity, Orbits, and Kepler's Laws</u>

Name: ____

Lab Section: __________

Date: __________

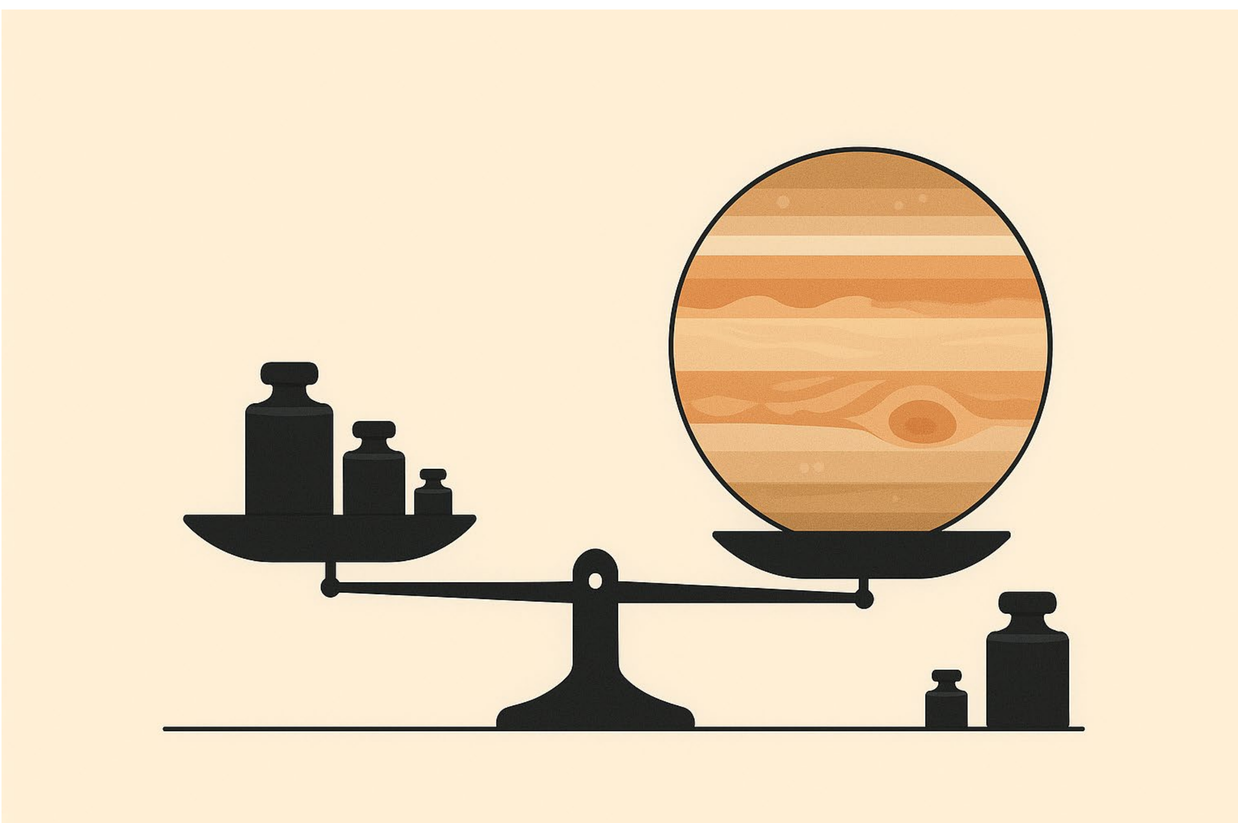
Lab H
Measuring the Mass of Jupiter

PURPOSE:

To determine the mass of the planet Jupiter by measuring the orbital properties of several of its moons and utilizing Newton's version of Kepler's Harmonic Law.

EQUIPMENT:

CLEA Computer Program *Revolution of the Moons of Jupiter*, *Excel* spreadsheet



Historical Background

In 1609, Galileo Galilei heard of the invention of a new optical instrument by a Dutch spectacle maker, Hans Lippershey. By using two lenses, one convex and one concave, Lippershey found that distant objects could be made to look nearer. This instrument was called a telescope. Without even having seen an assembled telescope, Galileo was able to construct his own telescope with a magnification of about three. He soon perfected the design and construction of the telescope and became famous as the builder of the world's best telescopes. Galileo's best telescopes had a magnification of about thirty. Last week in lab, you built a replica of one of Galileo's telescope.

Galileo immediately began observing celestial objects with his crude instrument. He was a careful observer, and soon published a small book of his remarkable discoveries called the *Sidereal Messenger*. One can imagine the excitement these new discoveries caused in the scientific community. Suddenly, a whole new world was opened! Galileo found sunspots on the Sun, and craters on the Moon. He found that Venus had phases, much as the Moon has phases. He was able to tell that the Milky Way was a myriad of individual stars. He could see that there was something strange about Saturn, but his small telescope was not able to resolve the rings.

One of the most important discoveries was that Jupiter had four moons revolving around it. Galileo made such exhaustive studies of these moons that they have come to be known as the "Galilean" satellites. This "miniature solar system" was clear evidence that the Copernican theory of a Sun-centered ("heliocentric") solar system was physically possible.

In this lab, you are going to repeat Galileo's observations Jupiter's system of moons and use measurements of their orbital properties to determine Jupiter's mass.

Kepler's Harmonic Law

As we saw in a recent lab, Johannes Kepler discovered that the orbital sizes ("*a*") and periods ("*P*") of the planets in the Solar System are proportional to each other. This is known as the "Harmonic Law" and can be written:

$$P^2 = C \times a^3 \tag{1}$$

where C is a constant for proportionality whose value depends on the units used to measure *P* and *a*. Kepler didn't know why this relationship existed nor what the proportionality constant *C* represented. Isaac Newton later showed that Kepler's Law applies to any two objects orbiting each other and results from the Universal Law of Gravity. The full form of the Harmonic Law is given by:

$$P^2 = \frac{4\pi}{G(M_1 + M_2)} a^3 \tag{2}$$

where *G* is the "Gravitational Constant" and M_1 and M_2 are the masses of the two objects orbiting each other (e.g., the Sun and a planet). In a system where one body is much more massive than the other, such as in a Sun-planet or planet-moon system, only the mass of the larger body need be considered and **Equation (2)** reduces to:

$$P^2 = \frac{4\pi}{GM_1} a^3 \tag{3}$$

Where M_1 is the mass of the larger object. We can now rewrite **Equation (3)** to solve for M_1 in terms of the values of *P* and *a* for an object orbiting around M_1:

$$M_1 = \frac{4\pi^2}{G} \frac{a^3}{P^2} \tag{4}$$

In this lab, you will determine the values of *a* and *P* for the Galilean moons of Jupiter and then use Equation (4) to calculate M_1, the mass of Jupiter.

Jupiter’s Moons

The four Gallilean moons of Jupiter are named Io, Europa, Ganymede and Callisto, in order of distance from Jupiter. (You can remember the order by the mnemonic "*I Eat Green Carrots*.") Sometimes they are also referred to as I, II, III and IV. If you looked at Jupiter through any small telescope, the picture might look like this:

Figure 1: Jupiter and its Moons as seen through a telescope

The moons appear to be lined up because we are looking edge-on to the orbital plane of the moons around Jupiter. Each day, the alignment of the four moons changes because, as time goes by, the moons will move about Jupiter. While the moons move in roughly circular orbits, you can only see the apparent, or projected, distance of the moon to the line of sight between the Earth and Jupiter (i.e., $R_{apparent}$). The situation looks like this:

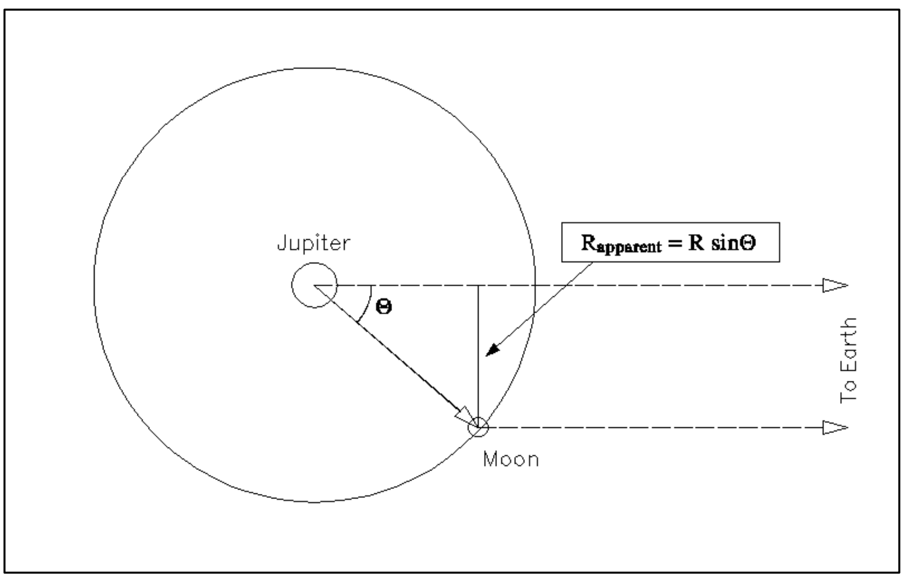


Figure 2: View of Jupiter and one of its moons from “above.”

Therefore, the apparent distance of the moon from Jupiter should be a sinusoidal curve if you plot it versus time. **By taking enough measurements of the observed apparent position of a moon, you can fit a sine curve to the data and determine the radius of the orbit (the semi-amplitude of the sine curve) and the period of the orbit (the period of the sine curve).** Once you know the radius and period of the orbit of that moon and convert them into appropriate units, you can determine the mass of Jupiter by using Newton’s modification of Kepler's Harmonic Law.

Acquiring The Data

In this lab, you will measure the apparent positions of Jupiter's Galilean satellites over a roughly two-week period, with observing sessions spaced 12 hours apart. The data could be obtained using a small telescope or binoculars over several weeks of good weather and little sleep. However, in the interests of time and comfort, you will use a computer simulation program called *The Revolution of the Moons of Jupiter* to replace the actual outdoor observing sessions.

The program simulates the operation of a computer-controlled telescope with a camera that sends a video image to the computer screen. It has a sophisticated program that allows convenient measurements to be made at the computer. The simulation is realistic in all important ways and using it will give you a good feel for how astronomers collect data and control their telescopes. The computer simulation will show you telescopic views of the Jupiter system (such as in **Figure 1**) and allow you to measure the apparent separations of the moons from the center of Jupiter, in units of Jupiter diameters (D_J). It is based on the actual orbital data for each satellite and, if you were to set the simulation for today's date and time, you could verify the position of the Jovian moons by direct observation through the telescope at Villanova's Public Observatory.

SETTING UP THE PROGRAM:

Launch *The Revolution of the Moons of Jupiter* program by double clicking on its icon. Click **File, Log In...** to enter the STUDENT ACCOUNTING screen. Enter your name and then click **OK.** Select "The Revolution of the Moons of Jupiter" from the list of possible exercises, followed by **OK**. Now click **File, Run…** and a dialog box will open so that you can tell the computer the date you wish to begin your observations. Each student will perform and analyze a *different* set of observations based on the date of your birth. In the **Universal Time (UTC)** dialogue box enter the Year, Month, and Day of your birth. Unless you know at exactly what time you were born, leave the hours, minutes, and seconds at 00:00:00. Click **OK**. The simulation will begin and the main telescope screen, as shown in **Figure 3** below, will open.

Finally, click **File, Timing…** and set the **Observation Step** to 12.0 hours. This will space your observing sessions by half a day.

There are two optional setup features you may wish to use:

- click **File, Features…** and check the box **Use ID colors,** to color code the moons, making it easier to find the ones whose orbits you will measure.
- click **File, Features…** and check the box **Top View**, to open a second window showing a "top down" view of the Jupiter system and showing the actual locations of the moons in their orbits.

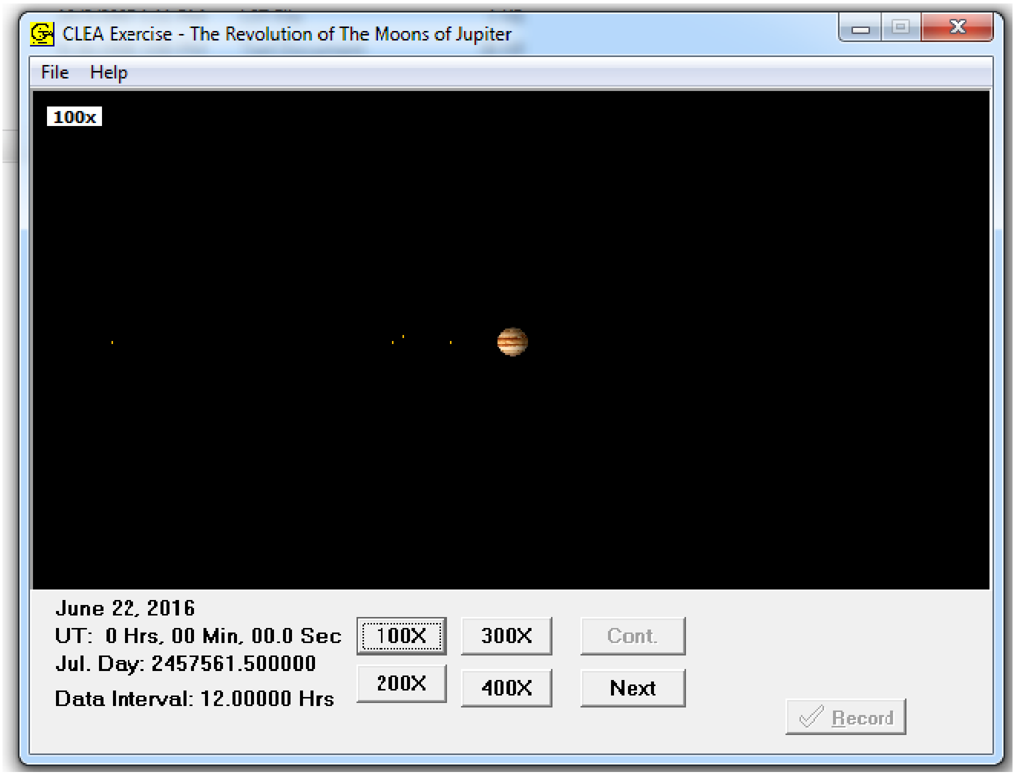


Figure 3: The Main Telescope Screen

THE MAIN TELESCOPE SCREEN:

You control the observing session from this screen. Notice that Jupiter is displayed in the center of your computer screen. To either side are the small point-like Galilean satellites. Even at high magnifications, they are very small compared to Jupiter. The Julian Date and UTC time (the time in Greenwich, England) are displayed in the lower left part of the screen, as well as the date. The magnification of the telescope can be controlled by clicking the magnification buttons. Try it now. In the upper left, you can click on a **Help** screen, or quit the program altogether (**File, Exit**). You cannot continue where you left off if you quit the program.

