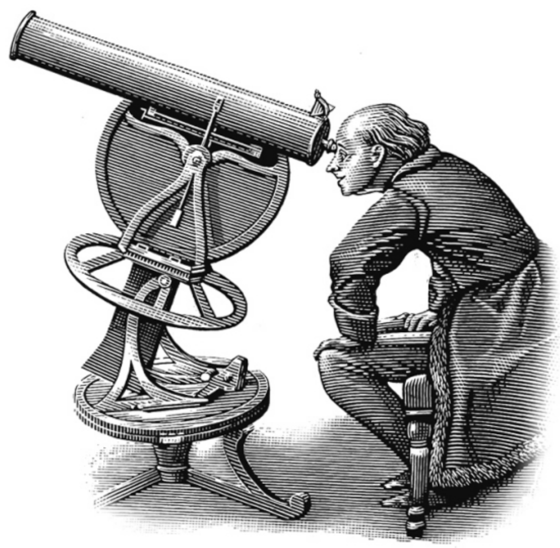
MSE2150

Astronomy Laboratory – Planets

Lab Manual



Department of Astrophysics & Planetary Science
Villanova University

Fall 2019

Astronomy Laboratory – Planets
MSE2150
Fall 2019 Lab Schedule

Week 1: Introductory meeting
Lab A assigned as take-home lab
Week 2: Lab B – Measurements & Experimental Uncertainty
Week 3: Lab C – Lunar Eclipses & the Saros Cycle
Week 4: Lab D – The Next 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

Observing sessions for the "Observatory Lab" will be scheduled throughout the semester.

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

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

14" Celestron Schmidt-Cassegrain 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.
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 3rd, the Observatory will be open Monday thru Thursday evenings, initially from 8-10 PM and then, after Daylight Savings Time ends on November 3, 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 12. 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 13.

<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. In this phase, 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 2019 semester, First Quarter phases occur on **Sep 5**, **Oct 5**, **Nov 4**, and **Dec 4**.

The planets Jupiter and Saturn will be visible with the telescope during the first ~half of the semester. Afterwards, they'll be setting too early to get a good look. Mercury and Venus will be too close to the Sun to be visible with our telescope and Mars will be a daytime object throughout the semester. 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

Astronomy Laboratory - Planets
Mendel Science Experience 2151
Fall 2019

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

Name: ____

Lab Section: __________

Date: __________

Observatory Assistant
Name: ____
Signature: ____
Date: ____

Lab A
Working with Numbers, Graphs, and the Computer

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 <u>not</u> 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.*

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 <u>exactly</u> 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"*. <u>This notation must be used to enter scientific notation into Excel.</u>

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.

<u>PART 2: LOGARITHMS</u>

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.*

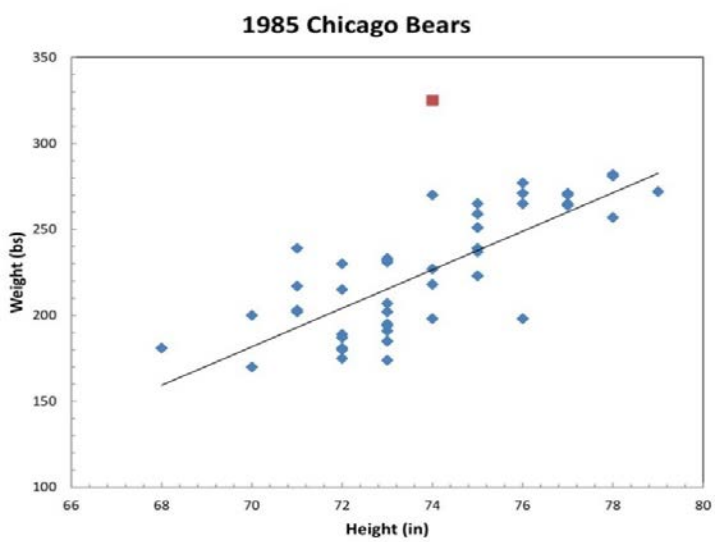
NOTE**:** Logarithms are never expressed in scientific notation. Always use standard notation.