TAKING DATA:

(Read this whole section before taking data!!!)

Center the computer cursor on a moon. By pressing down and holding the left mouse button the measurement system turns on. When the cursor is positioned over a moon the display in the lower right shows the moon's name and the number of D_J the moon is away from the center of Jupiter (X= **.**). Notice that the edge of Jupiter is 0.5 D_J.

Begin the data collection process by recording the positions of the 4 moons on the attached data sheet or on the EXCEL spreadsheet provided by your instructor:

Column 1: Sequential day number, such as 1.0, 1.5, 2.0, etc.

Column 2: Universal Date
Column 3: Universal Time
Columns 4 -7: Enter the values of D_J in the columns for the appropriate moons

Use positive values of D_J for positions West of Jupiter and negative values for positions East of Jupiter. For example, if Callisto is selected and had X=2.20W, this becomes +2.20 in column 7. If, on the other hand, the moon Ganymede is 5.85 D_J East of Jupiter, this would become –5.85 in column 6.

To measure a moon, use the highest magnification that leaves the moon on the screen. **It is important to use the highest magnification possible for the best accuracy in centering the cursor.** When the moons are far away from Jupiter, you must use lower magnifications to get them in your field of view so you can measure them. But remember to again increase magnification as soon as you can. Sometimes the moons are so close together that they can't be resolved by the telescope. In that case, try a higher magnification. If they still can't be separated, record them both as the same distance. Sometimes a moon is behind Jupiter, so it can't be seen at all. When that happens, record the distance for that moon as zero.

After you've recorded the data for each moon, press **Next** to move on to the next set of observations. During your observations you may encounter a **Cloudy Night**. (You'll know it when you see it!) In this case, no data can be taken. Fill out the first three columns of the data sheet and leave the last four columns blank (in the case of the EXCEL spread sheet) or write in "CLOUDY" (in the case of the paper datasheet) and press **Next** to move on.

Your completed datasheet should look something like:

Day	Date	Time	Io	Europa	Ganymede	Callisto
1	12/30/17	0.0	+2.90	0.00	-5.85	+2.20
1.5	12/30/17	12.0	-1.35	-3.80	-3.35	-0.25
2.0	12/31/17	0.0	*********	CLOUDY	*********	*********
2.5	12/31/17	12.0	+2.30	-2.25	+3.05	-5.05
3.0	01/01/18	0.0	+1.40	+1.80	+5.60	-7.75
etc.						

Figure 4: Example Data Sheet

How To Analyze The Data

(Read this section before analyzing your data!)

Once all the observations are complete, you will need to analyze your data. The goal is to determine each moon's orbital period *P* and semi-major axis *a* (which, in this case, is the radius of the nearly circular orbits).

By plotting position versus time, you will use your data for each moon to obtain a graph similar to the one shown below in **Figure 5** for an imaginary moon named Triscaleon. Each dot in the figure is one observation of the moon. Note that there are some missing points (e.g., at day 2.0 and 9.0), which is due to bad weather. The smooth curve drawn through the data is what would have been observed if the observations had been spaced in very short intervals and if the measurements were made perfectly. Because the orbit of Triscaleon is regular, i.e., it moves at a constant speed and the orbital radius does not change, the peaks of the curve all have the same absolute values and the peak-to-peak widths are the same. As noted in the discussion of **Figure 2**, this curve is called a *sine curve*. Note that the curve does not have to pass exactly through each of the data points (e.g., look at day 4.0) because the actual individual measurements have some uncertainties.

The orbital period *P* and semi-major axis *a* for Triscaleon can be measured as illustrated in **Figure 5**. The period is the time it takes the moon to travel all the way around Jupiter and return to the same point in the orbit. Thus, any complete cycle in the sine curve is the orbital period. Two examples are shown in **Figure 5**, namely, the time between two adjacent maxima and between two adjacent minima. Note that the time between crossings at $D_J = 0$ is equal to half of the period because this is the time it takes to get from the front of Jupiter to the back of Jupiter, or halfway around.

Figure 2 shows that the maximum apparent separation between a moon and Jupiter occurs when the angle θ is $\pm 90^\circ$. At these times, the apparent separation D_J is exactly equal to the orbital radius *a*. Thus, *a* can be measured from the heights of the maxima or minima in **Figure 5**. Two such possible measurements are indicated in the figure. The sine curve should have the same absolute height at each of the maxima/minima, although there won't necessarily be a measured data point at these positions.

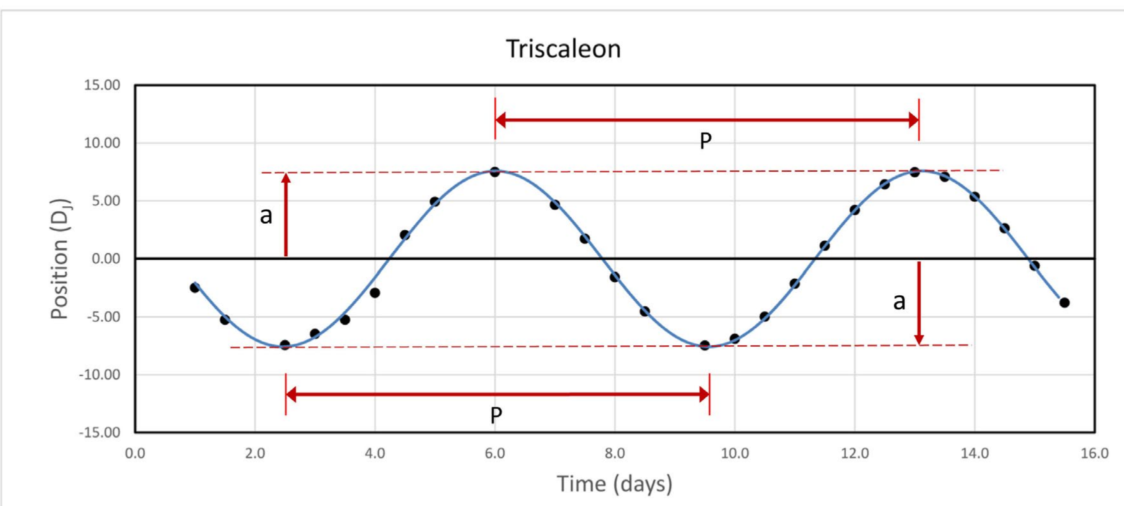


Figure 5: Example Measurements

Analyzing YOUR Data

Using the two pieces of graph paper supplied at the end of the Lab H manual, plot time (from column 1 of the **Table 1**) versus D_J for the moons **Europa** and **Ganymede**. The axes and labels have been supplied for you, so all you have to do is *very carefully* plot the data, using small circles to represent each data point. (You should be able to plot them with an accuracy of ±0.1 D_J.) After you have finished plotting the data, draw in by hand your estimate of the sine curves that best fit the data for each of the moons.

Use Figure 5 for reference and follow the "rules" described in the section above for properly drawing the sine curves! You will be graded on the neatness and accuracy of your plots!!!

Now measure P and a on the graphs for each moon. Use a ruler to measure these values in millimeters, and then convert them to the appropriate units. ***Indicate on your graphs how you determined these values*** and enter them in **Table 2**. The period P, which is measured in units of days, goes in column 2 and the orbital size a, which is measured in units of D_J, goes in column 3. Again, refer to **Figure 5** and the discussion in the section above for how to measure P and a.

You must indicate on your graphs exactly how you measured P and a! I.e., how did you convert from measurements in millimeters to values of P and a?

Finally, compute the mass of Jupiter M_J from the measurements for each moon, using the results of page H-2. By choosing the appropriate units, **Equation 4** simplifies to:

$$M_J = 7.93 \times 10^{10} \frac{a^3}{P^2} \quad \text{kg} \qquad (5)$$

where a is in units of km, P is in units of days, and the resultant value of M_J is in kg. To use this equation, you'll first have to convert your values of a to units of km by multiplying by the diameter of Jupiter, which is 143,000 km. Enter these values of a in column 4 of **Table 2.** After computing the M_J in kg, convert them to units of Earth masses M_E by dividing by the mass of the Earth, which is 5.976×10^{24} kg. Finally, compute the mean values of M_J, in both kg and M_E. Enter all these results in **Table 2**.

Discussion and Questions

Question 1: *How well did you do? Open a browser window and search for the accepted value of the mass of Jupiter, in units of* M_E*. What is it? What is your percentage error? (Remember, Δ% = (your value–accepted value)/accepted value x 100%). What internet source did you use?*

Question 2: *You made two measurements of* M_J*. The values were probably very similar. Should you have expected this or were you just lucky? If you think you should have expected it, why? What was the point of making two measurements?*

Question 3: *Jupiter has many moons, some located very far beyond the orbit of Callisto, which is the most distant of the 4 moons shown in the simulation. Will they have larger or smaller orbital periods than Callisto? Explain why this is to be expected. How would your observing strategy have to be changed to determine the mass of Jupiter from one of these distant moons?*

Table 1: Projected Distances of Jupiter's Moons

Day	Date	Time	Io	Europa	Ganymede	Callisto
1.0		0.0				
1.5		12.0				
2.0		0.0				
2.5		12.0				
3.0		0.0				
3.5		12.0				
4.0		0.0				
4.5		12.0				
5.0		0.0				
5.5		12.0				
6.0		0.0				
6.5		12.0				
7.0		0.0				
7.5		12.0				
8.0		0.0				
8.5		12.0				
9.0		0.0				
9.5		12.0				
10.0		0.0				
10.5		12.0				
11.0		0.0				
11.5		12.0				
12.0		0.0				
12.5		12.0				
13.0		0.0				
13.5		12.0				
14.0		0.0				
14.5		12.0				
15.0		0.0				
15.5		12.0				

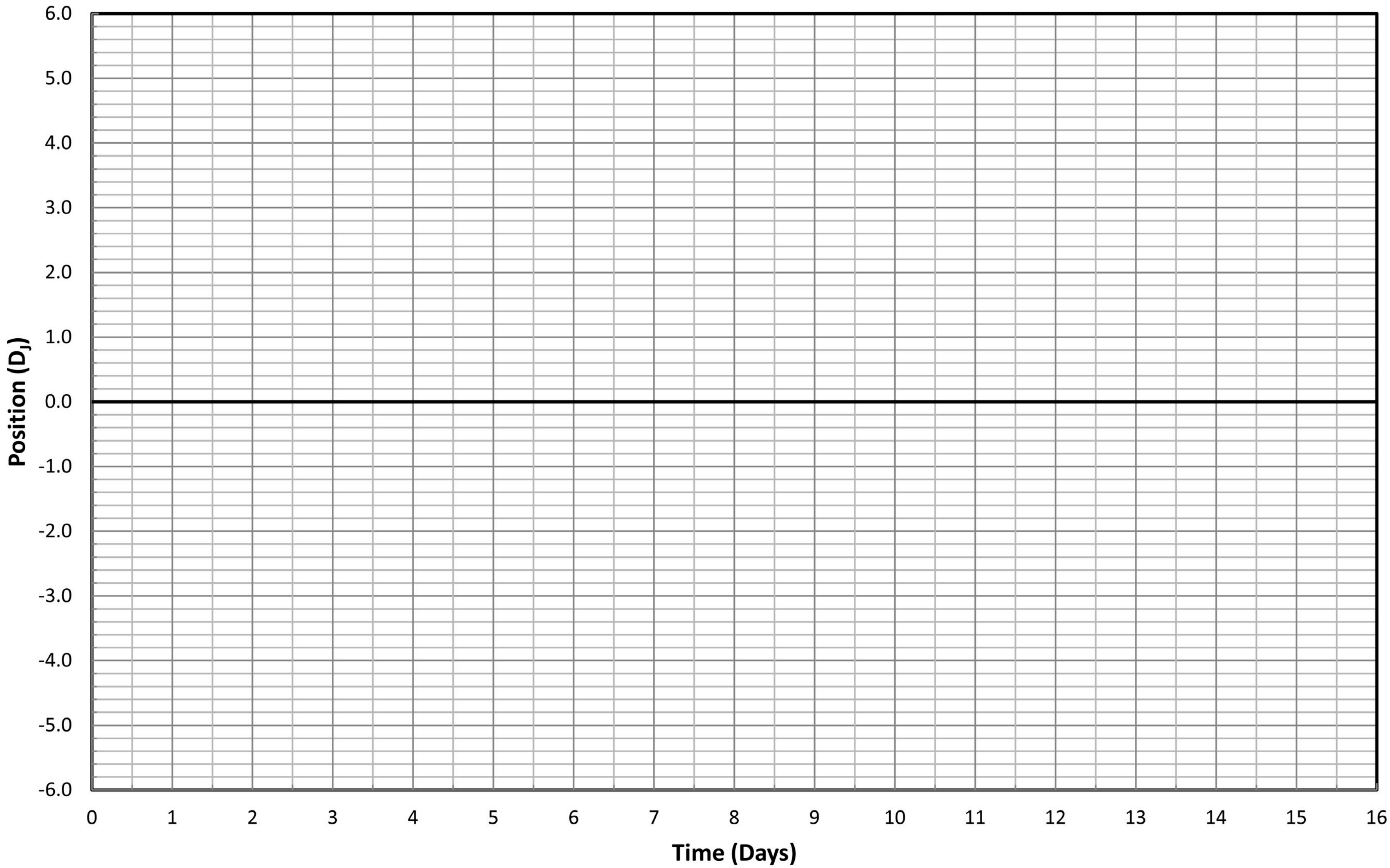
Table 2: The Mass of Jupiter

	P (days)	a (D_J)	a (km)	M_J (kg)	M_J (M_E)
Europa					
Ganymede					
			mean values:		

P = ____________

a = ____________

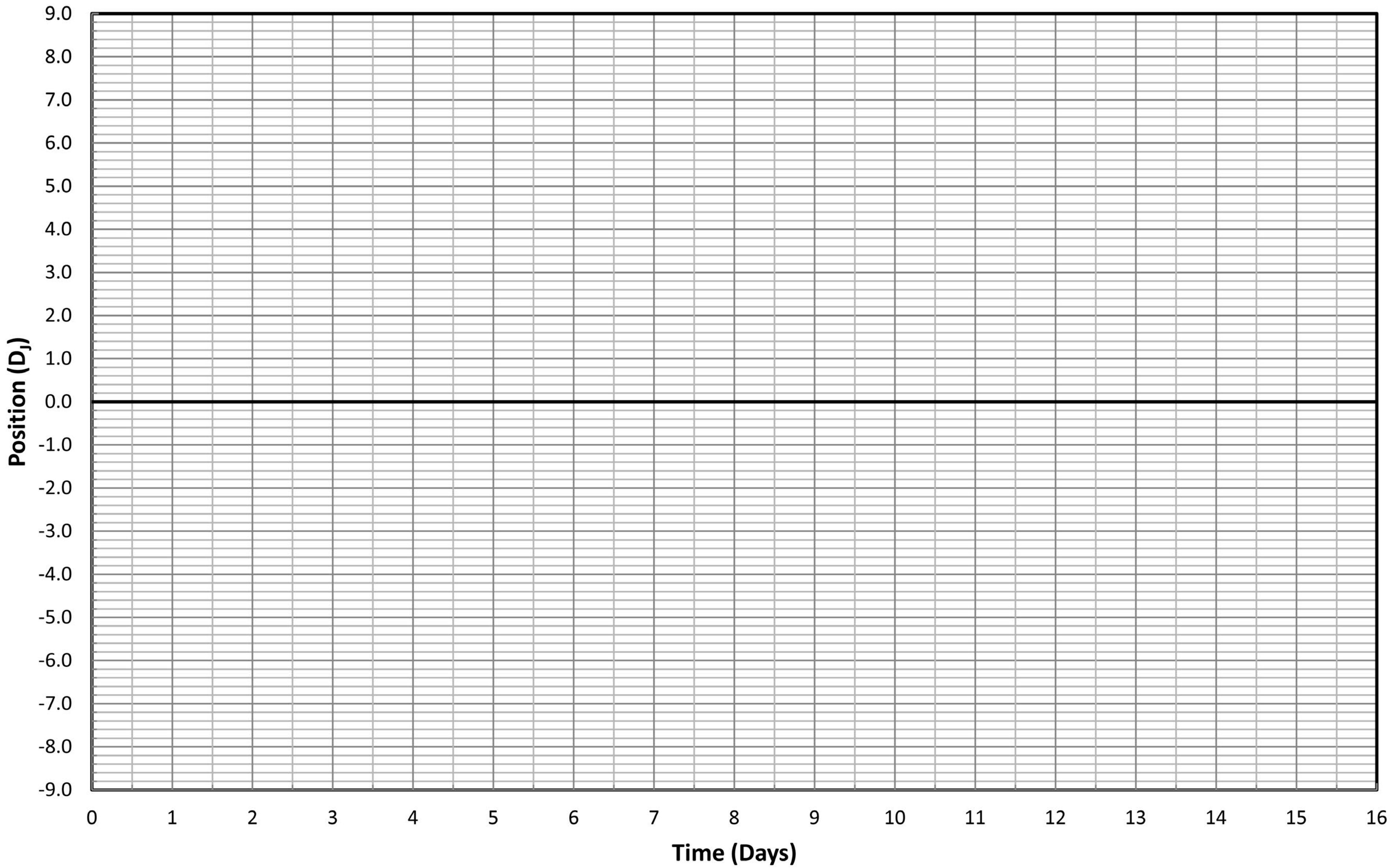
Moon: Europa



P = ___________

a = ___________

Moon: Ganymede



Lab Report Cover Page

Astronomy Laboratory – Planets
Mendel Science Experience 2150
Fall 2025

Lab H
Measuring the Mass of Jupiter

Name: ____

Lab Section: __________

Date: __________

Lab I
Roemer's Measurement of the Speed of Light

Adapted from: Planet Earth, Maloney & Maurone

PURPOSE:

To recreate the technique used by Danish astronomer Ole Rømer to measure the value of the speed of light over 300 years ago.

EQUIPMENT:

Starry Night College computer program, EXCEL spreadsheet

Background

The speed of light ("*c*") is by now a well-known quantity and, as a result of modern electronics and high-precision clocks, can be measured accurately in a laboratory. It is surprising, therefore, to realize that *c* was first measured nearly 350 years ago, long before the age of high-precision instrumentation. In the late 1600's the Danish astronomer Ole Rømer, recognized that Nature actually provides an astronomical "clock," which could be used to determine *c*. That clock is the Jupiter-Io system. Once per orbit, Jupiter's moon Io can be seen to move across ("transit") the face of Jupiter. See **Figure 1**. This occurs at a fixed interval, known as Io's synodic period ("P_{syn}").

The transits of Io across Jupiter are like the ticking of a celestial clock, and P_{syn} is the interval between ticks. We know that this clock runs at a steady, predictable rate because the synodic period of Io depends only on Io's and Jupiter's orbital periods. These orbital periods, in turn, depend only on the sizes of the orbits and the masses of Jupiter and the Sun. (Remember a recent lab?) Since the orbital sizes and the masses do not change with time, the orbital periods do not change with time, and P_{syn} is constant.

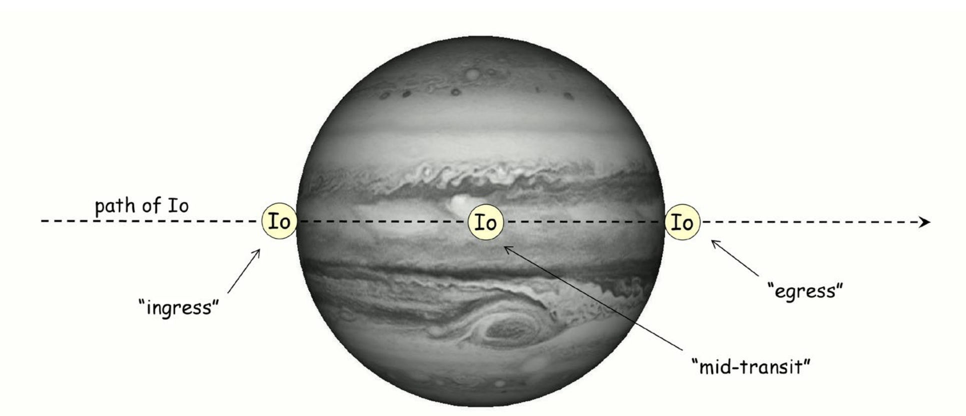


Figure 1: A schematic view of a transit of Io across Jupiter

Ole Rømer recognized this potential and made careful measurements of the regularity of the Jupiter-Io clock. He discovered something puzzling: the clock seemed to periodically speed up and slow down and that these variations were correlated with distance separating the Jupiter system and the Earth! Why should the Jupiter-Io clock care where the Earth is? Roemer realized that this phenomenon indicates that light does not propagate instantaneously through space (a common thought at the time) and that the time it takes the "ticks" to reach Earthly observers changes as the separation between Earth and Jupiter changes. Rømer's observations allowed the first estimate of the speed of light. In this lab you will repeat Rømer's technique and measure the value of *c*, utilizing the *Starry Night College* simulation program to make your observations.

Measuring the Speed of Light

SETTING UP:

Launch the *Starry Night College* program as you have done in earlier labs and set up today's simulation by clicking **Favorites, MSE2150, Speed of Light Lab**. You are now looking at the planet Jupiter. The field of view is 7' wide and shows you what Jupiter might look like through a small telescope. You should also see several of Jupiter's Galilean satellites (Io, Ganymede, and Europa) on the screen, as well as the small moon Amalthea.

The time and date of the simulation is 12 AM on June 7, 1675. This is the time that Jupiter was in "Opposition" in the approximate year that Roemer made his measurements. I.e., Jupiter was in the opposite direction in the sky from the Sun, and at its closest approach to the Earth. (See **Figure 2** below.) You are going to calibrate the Jupiter-Io clock with observations made when Jupiter and Earth are at their closest.

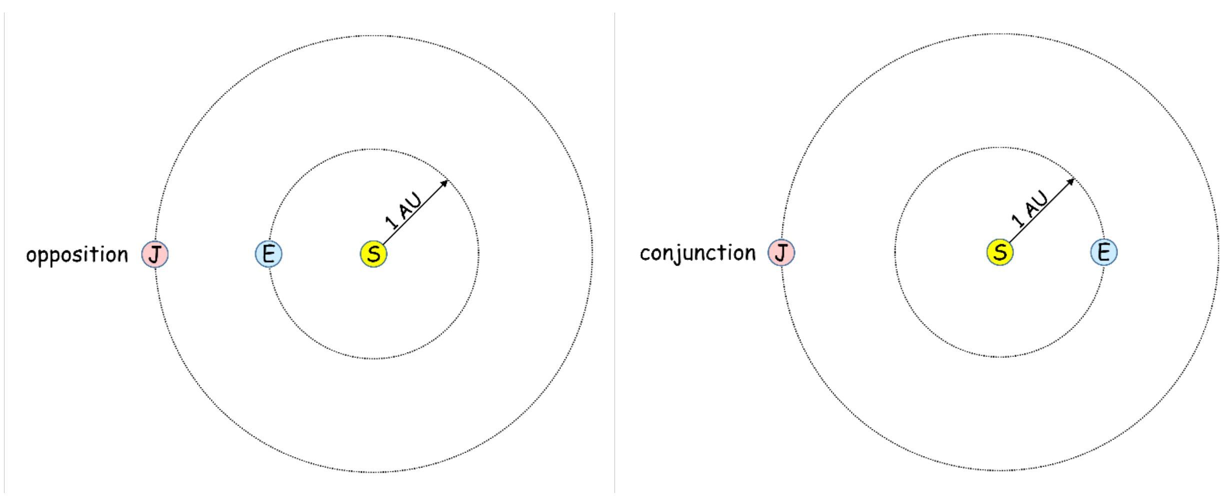


Figure 2: Relative positions of Sun (S), Earth (E), and Jupiter (J) at Opposition (on left) and Conjunction (on right)

<u>MEASURING IO'S SYNODIC PERIOD</u>:

You will now make a precise measurement of the "synodic" period, P_{syn}, for Io. The synodic period is the time it takes specific alignments among astronomical objects to repeat. In this case, you will measure the time it takes Io to go from "mid-transit" to "mid-transit" as viewed from Earth (see **Figure 1**).

Zoom in on Jupiter until it nearly fills your screen. Move forwards in time with *Starry Night College*, first by minutes then, perhaps, by seconds to bring Io to the east limb (left edge) of Jupiter. This time is known as "ingress." (It should occur at around 5 AM on June 7.) From the display in the upper left corner of the screen, record the Julian date of ingress for the June 7 transit in the first row of **Table 1**. Get the most precise estimate you can for the moment of ingress and keep all 5 decimal places of the Julian Date. Next, advance the time by minutes then, perhaps, seconds to find the time of "egress," i.e., when Io moves beyond the face of Jupiter. Record the Julian date of egress in **Table 1**.

Calculate the mid-transit time (the average of ingress and egress) and enter this value into **Table 1**. This would be the time that Io is directly in front of Jupiter. <u>Set the simulation to this time to verify Io's position.</u>

You could now simply move forward in time until the next mid-transit occurs and compute P_{syn} from the elapsed time. The problem with this approach is that the uncertainty in the measurement of P_{syn} will depend strongly on how accurately you are able to measure the two mid-transit times – and will be too large for us to reliably measure the speed of light. Instead, you will do something cleverer and more precise. You will move forward many synodic periods and compute the average synodic period from the total elapsed time divided by the number of periods that have passed by. This greatly increases the precision of your measurement since the uncertainty in measuring the exact time of the first and last mid-transits is now essentially divided among all the transits.

How far ahead should you move? In general, moving ahead in time will cause the distance between Earth and Jupiter to change, resulting in different pathlengths traveled by the "ticks" of the clock and ruining the accuracy of the period determination. However, if we are clever, we can jump ahead to a time when Jupiter is once again in Opposition (see **Figure 2**) and the Earth-Jupiter distance is the same as for the June 7 measurement. This period of time is known as Jupiter's synodic period and corresponds to approximately 224 orbits of Io.

To make this jump, which corresponds to a little more than 396 days, set the Time Step menu to 396 days and make one step ahead. Io will be off your screen, to the east (left) of Jupiter. (Verify this by zooming out using the FOV Box.) Now determine the time of the next transit. Advance the time by hour increments, then minutes, and then, perhaps, seconds to determine the times of ingress and egress, as you did above, and compute the mid-transit time. Record these times in **Table 1**. The date of this transit should be July 7, 1676. <u>Set the simulation to this date and time to verify Io's position at mid-transit</u>.

Compute the total elapsed time (a positive quantity) between the June 7, 1675 and July 7, 1676 mid-transits and enter it in **Table 1**. This is the time it took Io to complete 224 synodic periods. Compute the value of one synodic period(by dividing the total elapsed time by 224 and enter it in **Table 2**. Keep 7 decimal places in this result. Notice that you seem to have gained significant figures in this result. This is because you essentially averaged the results from 224 periods to get your answer.

Now that you have measured the precise synodic period of Io, you can predict when all future transits should occur. You have just calibrated the Jupiter-Io "clock."

PREDICTING A FUTURE TRANSIT:

Let's now "synchronize our watches" by placing Io in its mid-transit position for the July 7, 1676 event (if it's not already there). You can predict when future mid-transits will occur by simply adding multiples of Io's synodic period to this mid-transit time. You will choose a future time when the distance between Jupiter and Earth is significantly different than for the July 7 mid-transit. The most extreme difference will be when Jupiter is at "Conjunction," and the Jupiter-Earth distance is at its largest value. (See **Figure 2**.) This event will occur in a little more than half a year, which is the time it will take the Earth to move to the opposite side of the Sun from Jupiter. This corresponds to about 113 synodic periods. ***Therefore, you will predict when mid-transit should occur for the 113th transit after the July 7, 1676 event.***

Compute the predicted moment of this mid-transit by adding 113 synodic periods to the July 7, 1676 mid-transit time and enter this result in the last column of **Table 3**. Notice the date of this mid-transit. It should occur on January 23, 1677.

To test your prediction, set *Starry Night College* to this time. You should see Io projected on the face of Jupiter, but not quite at mid-transit. Go backward and forward in time to measure the exact moments of ingress and egress for this transit, as you did earlier, and compute the observed moment of mid-transit. Enter all these results in **Table 3**.

COMPUTING THE SPEED OF LIGHT:

Now compute the difference between your predicted and observed January 23 mid-transit times (in both days and in seconds) and enter them in the last rows of **Table 3**. (To convert from days to seconds, you'll need to remember that there are 24 hours in a day, 60 minutes in an hour and 60 seconds in a minute.) You should see that the mid-transit happened a little later than you predicted. This is because Jupiter is now farther away than it was when we "synchronized our watches" with the July 7 mid-transit. The extra distance delayed the arrival of the signal from Jupiter and makes it appear that the clock is running slow.

The size of the time delay you observed is determined by the speed at which light travels and the extra distance traveled by the light on January 23. These quantities are all related by the simple formula:

$$\text{speed of light} = \frac{\text{extra distance traveled}}{\text{time delay}} \tag{1}$$

Because you know two of these three quantities, you can compute the third, i.e., the speed of light.

From considering the relative positions of the planets in **Figure 2**, you can see that the extra distance traveled by light from Jupiter at Conjunction compared to Opposition is *approximately* 2 Astronomical Units (AU). But you can get a more precise value by actually measuring the Jupiter-Earth separations.

Move your viewpoint in *Starry Night College* to a position about 50 AU above the Solar System, looking "down" on the Sun and its planetary family. To do this, select **Favorites, MSE2150, Outer Solar System.** Zoom in until Jupiter's orbit fills the screen. Now set the date and time to the moment of mid-transit on July 7, 1676. Jupiter and the Earth should be on the same side of the Sun and as close to each other as they can get. To measure the separation, select **Angular Separation** in the Cursor Menu. Then drag a line between the Earth and Jupiter. Their separation will appear on the screen, in units of AU. Record this distance in **Table 4**. Move to the moment of mid-transit on January 23, 1677, repeat the measurement, and enter the result in **Table 4**. In this case, you should see Jupiter and Earth on opposite sides of the Sun, and as far apart as they can get. Compute the difference in the distances (in AU) and record it in **Table 4**.

You're now ready to compute your estimate of *c*. Convert the difference in distance you just measured into km and enter it in Table 4. (Remember that 1 AU = 149,600,000 km.) Copy the time delay (in seconds) you measured in **Table 3** into the appropriate place in **Table 4**. Finally, compute the speed of light from Equation 1 and enter it in **Table 4**.

Questions and Discussion

Question 1: *How well did you do? Open a browser and find the accepted value for the speed of light. What is it? What was the percent error in your result? Remember that accuracy can be expressed as a percentage using the formula:*

$$\%\text{E} = \frac{\text{observed value} - \text{accepted value}}{\text{accepted value}} \times 100\% \qquad (1)$$

You should expect your result to be within ~ ±20% of the accepted value. If you are outside this range, go back and check your measurements and calculations.

Question 2: *What do you think were the major sources of uncertainty in your measurements?*

NOTE!
The following questions test your understanding of the lab (and whether you read it!) You may not ask your instructor for help on them.

Question 3: *Why do you think you used the ingress and egress times to determine the moments of mid-transit, rather than just moving Io to the center of Jupiter?*

Question 4: *Explain why you used 224 revolutions of Io around Jupiter to determine the synodic period, rather than simply measure the elapsed time between one mid-transit and the next.*

Question 5: *Explain why we think that the Jupiter-Io system provides a steady, reliable "clock," and thus provides a reasonable way to measure the speed of light.*

Table 1: Elapsed Time for 224 Synodic Periods of Io

	Ingress Time (JD)	Egress Time (JD)	Mid-Transit
June 7, 1675 Transit			
July 7, 1676 Transit			
		Elapsed Time (days)	

Table 2: Io's Synodic Period

$P_{synodic}$ (days)	

Table 3: Predicted vs. Observed Transit Times

	Ingress Time (JD)	Egress Time (JD)	Mid-Transit Time
Jan 23, 1677 Transit - PREDICTED			
Jan 23, 1677 Transit - OBSERVED			
		Time Delay (days)	
		Time Delay (sec)	

Table 4: Your Speed of Light Determination

Earth-Jupiter distance on July 7, 1676	**AU**
Earth-Jupiter distance on Jan 23, 1677	**AU**
Extra distance traveled on Jan 23, 1677	**AU**
Extra distance traveled on Jan 23, 1677	**km**
Time Delay	**sec**
Speed of Light	**km/sec**

Lab Report Cover Page

Astronomy Laboratory – Planets
Mendel Science Experience 2150
Fall 2025

Lab I
Roemer's Measurement of the Speed of Light

Name: ____

Lab Section: __________

Date: __________

Lab J
Comets

PURPOSE:

To examine the general orbital properties of comets and look closely at a few recent visits by Halley's Comet and comet Swift-Tuttle. We will also see some of the consequences of a comet's rapid passage through the inner Solar System.

EQUIPMENT:

Starry Night College and PhET interactive simulation program *Gravity*

Introduction

Comets are visitors from the outer Solar System. They are icy objects, some 10's of km in diameter, which formed far from the Sun. Most remain in the outer Solar System, effectively unobservable from Earth, but a small number have their original orbits disturbed and "fall" into the inner Solar System. As they approach the Sun, they may produce a spectacular display in the sky as the increased level of solar radiation evaporates their icy surface material. This evaporated material, streaming off the surface of the comet, creates the bright tail which is the hallmark of cometary apparitions. Just how spectacular a comet will appear depends on a number of factors, including how close it gets to the Earth and how close it is to the Sun at the time, since the tail is longest and brightest when the comet is closest to the Sun. In the following lab we will first look at the orbital properties of comets in general and then examine a few specific "periodic" comets, which have made repeated visits to the inner Solar System.

Lab Procedure

THE ORBITS OF COMETS:

Open the PhET simulation called *Gravity*[1] on your computer. Check that the following options are set or checked:

- Check box for System Centered
- Check box for Show Traces
- Check box for Show Grid
- Slider set to "accurate"
- Number of bodies set to 2

Now let's create a simple Solar System consisting of the Sun and one distant cometary body:

- For body 1 (the Sun) : mass = 500, [X,Y] position = [0,0] and [X,Y] velocity = [0,0]
- For body 2 (the comet): mass = 0.001, [X,Y] position = [400,0], [X,Y] velocity = [0,112]

In our imaginary Solar System, the cometary body resides far beyond the orbit of Jupiter. Start the simulation and observe the shape and orbital period of the comet. With an orbit like this, the cometary body would always remain far out in the Solar System and likely always be unobservable from the Earth. However, the orbits of cometary bodies may be disturbed, perhaps due to collisions with other distant objects, and the properties of their orbits altered.

"Reset" your simulation and decrease the initial Y-velocity of the cometary body to 40. Start the simulation and observe the comet for several orbits. Note the new shape of the orbit and its period. The smaller starting velocity in this simulation, corresponding to less kinetic energy in the comet, results in a drastically different orbit. The comet is not able to resist the Sun's gravity so well and it "falls" towards the Sun before climbing back to its starting point. **A gravitational interaction with another object, or even a direct collision could rob a comet of kinetic energy and trigger the kind of change in its orbit that you've just observed.**

[1] Available from PhET website: http://phet.colorado.edu/en/simulation/my-solar-system

Question 1: *Describe your observations: What was the original shape of the cometary orbit? What was the semi-major axis (a) of the orbit? Its period (P)? How did the orbit change when the starting velocity was decreased? What is its new shape? Where is the Sun located in the new orbit? What is the new period and new semi-major axis? (Hint: use the Tape Measure and the "time" output of the simulation to make these measurements). Where does the comet spend most of its time in this new orbit? (I.e., where is it moving slowest?) Where does it spend the least time? (I.e., where is it moving fastest?) Does Kepler's Harmonic Law work for comets? According to this law,* $P^2 = C \times a^3$*, where C is a constant. Thus, the ratio* P^2/a^3 *should be the same for both the old orbit and the new orbit. Is this true? (You can consider small differences, i.e., 3-4%, to be due to uncertainties in the measurements.) Enter your results in Table 1.*

In its new elliptical orbit, the comet regularly comes zooming into the inner Solar System, before heading back out to its former home. Such a comet is known as a "periodic comet." As described in the Introduction, the comet begins to evaporate as it approaches the Sun (particularly when inside the orbit of Jupiter), potentially produces a striking display in the nighttime sky.

If the life of a comet were so simple, it would be relatively easy to predict their paths and the return dates of such periodic comets. However, the Solar System is not a simple place and gravitational interactions with objects other than the Sun can influence a comet's orbit

Let's look at a slightly more complex Solar System – one which has a large planet (i.e., Jupiter) in a much smaller orbit than the comet. Set up the simulation as follows:

- Select number of bodies =3
- Body 1 (the Sun): mass = 500, [X,Y] position = [0,0] and [X,Y] velocity = [0,0]
  Body 2 (the comet): mass = 0.001, [X,Y] position = [400,0], X velocity = 0, Y-velocity between 30 and 40
- Body 3 (Jupiter): mass = 1, [X,Y] position = [50,0], [X,Y] velocity=[0,319]

Start the simulation and observe what happens. Watch the comet through at least 10 full orbits.

Question 2: *What do you observe? Is the comet affected by the presence of Jupiter? What effect does Jupiter have on the comet's orbit? After watching a number of orbits, were you able to predict when a noticeable orbit change would occur?*

The "evolution" of a comet's orbit via gravitational interactions with Solar System bodies is a well-known phenomenon, and, in at least one case, had fatal consequences (for the comet). In 1994, the comet Shoemaker-Levy 9 spectacularly crashed into the planet Jupiter. This comet had actually been captured, and broken up into pieces, by Jupiter's gravity before crashing into the planet. In this respect, Jupiter acted as a cosmic "vacuum cleaner." In other cases, interaction with Jupiter may cause a comet to be ejected from the Solar System! All the inner Solar System planets have been victims of cometary collisions in the past. The "Tunguska event" which occurred in Siberia in 1908 may have been Earth's most recent meeting with a comet.

Close the *My-Solar-System* window before proceeding with the rest of the lab.

HALLEY'S COMET:

Halley's Comet is a periodic comet, which reappears once every ~75-76 years. Its highly elliptical orbit extends from beyond the orbit of Neptune ("aphelion") to inside the orbit of Venus ("perihelion"). Halley's Comet most recently appeared in 1910 and 1986. The next visit will not occur until ~2061. The earliest certain sighting of the comet occurred in ~240 BC!

Let's first observe the 1910 apparition of Halley's Comet. Open the program *Starry Night College* by clicking on the *SN7* icon. Set up the simulation by clicking **Favorites, MSE2150, Comet Lab, Halley 1910.** This places you about 4 AU "above" the Solar System (i.e., above the Earth's north pole) and looking down on the inner planets. The inner planets should be labeled, and their orbits shown.
The date is Dec 1, 1909, when Halley's comet was still beyond the orbit of Mars and near the time when it first became visible in the night sky. Begin the simulation by clicking the Play button. Soon Halley's Comet will appear on the screen (it will be labeled "Halley 1910"). When you see it, stop the simulation by pressing the Pause button and turn on the comet's orbit (right click on the comet and check **Orbit**). Although it may appear from the screen that Halley's elliptical orbit actually crosses the Earth's orbit in 2 places (and thus creating a possible collision danger!), this is not so. Halley's orbit is highly tilted with respect to the Earth's orbital plane and currently does not cross the path of any of the inner planets. To see this, click **Location Scroller** in the Cursor Menu, then drag the cursor around the screen to change your point of view.

Now continue moving forward in time. Notice that as the comet moves through space in its elliptical orbit around the Sun it will eventually catch up to the Earth. Carefully estimate the date of closest approach of the comet with Earth. Step both forward and backward in time to get the best estimate. You can read see the Earth-comet separation in the comet's **Info** box or measure the separation using the **Angular Separation** tool in the Cursor Menu. Record the date of closest approach, as well as the comet-Earth distance and comet-Sun distance on this date, in **Table 2**.

Note: As you watch the simulation, you will see another version of Halley's Comet appear on the screen, labeled "Halley (1P)". There are not two different Halley's comets! Interactions with the gravitational fields of the planets alter the orbital properties of Halley's Comet each time it makes an appearance in the inner Solar System. (Recall what you just saw in the first part of this lab!) *Starry Night College* takes this into account by creating different versions of the comet, corresponding to different apparitions. "Halley (1P)" refers to the 1985 apparition, which you can ignore for now.

> ***Question 3**: How is the tail of Halley's Comet oriented on the date of closest approach during the 1910 apparition? Describe it with respect to the Earth's position and with respect to the Sun's position.*

Now let's move on to the most recent apparition of Halley's Comet. Set up the simulation by clicking **Favorites, MSE2150, Comet Lab, Halley 1985.** The view is similar to the one for the 1910 apparition, but the date is now Oct 1, 1985. Once again, you will see two versions of Halley's Comet on your screen. "Halley (1P)" refers to the 1985 apparition; you can safely ignore "Halley 1910".

Start the simulation and find the date of closest approach of Halley (1P) to Earth. Record the date in **Table 2**, along with the comet-Earth and comet-Sun distances on that date.

> ***Question 4**: How is the tail of Halley's Comet oriented on the date of closest approach during the 1986 apparition? Describe it with respect to the Earth's position and with respect to the Sun's position.*

Question 5: *The 1910 apparition of Halley's Comet was reportedly a spectacular event, while the 1986 apparition was considered a disappointment. Describe how this can be understood based on the observations you recorded in Table 2. In particular, consider the comet's distance from the Sun when it is at its closest approach to Earth. (The closer the comet is to the Sun, the more spectacular its tail structure. The closer it is to the Earth, the better our view of it.)*

COMET SWIFT-TUTTLE:

Another periodic comet is Swift-Tuttle (named after its discoverers), with an orbital period of 133 years. The most recent appearance of Swift-Tuttle occurred in 1992. Let's examine this apparition and the next scheduled return in 2126.

Set up the simulation by clicking **Favorites, MSE2150, Comet Lab, Swift-Tuttle 1992.** Once again you are looking down on the Solar system, this time on July 1, 1992. When you see the comet, stop the simulation and switch on Swift-Tuttle's orbit. Then restart the simulation. Swift-Tuttle's highly elliptical orbit has an aphelion beyond the orbit of Pluto and a perihelion of about 1 AU. In contrast to Halley's Comet, Swift-Tuttle's orbit actually does come very close to the Earth's orbit. Verify this by examining the orbit using the **Location Scroller** in the Cursor Menu as you did for Halley's Comet.

Determine the date of closest approach between Swift-Tuttle and Earth during the 1992 apparition. Record this date, along with the comet-Earth and comet-Sun distances on that date, in Data Table 2

Question 6: *Based on your measurements (and comparing with Halley's Comet), do you think the 1992 apparition of Swift-Tuttle was a very spectacular event? Explain your answer.*

Now let's look at the next apparition of Swift-Tuttle (which most of us won't be around to see). Set the date *in Starry Night College* to May 1, 2126 and once again step forward in time until Swift-Tuttle appears in the inner Solar System. Find the date of closest approach for this apparition and record the results, including comet-Earth and comet-Sun distance, in Data Table 2. (Note: to get an accurate measurement, you may have to center/lock on the Earth and zoom in to find the time of closest approach.)

Question 7: *Based on your measurements, do you think the 2126 apparition of Swift-Tuttle will be a very spectacular event? Explain your answer.*

There is actually a non-zero chance of a collision between Swift-Tuttle and Earth in 2126! The actual likelihood of collision won't be known for some time, due the perturbations that occur in cometary orbits due to the influence of other Solar System objects (as you saw earlier in this lab). Hopefully, by then our technology will allow us to deflect the comet and avoid a collision.

(But what about comets presently on a collision course with Earth, possibly arriving in the next few decades?!? Cue the ominous music.)

COMETS AND METEOR SHOWERS:

Since we are still here and comet Swift-Tuttle is still out there, is clear that the Earth has passed safely through Swift-Tuttle's orbit every year for many years in the past. One might wonder whether there are any consequences arising from a planet moving through a comet's path, even when the comet doesn't happen to be nearby. Use your *Starry Night College* simulation to determine the calendar date every year (month and day) that Earth passes through (or as close as possible to) Swift-Tuttle's orbit, then answer the following question:

> ***Question 8:*** *On what date does Earth cross Swift-Tuttle's orbital path? What happens every year when Earth runs through the path? To answer this question, open a browser window and do a search on the "Perseids meteor shower." What day of the year does Earth cross Swift-Tuttle's orbit? When does the Perseids meteor shower occur every year? Is this a coincidence? What is a meteor shower? What is the relationship between Swift-Tuttle and the Perseids? Is this the only example of a connection between a comet and a meteor shower? If not, name another one.*

Table 1: Comet Orbits

	Semi-Major Axis	Orbital Period	P^2/a^3
Original Orbit			
New Orbit			

Table 2: Comets Halley and Swift-Tuttle

	1910 Halley	1985 Halley	1992 Swift-Tuttle	2126 Swift-Tuttle
Date of closest approach… (mm/dd/yyyy)				
Distance to Earth (AU)…				
Distance to Sun (AU)…				

Lab Report Cover Page

Astronomy Laboratory - Planets
Mendel Science Experience 2150
Fall 2025

Lab J
<u>Comets</u>

Name: ____

Lab Section: __________

Date: __________

Lab K
Detecting Extrasolar Planets[1]

PURPOSE:

To examine the two main techniques currently used to detect the presence of planets around stars other than the Sun.

EQUIPMENT:

NAAP computer programs *Exoplanet Radial Velocity Simulator* and *Exoplanet Transit Simulator*

[1] Adapted from the Nebraska Astronomy Applet Project (NAAP) at http://astro.unl.edu/naap/

Background Material

Double-click the **NAAP Labs** icon on your Desktop. Then select exercise 12, *Extrasolar Planets* to bring up the Home page for today's lab. Review the Background Materials pages entitled *Introduction, Center of Mass, Doppler Shift*, and *Detection*[2]. Then complete the following two questions.

Answer questions 1 and 2 using the large versions of the figures found on page K-7 of the lab write-up. Your instructor may require you do answer these questions as a pre-lab exercise.

> ***Question 1:*** *Label the positions on the star's orbit (i.e., the inner orbit) with the letters corresponding to the labeled positions of the radial velocity curve. Remember, the radial velocity is positive when the star is moving away from the earth and negative when the star is moving towards the earth. (see footnote 2 below.)*

> ***Question 2:*** *Label the positions on the planet's orbit (i.e., the outer orbit) with the letters corresponding to the labeled positions of the radial velocity curve. Hint: the radial velocity in the plot is still that of the star, so for each of the planet positions determine where the star would be and in which direction it would be moving.*

The Radial Velocity Technique

You will use now use the *Exoplanet Radial Velocity Simulator* it to investigate the effect that a planet has on a star's radial velocity. In using this simulation, there two important points to remember:

1) "Radial velocity" refers only to the portion of an object's velocity that is along its line of sight. An object moving in a direction perpendicular to its line of sight will have a radial velocity of zero, even though it may be moving very rapidly through space.
2) You are seeing and measuring the velocities of the star, not its planet. The planet is too small and faint to observe directly. Its presence is revealed indirectly, by the effect it has on its parent star.

Click *Exoplanet Radial Velocity Simulator* on the *Extrasolar Planets* Home page. You should note that there are several distinct panels in the Simulator's window:

- A **3D Visualization** panel in the upper left where you can see the star and the planet (magnified considerably). Note that the orange arrow labeled ***earth view*** shows the perspective from which we view the system.
  - The **Visualization Controls** panel allows one to check ***show multiple views***. This option expands the 3D Visualization panel so that it shows the system from three additional perspectives:
- A **Radial Velocity Curve** panel in the upper right where you can see the graph of radial velocity

[2] Note that there is a significant typo in the Background Materials *Detection* page. In the **Radial Velocity Methods** section, the second bullet point should read: " A redshift (yielding positive radial velocities) occurs when a star is moving away from Earth." (The page incorrectly reads "… moving toward Earth.")

versus phase for the star. The graph has ***show theoretical curve*** in default mode. A readout lists the ***system period*** and a cursor allows one to measure radial velocity and thus the ***curve amplitude*** (the maximum value of radial velocity) on the graph. The scale of the y-axis renormalizes as needed and the phase of perihelion (closest approach to the star) is assigned a phase of zero. Note that the vertical red bar indicates the phase of the system presently displayed in the 3D Visualization panel. This bar can be dragged and the system will update appropriately. The length of time covered by 1 unit of orbital phase is the orbit period.

- There are three panels that control system properties:
    - The **Star Properties** panel allows one to control the mass of the star. Note that the star is constrained to be on the main sequence – so the mass selection also determines the radius and temperature of the star.
    - The **Planet Properties** panel allows one to select the mass of the planet and the semi-major axis and eccentricity (i.e., ellipticity) of the orbit
    - The **System Orientation** panel controls the two perspective angles:
        - ***Inclination*** is the angle between the Earth's line of sight and the plane of the orbit. Thus, an inclination of 0º corresponds to looking directly down on the plane of the orbit and an inclination of 90º is viewing the orbit on edge.
        - ***Longitude*** is the angle between the line of sight and the long axis of an elliptical orbit. Thus, when eccentricity is zero, longitude will not be relevant.
- There are also panels for **Animation Controls** (start/stop, speed, and phase) and **Presets** (pre-configured values of the system variables).

CIRCULAR ORBITS:

Select the preset labeled Option A and click set. This will configure a system with the following parameters – inclination: 90º, longitude: 0º, star mass: 1.00 M_{Sun}, planet mass: 1.00 M_{Jup}, semi-major axis: 1.00 AU, eccentricity: 0 (This is equivalent to placing a planet as massive as Jupiter in the Earth's orbit.)

Question 3: *Describe the radial velocity curve. What is its shape? What is its amplitude? What is the orbital period?*

Increase the planet mass to 5.0 M_{Jup} and note the effect on the system and on the radial velocity curve. Now increase the planet mass to 50.0 M_{Jup} and note the effect on the system.

Question 4: *In general, how does the amplitude of the radial velocity curve change when the mass of the planet is increased? Does the shape of the curve change? Explain why this happens. (Hint: When the simulation is running, do you notice anything different when the planet mass is set to* 50.0 M_{Jup}? Think "center of mass."*)*

Return the simulator to the values of Option A. Increase the mass of the star to 1.2 M_{Sun} and note the effect on the system. Now increase the star mass to 2.0 M_{Sun} and note the effect on the system.

Question 5: *How is the amplitude of the radial velocity curve affected by increasing the star mass?*

Explain why this happens.

Question 6: *Based on your observations, which would be easiest to detect: a massive planet around a massive star, a massive planet around a low mass star, a low mass planet around a massive star, or a low mass planet around a low mass star? Explain your answer. Note: "easiest to detect" means largest radial velocity amplitude.*

Return the simulator to the values of Option A.

Question 7: *How is the amplitude of the radial velocity curve affected by decreasing the "semi-major axis" of the planet's orbit? How is the period of the system affected? NOTE: the "semi-major axis" is ½ of the largest diameter of the orbit; for a circular orbit, it corresponds to the orbit's radius.)*

Question 8: *Which would be easiest to detect, a planet with a very large semi-major axis (and long period) or a planet with a small semi-major axis (and a short orbital period)? Explain your answer.*

Return the simulator to the values of Option A so that we can explore the effects of system orientation. It is advantageous to check **show multiple views**. Note the appearance of the system in the **earth view** panel for an inclination of 90º. Decrease the inclination to 75º and note the effect on the system. Continue decreasing inclination to 60º and then to 45º.

Question 9: *In general, how does decreasing the orbital inclination affect the amplitude and shape of the radial velocity curve? Why does this happen? (Hint: Remember that you are measuring the radial component of the star's velocity.)*
Question 10: *Assuming that systems with greater amplitude (i.e., larger radial velocities) are easier to observe, are we more likely to observe a system with an inclination near 0° or 90°. Explain your answer.*

Return the simulator to Option A. Note the value of the radial velocity curve amplitude. Increase the mass of the planet to 2 M_{Jup} and decrease the inclination to 30°. Note the maximum value of the radial velocity curve amplitude. Try to find other values of inclination and planet mass that yield the same amplitude?

Question 11: *Did you find other combinations of planet mass and inclination angle that givse the same maximum amplitude as for the case of 2 M_{Jup} and 30°? If so, list the masses inclination angles, and maximum amplitudes for two such examples?*

Question 12: *Suppose that you are able to measure the amplitude of the radial velocity curve but do not know inclination of the system. Is there enough information to uniquely determine the mass of the planet? Explain your answer.*

ELLIPTICAL ORBITS:

Select the preset labeled **Option B** and click **set**. This will configure a system with the following parameters – inclination: 90º, longitude: 0º, star mass: 1.00 M_{Sun}, planet mass: 1.00 M_{Jup}, semi-major axis: 1.00 AU, eccentricity: 0.4. Thus, all parameters are identical to the system used earlier *except that the orbit is* *noticeably elliptical.*

***Question 13**: Does the radial velocity curve for an elliptical orbit differ from that of a circular orbit? How? Do you think it is possible for an astronomer to determine whether an exoplanet has an elliptical orbit from the properties of the radial velocity curve? Could he or she determine how elliptical the orbit is? (Note: try varying the orbital eccentricity to get a feeling for how it affects the radial velocity curve.*

"NOISY" DATA:

In a perfect world, we would be able to make continuous measurements and each measurement would have no associated uncertainties. However, in the real world, there is typically some time gap between successive measurements and the data we collect can be "noisy," i.e., there is some random error in the measurements The Radial Velocity Simulator has the capability to simulate "noisy" radial velocity measurements. What we call "noise" in this simulation combines uncertainties due to imperfections in the detector with natural variations and ambiguities in the signal. A star is a seething hot ball of gas and not a perfect light source, so there will always be some variation in the signal. Such noise limits the precision to we can which we can measure a radial velocity curve and limits the smallest radial velocity values that can be detected reliably. The best ground-based radial velocity measurements have a noise level of about 3 m/s.

Select the preset labeled **Option A** and click **set** once again. Remember that this preset effectively places the planet Jupiter in the Earth's orbit. Check **show simulated measurements**, set the noise to 3 m/s, and the number of observations to 50.

***Question 14:** Do you believe that the shape and amplitude of the theoretical curve could be determined from the measurements in this case? (Advice: check and uncheck the **show theoretical curve** checkbox and ask yourself whether the shape of curve could reasonably be inferred from the measurements if you weren't shown the theoretical curve for guidance.) Explain.*

Select the preset labeled **Option C** and click **set**. This preset effectively places the planet Neptune (with a mass of 0.05 M_{Jup}) in the Earth's orbit.

***Question 15:** Do you believe that the theoretical curve shown could be determined from the observations shown? Explain.*

Select the preset labeled **Option D** and click set. This preset effectively describes the Earth (0.00315 M_{Jup}) orbiting at 1.0 AU around a 1 M_{Sun} star. Set the noise to 1 m/s.

***Question 16:** Suppose that the intrinsic noise in a star's Doppler shift signal – the noise that we cannot control by building a better detector – could be reduced to about 1 m/s. How likely are we to detect a planet like the Earth using the radial velocity technique? Explain.*

RADIAL VELOCITY TECHNIQUE SUMMATION:

Imagine you have been running an observing program hunting for extrasolar planets in circular orbits using the radial velocity technique. Suppose that all of the target systems have inclinations of 90°, stars with a mass of 1.0 M_{Sun}, and no eccentricity. Your program has been in operation for 8 years and your equipment can make radial velocity measurements with a noise level of 3 m/s. ***Thus, for a detection to occur, the radial velocity curve must have a sufficiently large amplitude (at least twice the level of the noise) and the orbital period of the planet should be less than the duration of the project so that at least one full orbit is observed.*** Use the Simulator to explore the detectability of each of the systems listed in Data Table 1 on page 8 of the lab and complete the Table. Describe the detectability of the planet by checking Yes, No, or Maybe. If the planet is undetectable, check a reason such as "period too long" or "amplitude too small". Two examples have been completed for you. (Note: in actual practice, astronomers usually observe several complete cycles before claiming a planet detection.)

> ***Question 17****: Use the results in Data Table 1 to summarize the effectiveness of the radial velocity technique. What types of planets is it most effective at finding? Mention both the physical and orbital properties of the planets.*

<u>The Transit Technique</u>

You will use now use the *Exoplanet Transit Simulator* to see how the brightness of a star can be affected by the passage of a planet in front of it and how some of the properties of the planet and its orbit can be deduced. This is another example of an indirect way of detecting the presence of a planet.

Open the simulator by clicking on *Exoplanet Transit Simulator* on the *Extrasolar Planets* Home page. Note that most of the control panels are identical to those in the *Radial Velocity Simulator*. However, the panel in the upper right now shows the variations in the total amount of light received from the star. The visualization panel in the upper left shows what the star's disc would look like from earth if we had a sufficiently powerful telescope. The relative sizes of the star and planet are to scale in this simulator (they were exaggerated for clarity in the radial velocity simulator.) Experiment with the controls until you are comfortable with their functionality.

Select **Option A** and click set. This option configures the simulator for Jupiter in a circular orbit of 1 AU around a Sun-like star, with an inclination of 90°. The 1% dip in the normalized flux shows the eclipse that occurs when the planet passes directly in front of the star. Note that, in general, the deeper the eclipse, the easier it is to detect.

> ***Question 18:*** *Determine and describe how increasing each of the following variables would affect the depth and duration of the eclipse. (Note: the transit duration is shown underneath the flux plot.)*
>
> *a. Radius of the planet*
> *b. Mass of the planet*
> *c. Semi-major axis of the orbit*
> *d. Mass (and thus, temperature and radius) of the star*
> *e. Inclination of the orbit*

The ***Kepler*** spacecraft (http://kepler.nasa.gov) was launched in March 2009. Its primary mission, which continued for ~4 years, was to photometrically detect the transits of exoplanets across the faces of their home stars, as you have just done with the *Transit Simulator*. The goal of the ***Kepler*** mission was to achieve a noise level of 20 parts per million (i.e., a noise of 0.00002); but a variety of effects conspired to elevate the best-achievable noise level to about 50 parts per million (0.00005). Nevertheless, ***Kepler*** was a stunning success with, at the present time, over 2500 confirmed detections of exoplanets.

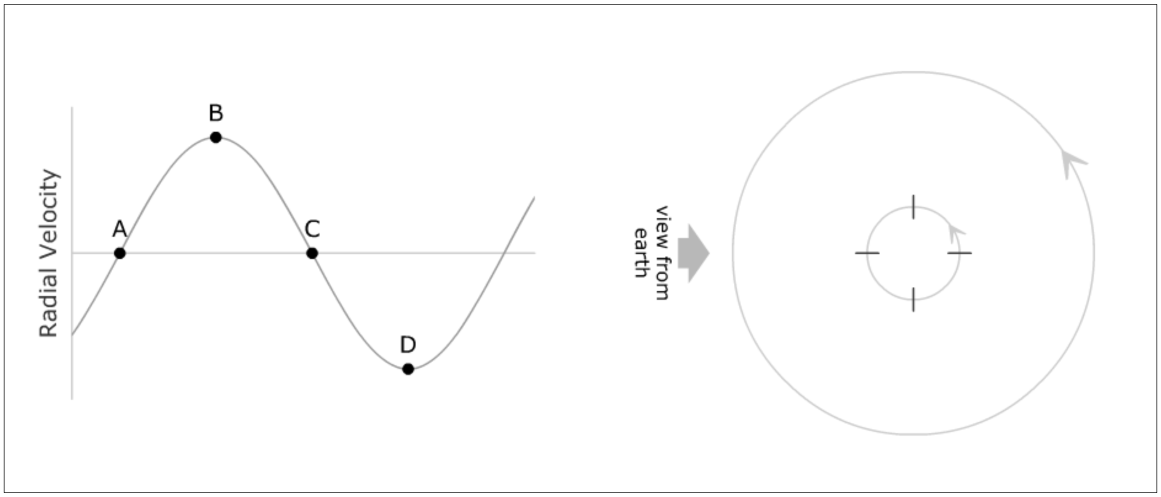
Select **Option B** and click set. This preset is very similar to the Earth in its orbit. Select **show simulated measurements** and set the noise to 0.00005.

> ***Question 19:*** *Do you think Kepler has been able to detect Earth-sized planets in Earth-like orbits around Sun-like stars? If not, about what noise level do you think would be required to definitely succeed? Explain your answers.*

> ***Question 20:*** *How long does the eclipse of an Earth-like planet in an Earth-like orbit around a Sun-like star take? How much time passes between eclipses? What obstacles would a ground-based telescope (i.e., one located on Earth's surface) face in trying to detect Earth-like planets?*

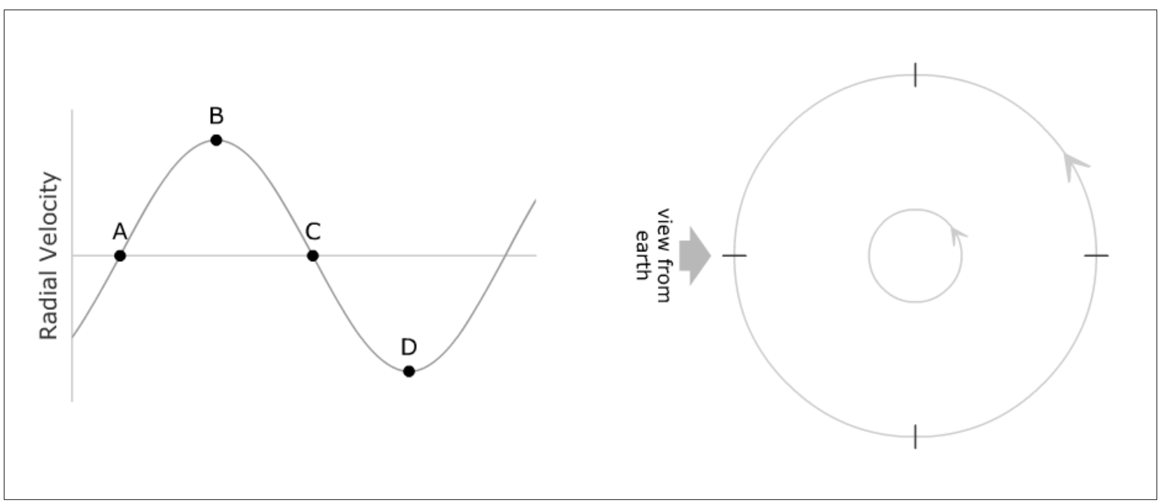
Question 1

Label the positions on the <u>star's orbit</u> (i.e., the inner orbit) with the letters corresponding to the labeled positions on the star's radial velocity curve.



Question 2

Label the positions on the <u>planet's orbit</u> (i.e., the outer orbit) with the letters corresponding to the labeled positions on the star's radial velocity curve.



Data Table 1

Planet's Mass (MJup)	**Semi-Major Axis** (AU)	**Amplitude** (m/s)	**Period** (days)	**Detectable?**			**Rationale?**	
				Y	N	M	A too small	P too big
0.1	**0.1**	8.9	11	X				
1	**0.1**							
5	**0.1**							
0.1	**1**							
1	**1**							
5	**1**							
0.1	**5**							
1	**5**							
5	**5**	63.4	4070		X			X
0.1	**10**							
1	**10**							
5	**10**							

Lab Report Cover Page

Astronomy Laboratory – Planets
Mendel Science Experience 2150
Fall 2025

Lab K
<u>Detecting Extrasolar Planets</u>

Name: ____

Lab Section: __________

Date: __________

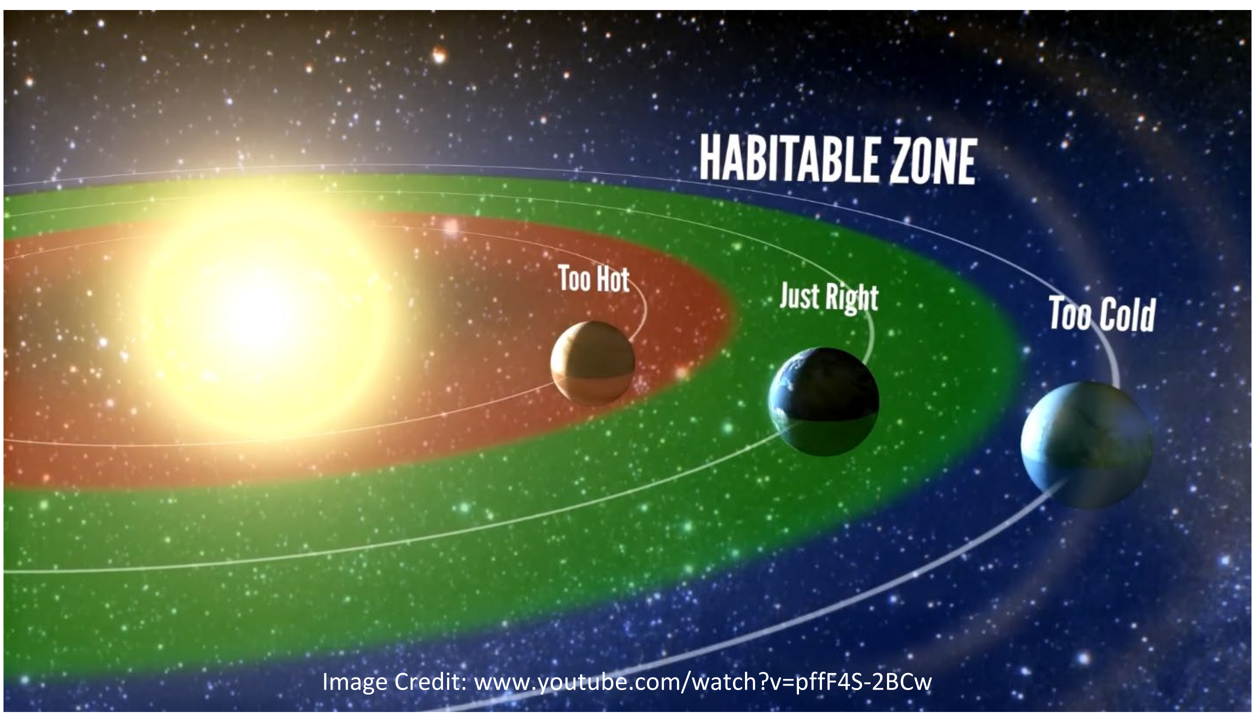
Lab L
Exploring Habitable Zones[1]

PURPOSE:

To explore the environments around stars and within our Galaxy in which it might be possible for life-as-we-know-it to develop on Earth-like planets.

EQUIPMENT:

NAAP computer programs *Circumstellar Habitable Zone Simulator* and *Milky Way Habitability Explorer*



[1] Adapted from the Nebraska Astronomy Applet Project (NAAP) at http://astro.unl.edu/naap/.

Background Material

Double-click the **NAAP Labs** icon on your Desktop. Then select exercise 15, *Habitable Zones,* to bring up the Home page for today's lab. Read through the Background pages entitled *Life in the Universe*, *Circumstellar Habitable Zones*, and *Galactic Habitable Zones* before working on the exercises below.

The Circumstellar Habitable Zone

You will now use the *Circumstellar Habitable Zone Simulator* to explore how the properties of a star affect the likelihood of finding planets suitable for sustaining life. Click *Circumstellar Habitable Zone Simulator* on the *Habitable Zones* Home page to begin the exercise. The simulator window that opens has four main panels:

- The top panel simulation displays a visualization of a star and its planets looking down onto the plane of the planetary system. The Circumstellar Habitable Zone (shaded blue region; hereafter "CHZ") is displayed for the particular star being simulated. When a planet's orbit falls within the CHZ, the conditions are such that water can be in the liquid state on its surface and the planet is potentially suitable for life (i.e., "habitable"). You can click anywhere within the panel and drag the cursor either toward the star or away from it to change the scale being displayed.

- The **General Settings** panel provides two options for creating standards of reference in the top panel.

- The **Star and Planets Setting and Properties** panel allows you to display our own Solar System, several known planetary systems, or create your own star-planet combinations in the "none-selected" mode. Adjusting the initial mass of the star fixes its initial surface temperature, radius, and luminosity, as shown in the display and in the small graph on the right-hand side of the panel

- The **Timeline and Simulation Controls** allows you to demonstrate the time evolution of the star system being displayed. As time progresses, the star will "evolve" as its fuel supply is depleted. This results in a continuing change in the star's surface temperature, radius, luminosity and, sometimes, mass. The changing stellar properties can be followed in the display in the Star and Planet Settings and Properties panel. Several important events in the evolution of the system are shown at the bottom of the panel. These controls are described more fully below.

The simulation begins with our Sun being displayed as it was when it formed and a terrestrial (i.e., rocky) planet at the position of Earth. You can change the planet's distance from the Sun either by dragging it or by using the planet distance slider. Try moving it around. Note that the appearance of the planet changes depending upon its location. There are five possible "faces" for the planet, as shown in **Figure 1** below. It appears earth-like, i.e., habitable, when within the CHZ (face "a"). When dragged inside of the CHZ it becomes desert-like and too hot to support liquid water (face "b"), while outside the CHZ it is too cold for liquid water (face "c"). Planets that are tidally locked on their stars, i.e., with one side always facing the star, are show as half desert-like and half frozen (face "d") and planets which have been destroyed or severely damaged by stellar evolution events are shown by face "e".

Figure 1: The five planetary faces

SIZE & LOCATION OF THE CHZ:

Now drag the planet to the inner boundary of the CHZ. **You should position the planet so that the boundary of the CHZ passes through the middle of the planet's face.** (In some cases, this will be the point at which the face changes.) Note this distance from the Sun. Then drag it to the outer boundary and note this value. Lastly, take the difference of these two figures to calculate the "width" of the Sun's original CHZ. Enter the results in Data **Table 1** of the lab write-up.

Now explore the width of the CHZ for other stars. Complete Data **Table 2** for stars with a variety of initial masses.

> ***Question 1:*** *Carefully examine your results in Data Table 2. What general conclusion can be made regarding the* <u>*location*</u> *of the CHZ for different types of stars?*
>
> ***Question 2:*** *Again, using Data Table 2, what general conclusion can be made regarding the* <u>*width*</u> *of the CHZ for different types of stars?*
>
> ***Question 3:*** *If the likelihood of there being a planet hosting complex life forms (like on Earth) around a particular star depended only on the width of the star's CHZ, then which types of stars would be the best ones to examine in searching for evidence of such life. Explain your answer.*

TIME EVOLUTION OF THE CHZ:

The properties of stars change as they get older. This is known as "stellar evolution." While in the "Main Sequence" phase (which spans about 90% of their entire lives), stars fuse hydrogen atoms into helium atoms in their cores. As this process progresses, the rate of the fusion reactions gradually speeds up and the amount of stellar energy generated (and released) increases and changes the location of the CHZ. This is important because it means that planets may move into, or out of, a star's CHZ as it ages and evolves. We know that **simple life** appeared on Earth early in its history, but **complex life** did not appear until approximately 1 billion years ago (i.e., about 3.5 billion years after Earth formed). If life on other planets takes a similar amount of time to evolve, we would like to know how long a planet lies in its CHZ, in order to evaluate the likelihood of complex life being present.

We will now look at the evolution of star systems over time and investigate how this affects the CHZ. We will focus exclusively on the phases of stellar evolution that are well understood and assume that planets remain in their orbits indefinitely. Many researchers now believe that planets migrate due to gravitational interactions with each other and with smaller debris, but that is not shown in our simulator.

We will make use of the **Time and Simulation Controls** panel. This panel consists of a button and slider to control the passing of time and 3 horizontal strips:

- The first strip is a timeline encompassing the complete lifetime of the star with time values labeled. Note that the total lifetime of a star increases with decreasing mass.

- The second strip represents the temperature range of the CHZ – the orange bar at the top indicates the inner boundary and the blue bar at the bottom the outer boundary. A curved black line in between shows the temperature of the planet for times when it is within the CHZ.

- The bottom strip also shows the length of time the planet is in the CHZ in dark blue as well as labeling important events during the lifetime of a star such as when it leaves the Main Sequence (i.e., when it runs out of hydrogen atoms in its core).

NOTE! The units of time used in the simulator are "My," which means "mega-years" (10^6 years), or "Gy", which means "giga-years (10^9 years). To convert from My to Gy, you must divide by 1000.

Configure the simulator for a star with an initial mass of 0.3 M_{Sun} and set the timeline cursor to time zero. Now drag the planet in the diagram so that it is just on the outer edge of CHZ. Then run the simulator until the planet is no longer in the CHZ. The time when this occurs gives the total amount of time the planet spends in the CHZ. Record this time for the 0.3 M_{sun} star in the last column of Data **Table 3**. Repeat this experiment a variety of initial stellar masses and record these data in Data **Table 3**. (Watch out for units! I.e., My vs. Gy.)

Question 4: *Based on your data in Table 3, how does the length of time a planet remains in the CHZ depend on the mass of its host star?*

Question 5: *If the likelihood of there being a planet hosting complex life depended only on the length of time a planet could stay in the star's CHZ, then which type of star would most likely have planets suitable for complex life? Explain your answer.*

Now, let's look a little more closely at the Earth. Configure the simulator for Earth (i.e., a 1 M_{Sun} star and an initial planet distance of 1 AU). Note that, immediately after our Sun formed (i.e., at an age of 0 years), Earth was in the middle of the CHZ. Drag the timeline cursor forward and note (as you just saw above) how the CHZ moves outward as the Sun gets brighter. Stop the time cursor at 4.6 billion years to represent the present age of our solar system.

Question 6: *Based on this simulation, how much longer will Earth be in the CHZ? To see this, run the simulation forward until Earth is no longer in the CHZ. Comment on the amount of time it took complex life to appear on Earth, compared to how much time Earth will remain habitable.*

Question 7: *What is the total lifetime of the Sun (i.e., up to the point when it becomes a small "white dwarf" star, which no longer generates energy through nuclear fusion reactions).*

Question 8: *What happens to Earth at this time in the simulator? (Discuss both the orbit and the habitability.)*

(You may have noticed the planet moving outwards towards the end of the star's life. This is due to the star losing about half of its mass as it becomes a white dwarf. This reduces its gravitational hold onto its planets.)

TIDAL LOCKING:

We have just seen that, the smaller the star, the longer a planet can remain in its CHZ. This is clearly a good thing for the possible formation and evolution of life. However, the proximity of the CHZ to a low mass stars can lead to problems.

Reset the simulator and set the initial star mass to 0.3 M_{Sun}. Drag the planet to the middle of the CHZ. Notice that the planet is shown with a dashed line through its middle (face "d" in **Figure 1**). What has happened is that the planet is now so close to its star that it has become "tidally locked" due to gravitational interactions. This is analogous to Earth's moon which always presents the same side towards Earth. For a planet orbiting a star, this means one side would get very hot and the other side would get very cold. **This is generally considered to be bad for the emergence of life!**

> ***Question 9:*** *What do you think would happen to Earth's water if it were suddenly to become tidally locked to the Sun? What would this mean for life on Earth?*

Complete Data **Table 4** by resetting the simulator, setting the initial star mass to the values in the table, and positioning the planet in the middle of the CHZ at time zero. Record whether or not the planet is tidally locked at this time.

CHZ SUMMATION:

We have seen that high mass stars have very large CHZs, but that the time a planet can stay within the CHZ is very short. Conversely, while the lowest mass stars have very small CHZs, the time a planet can stay within such a CHZ is very long. However, if the mass of the star is too low, such a planet may find itself tidally locked to its parent star.

> ***Question 10:*** *It took approximately 4 billion years for complex life to appear on Earth. In which of the systems in Data Tables 2, 3 and 4 do you think a planet harboring complex life could be found? Explain your reasoning. You must consider both the benefit of a long CHZ lifetime and the negative effects of tidal locking.*

What you have just discovered is known as the "Goldilocks Hypothesis" – i.e., that the most massive stars have CHZs that are too short-lived for complex life to form, and that the least massive stars have tidally-locked CHZs, which also hinders the formation of complex life. It is the medium-mass stars (like the Sun) that "are just right" and give the optimal opportunity for complex life to appear.

> ***Question 11:*** *Write out the following "Goldilocks Story," filling in the unwritten parts:*

"Not all stars are suitable for hosting habitable planets on which complex life can appear.
If the mass of a star is too high, then ________(write the bad thing that happens)_______.
If the mass of a star is too low, then ________(write the bad thing that happens)_______.
The mass range that appear to be "just right" for the presence of complex life is ________(identify the mass range)_____.

The Galactic Habitable Zone

Now we are going to investigate habitability zones on the scale of the entire Milky Way Galaxy, i.e., the Galactic Habitability Zone (GHZ). The two competing factors that we will look at are (1) the likelihood of planets forming (since we assume that life needs a planet to evolve on), and (2) the likelihood of life being wiped out by a cosmic catastrophe. These are described in detail in the *Galactic Habitable Zones* Background page.

Open the simulation by clicking *Milky Way Habitability Explorer* on the *Habitable Zones* Home page. Each of the two factors described above is illustrated in a graph as a function of distance from the Galactic center.

> ***Question 12:*** *What factor influences the rate of planet formation? How does this vary as a function of a star system's distance from the center of the Milky Way? Where do you expect to find the highest rates of planet formation?*
>
> ***Question 13:*** *What sort of events can wipe out life on a planet? How does the likelihood of extinction for life vary depending upon a star system's distance from the center of the Milky Way? Where in the Galaxy is the safest place for life to exist?*
>
> ***Question 14:*** *Write out the Goldilock's Hypothesis for the GHZ, filling in the unwritten parts:*
>
> > "Not all locations in the Milky Way galaxy are ideal places for the presence of habitable planets that are conducive to the formation of complex life. If the host star is located _________, then _________. If the host star is located _________, then _________. It appears that the "just right" location for stars with habitable planets capable of nurturing complex life is _________."

Table 1
Solar System CHZ Properties

CHZ Inner Boundary (AU)	CHZ Outer Boundary (AU)	Width of CHZ (AU)

Table 2
General CHZ Properties

Star Mass (M_{sun})	Star Luminosity (L_{sun})	CHZ Inner Boundary (AU)	CHZ Outer Boundary (AU)	Width of CHZ (AU)
0.3				
0.5				
0.8				
1.0				
2.0				
4.0				
8.0				
15.0				

Table 3
CHZ Lifetimes

Star Mass (M_{sun})	Initial Planet Distance (AU)	Time in CHZ (Gy)
0.3		
0.5		
0.7		
0.8		
1.0		
1.2		
1.5		
2.0		
4.0		
8.0		

Table 4
Tidal Locking in CHZ

Star Mass (M_{sun})	Tidally Locked?
0.3	
0.5	
0.7	
0.8	
1.0	
1.2	
1.5	
2.0	
4.0	
8.0	

Lab Report Cover Page

Astronomy Laboratory – Planets
Mendel Science Experience 2150
Fall 2025

Lab L
<u>Exploring Habitable Zones</u>

Name: ____

Lab Section: __________

Date: __________

Appendix 1

Microsoft Excel Tutorial

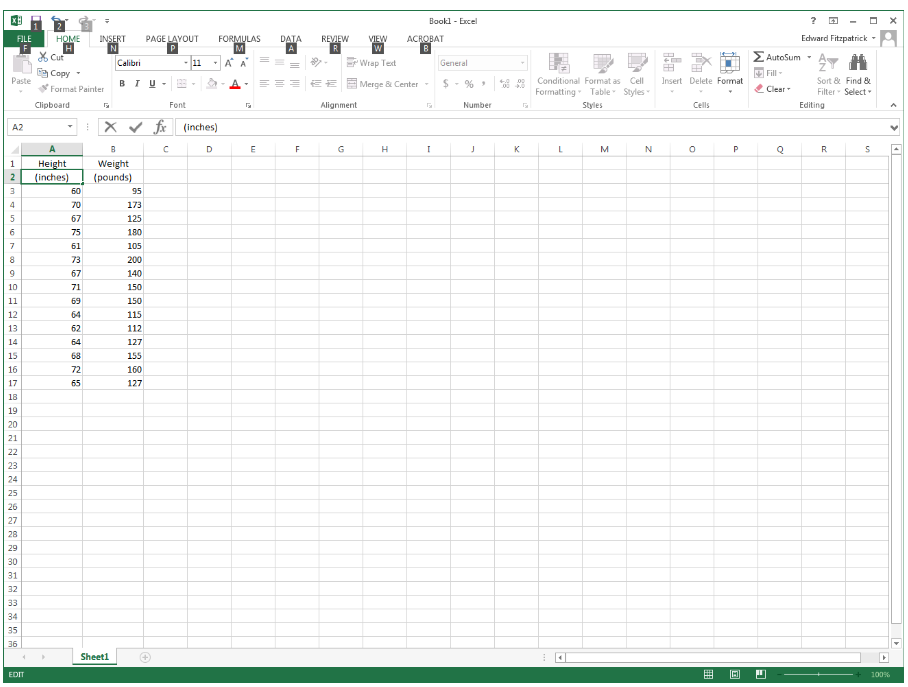
Microsoft Excel Tutorial

Creating a Linear Graph with Regression

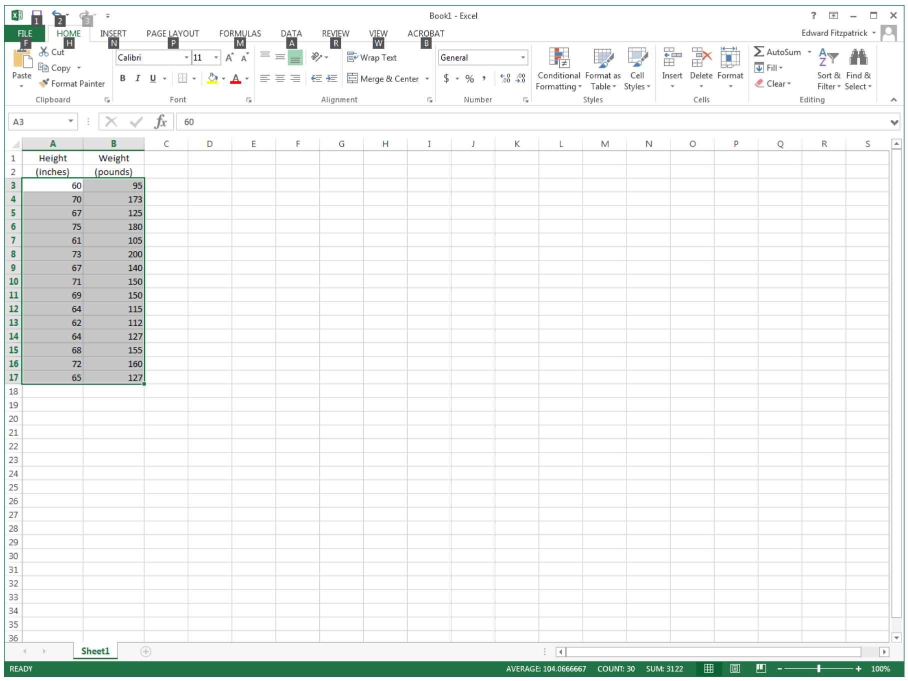
This tutorial is designed to teach you how to create a graph and perform a linear regression using Microsoft Excel. Excel is a spreadsheet program. This is a program that is designed to take data, usually numerical, and perform various operations on it and output those results as numbers or graphs. While designed primarily for business applications, Excel can also be used for scientific work. The version shown in the pictures will be for Microsoft Office Excel 2013 for Windows.

Launch Microsoft Excel 2013 by selecting its icon.

To begin the process of creating a graph, simply click the mouse in a cell and type the data into that cell. The data can be numbers, words, mathematical formulas, etc. When done, click the mouse in another box and enter the data there. In the example below, we've created two columns: Height and Weight (Height in column B, Weight in column C). This data is from *Lab A: Working with Numbers, Graphs, and the Computer*. When entering data, keep the first couple of rows available for column headings.



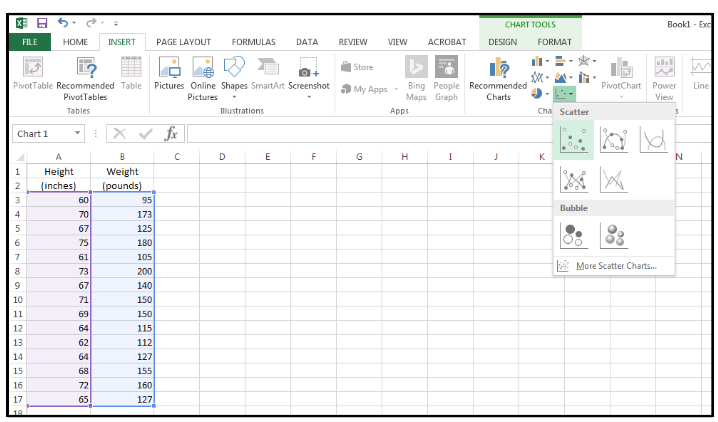
When you've entered all of your data, you can create a graph from it. To select the data that you want to graph, click and hold the left mouse button on the upper left cell, then drag the mouse to the lower right cell while holding the button down. The data will appear highlighted as seen below:



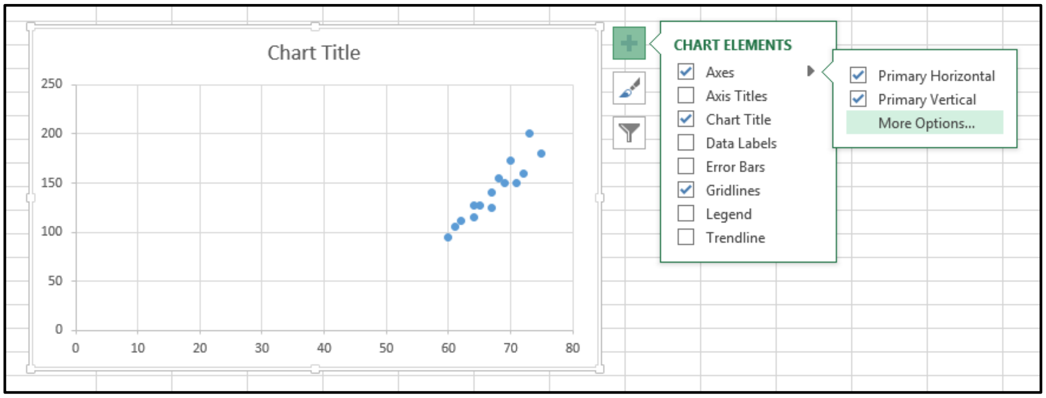
NOTE**:** To select two column which are not side-by-side, select the first column and then - while holding the CTRL button - select the second column. Both should now appear highlighted. Excel always chooses the leftmost column to be the x-axis of a graph.

To add a graph to the spreadsheet, you can go to the Insert menu and then choose Scatter in the “Charts” section. For the style of plot, click on the “Scatter with only Markers” type.

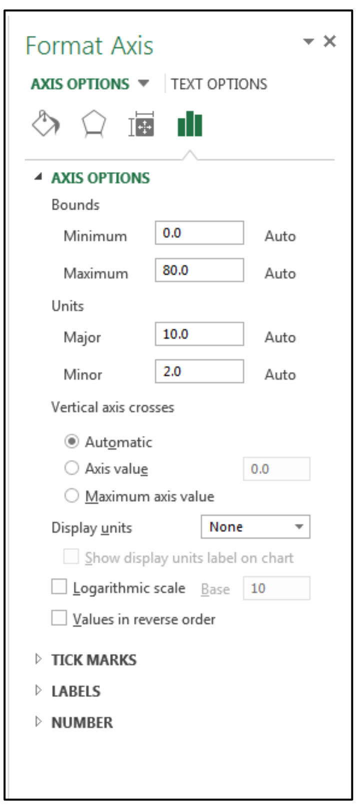
This is the usual style of graph that we will use in this class.



Once your chart appears on the screen, you may want to make changes in how it is displayed or make corrections to your data points. Here, it is necessary to set the range of both the x and y axis to see the data spread out on the page. To do this, click on the graph to highlight it and then select the large plus sign ("+") to the right of the chart:

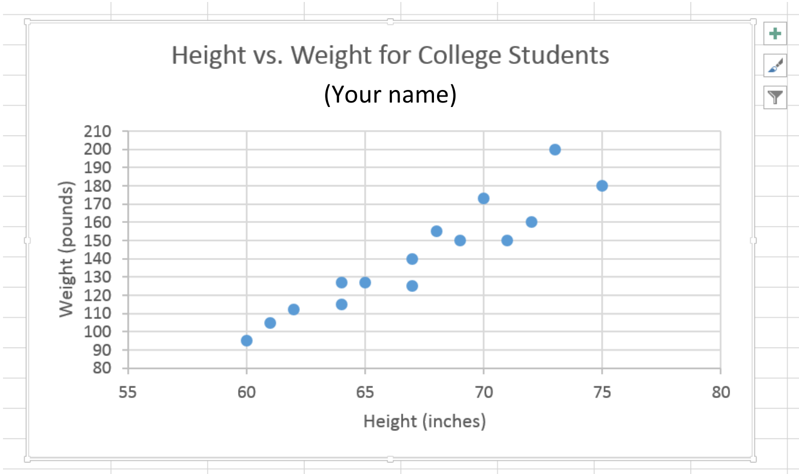


This brings up a number of options which allow you to change the appearance of the chart. To change the range of the graph, click the small arrow next to "Axes" in the "Chart Elements" box and then click "More Options". This brings up the "Format Axis" menu on the right side of the screen:



There are many options available to you (which you will have to explore!) To change the range displayed in the graph, highlight the axis you which to modify (i.e., click on it in the chart), then change the values listed in the "Bounds" section of the menu. You can also adjust the "Units" inputs to change the intervals between the tick marks displayed in the chart. For your Height vs. Weight chart, try x-axis bounds of 55 and 80, with "Major" units set to 5. Try y-axis bounds of 70 and 210, with "Major" units set to 10. Experiment with these values. The goal is for your data to fill the plotting area as much as possible, without wasting space (as in the default chart shown above, where the chart is blank for x-values less than 60 and y-values less than about 90.

It is now time to add axes labels and a chart title. This is done via the "Chart Elements" box. Simply check the "Axis Titles" and "Chart Title" boxes, and text boxes will appear on your chart in which you can type the desire titles and labels. There are options for "prettifying" the titles, which can be accessed through the menus which will appear on the right side of the Excel window. After typing in labels and a title, your chart should look something like:



Make sure you enter a descriptive title. It is IMPORTANT to include your name so you can identify your plot at the printer. The axis labels should describe the quantity being displayed (e.g., "Weight") and the units used.

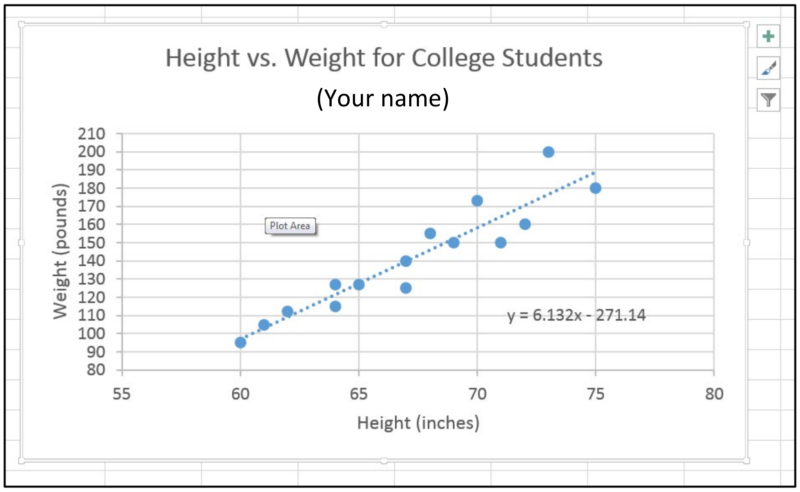
NOTE: After creating a beautiful chart, you may discover that you have entered some of the data incorrectly in the spreadsheet. No worries. Simply change the incorrect value in the spreadsheet and the new results will appear automatically on the chart!

TRENDLINES

It is clear from viewing the data in the chart above that height and weight for college students appear to be, on average, linearly related to each other. I.e., as one increases, the other increases in the same proportion. This relationship can be quantified in Excel by fitting a "Trendline" to the data.

To fit a Trendline to your data, simply check the "Trendline" box in the "Chart Elements" menu. (Remember? Highlight the graph and click the "+" sign to bring up the "Chart Elements" box). Clicking the small arrow next to "Trendline" will bring up the "Format Trendline" menu on the right side of the spreadsheet. There are several options but, in this case, a linear fit seems appropriate. Check the "Linear" option and Excel will perform a linear regression analysis on your data. A line will appear through your data representing the mean relationship between height and weight of college students. Check the "Display Equation on chart" box and the equation of this straight line will appear on the plot. You can drag this equation around to a convenient spot and, also, change the text size and style.

Your final graph will look something like this:



PRINTING

If you need to make a hardcopy of your graph, highlight the graph by clicking on it, then click on the "File" menu in the upper left corner of Excel and chose "Print" to get a view of the whole graph. If it looks OK, then print it and include it with your lab.

NOTE: If you click "Print" in the "File" menu **without** highlighting the graph, the whole spreadsheet will be formatted for printing. Printing this way allows you to include your data tables and charts on the same output page. Elements in the spreadsheet can always be moved around to allow for maximum visibility on the printed output.

FINAL COMMENT

Your charts and graphs should always have a title, axis labels and proper scaling of the axes. You have complete control of the appearance of your charts. Make them look professional!

Appendix 2

Excel Helpful Hints

Some Helpful Hints for Using Microsoft Excel

1. You can control whether Excel displays a number in normal format or in scientific notation. To change the format, right-click on the cell containing the number, select ***Format Cells…*** , then click the ***Number*** tab. Now choose either ***Number*** or ***Scientific,*** depending on your needs and specify the number of decimal places you'd like to display.

2. There is no easy way to tell Excel how many significant digits to display. You'll first have to figure out how many decimal places you need to yield the correct number of significant figures, and then use the ***Format Cells…*** command (as above) to specify the decimal places. Read your Significant Figures handout!

3. To input scientific notation into Excel, use the "E" character to replace "times 10 to the". For example, to input $\mathbf{4.00 \times 10^4}$ ("four times 10 to the fourth power") into Excel you would type **4.00E4.** Another example: to input $\mathbf{6.673 \times 10^{-8}}$ into Excel, you would type **6.673E-8.**

4. If you need to use the constant π (i.e., 3.14159…) in a calculation, you must type ***pi()***, i.e., the word "pi" followed by a set of empty parentheses.

5. When doing anything involving angles, Excel's native units are radians. So, if you want to take the sine of a particular angle, it must be expressed in radians. You can convert measurements in degrees into radians "on the fly" using the ***RADIANS*** function. For example, if you want to take the sine of 45° in Excel, you would type ***SIN(RADIANS(45)).***

6. If you have an angle specified in radians and want to display it in degrees, you can use the ***DEGREES*** function. For example, if you type ***DEGREES(pi()/4)*** Excel will display ***45*** since π/4 radians is the same as 45°

7. To create a "formula sheet", click ***CTRL-`***. This will show all the formulas you used on your Excel spreadsheets. You can then print this sheet (scaling to fit on one sheet and, possibly, using Landscape mode to save paper) and then click ***CTRL-`*** again to return to the normal view of your spreadsheet.

Appendix 3

Significant Digits

Significant Digits in a Measurement

Definition:

Significant Digits – All the digits in a numerical measurement that can be justified by the accuracy & precision of the measurement instrument.

✓ **The number of digits reported tells you something about the quality of the measurement:**

- Imagine four length measurements reported like this:

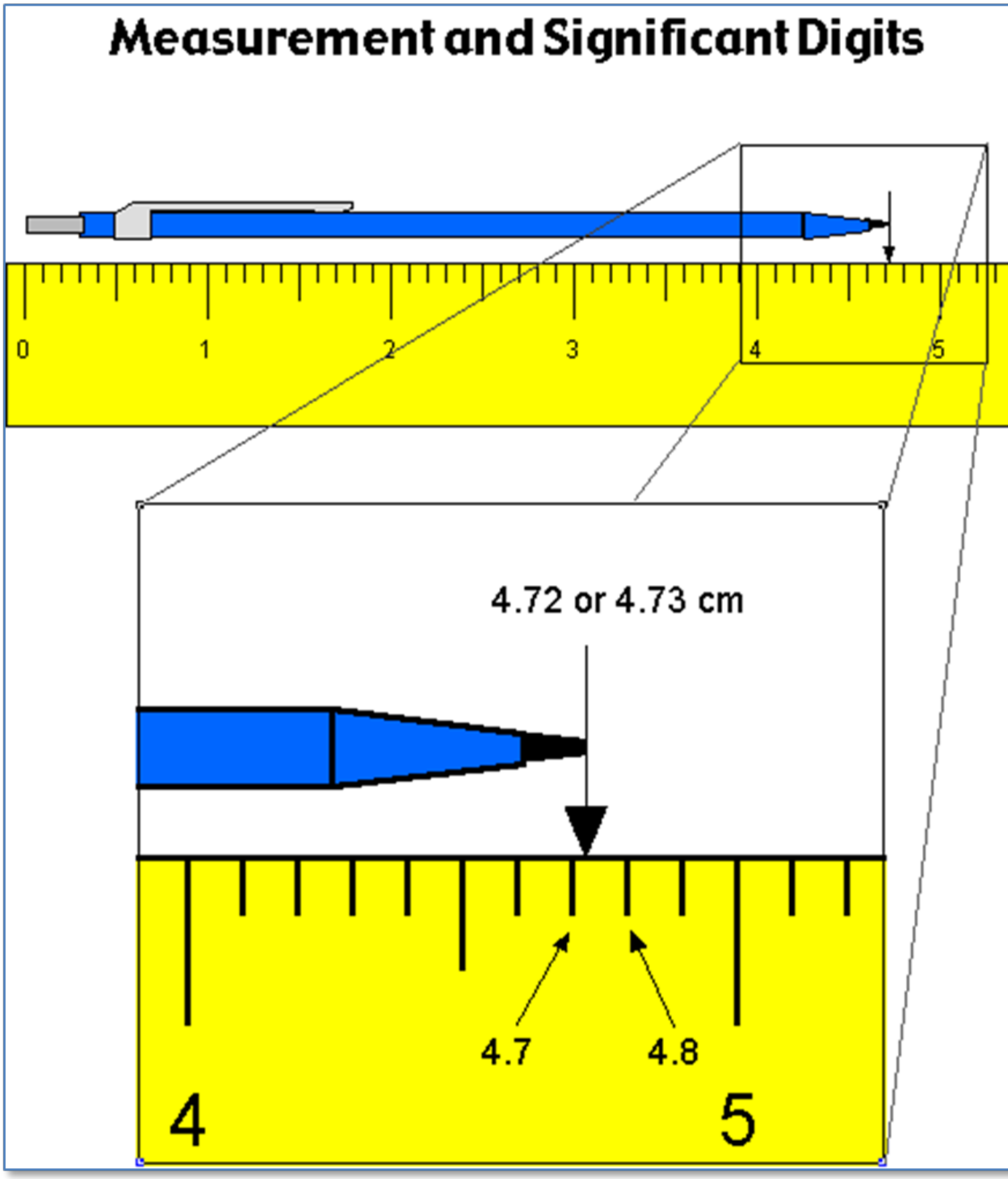
1 meter
1.0 meters
1.00 meters
1.0000 meters

- These might seem to be the same but actually imply different levels of precision:
  - "1 meter" suggests a "ballpark measurement"
    (could be off by a large fraction of a meter)
  - "1.0000 meters" indicates a very precise result
    (likely to be accurate to nearest millimeter)

✓ **How many digits should be reported:**

- It depends on the properties of the measurement instrument
- The smallest allowable digit in a measurement is the "uncertain digit" or the "estimated digit."
- The "estimated digit" lies between the smallest intervals marked on the measurement device.

✓ **In the sample measurement shown on the next page, either 4.72 or 4.73 are acceptable answers for the length of the pencil. It would not be appropriate to quote a measurement of 4.725.**



Source: *Significant Digits - LSRHS*

Significant Digits in a Calculation

The Big Idea:

The number of significant digits in the answer to a calculation will depend on the number of significant digits in the original data.

✓ **How to Tell (or Indicate) Whether a Digit is Significant?**

- Non-zero digits are always significant. Thus:

  22 has two significant digits
  22.3 has three significant digits

- With zeroes, the situation is more complicated:

  a. Zeroes placed before other digits are not significant; 0.046 has two significant digits.
  b. Zeroes placed between other digits are always significant; 4009 kg has four significant digits.
  c. Zeroes placed after other digits but behind a decimal point are significant; 7.90 has three significant digits.
  d. Zeroes at the end of a number are significant only if they are behind a decimal point as in (c). Otherwise, it is impossible to tell if they are significant. For example, in the number 8200, it is not clear if the zeroes are significant or not. The number of significant digits in 8200 is at least two but could be three or four.

- In scientific notation, all written digits are assumed to be significant. For example:

  8.200×10^3 has four significant digits
  8.20×10^3 has three significant digits
  8.2×10^3 has two significant digits

- In logarithms (or astronomical magnitudes), only the numbers to the right of the decimal point are significant digits.

  For example , consider the number 476.2. It has 4 significant digits. The logarithm of 476.2 should also be expressed using 4 significant digits and would be written as:

  $$\log(476.2) = 2.6778$$

✓ **Significant Digits in Multiplication, Division & Trigonometric Functions**

In a calculation involving multiplication, division, and trigonometric functions, the number of significant digits in an answer should equal the least number of significant digits in any one of the numbers being multiplied, divided, etc.

Thus, in evaluating sin(kx), where $k = 0.097\ m^{-1}$ (two significant digits) and $x = 4.73$ m (three significant digits), the answer should have two significant digits.

Whole numbers have essentially an unlimited number of significant digits. As an example, if a hair dryer uses 1.2 kW of power, then 2 identical hairdryers use 2.4 kW:

1.2 {2 sig. dig.} x 2 {unlimited sig. dig.} = 2.4 {2 sig. dig.}

✓ **Significant Digits in Addition and Subtraction**

When quantities are being added or subtracted, the number of *decimal places* (not significant digits) in the answer should be the same as the *least* number of decimal places in any of the numbers being added or subtracted. For example:

5.67	(two decimal places)
1.1	(one decimal place)
+ 0.9378	(four decimal place)
7.7	(one decimal place)

✓ **Keep Extra Digits in Intermediate Answers**

When doing multi-step calculations, *keep at least one more significant digit in intermediate results* than needed in your final answer.

For instance, if a final answer requires two significant digits, then carry at least three significant digits in calculations. If you round-off all your intermediate answers to only two digits, you are discarding the information contained in the third digit, and as a result the *second* digit in your final answer might be incorrect. (This phenomenon is known as "round-off error.")

✓ **The Two Greatest Sins Regarding Significant Digits**

1. Writing more digits in an answer (intermediate or final) than justified by the number of digits in the data.

2. Rounding-off, say, to two digits in an intermediate answer, and then writing three digits in the final answer.

Source: *Significant Digits Tutorial | Physics (uoguelph.ca)*