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 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.*

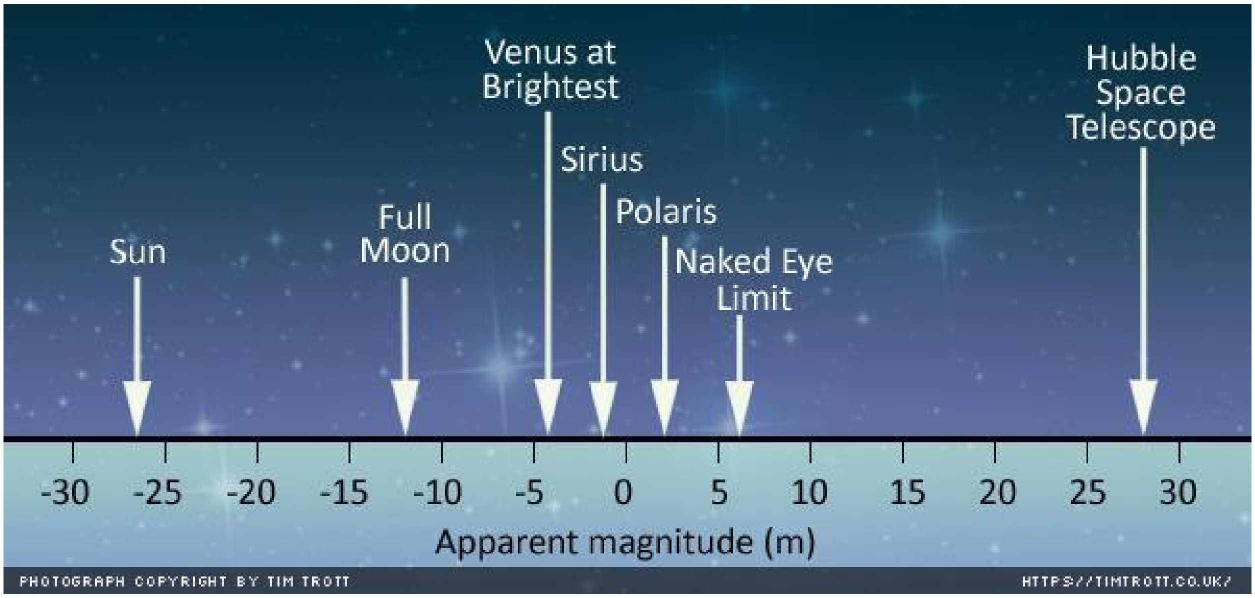
Your plot of Government Expenditures is interesting but notice how hard it is to distinguish among the values from earlier than about 1960. Also, you should see that it would be very difficult to use the graph to predict future spending with any confidence. Both problems might be reduced by looking at 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 2019

Lab A
<u>Working with Numbers, Graphs, and the Computer</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
Measurements and Experimental Uncertainty

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

PURPOSE:

To observe that measurement and analysis of errors are fundamental to science, to explore the use of measurement and error analysis in laboratory experiments, and to understand the distinction between precision and accuracy.

EQUIPMENT:

Clock, candle, twelve-inch ruler, a piece of cardboard with an eccentric hole, computer, and calculator.

Introduction: Measurement Accuracy vs. Precision

A principal objective of science is to describe the physical world through measurement. Indeed, almost all scientific experiments involve measurement, a process that may be defined as the assignment of numbers to certain properties. For example, 15 cm represents a length, 15 cm/sec represents a speed, etc.

This assignment of numbers is important. It enables us to distinguish between similar substances by measuring some characteristic physical property. For example, a solid block of aluminum can be distinguished from a hollow block of aluminum by comparing the numbers assigned to the density of each block. The assignment of numbers also permits detailed comparison between repeated measurements made by various observers and, of more importance, enables us to make predictions based on our measurements. For example, we can predict whether a block of aluminum will float on water. This would be of obvious importance to boat designer!

Before utilizing the results of measurements, it is important to understand both their ***precision*** and their ***accuracy***. If repetitive measurements always yield the same answer, the measurements are said to be ***precise***, even if the answer is actually incorrect. If the measurements yield the same correct answer, the measurements are said to be both precise and ***accurate***. Note that precision and accuracy are different concepts. *Accuracy is a measure of conformity between a single measurement and a standard value.* A standard value is one that is correct by definition. In contrast, *precision is a measurement of conformity among individual measurements in a series of measurements*. For example, suppose we are trying to cut table legs to a length of one foot, using a 12-inch ruler. Measuring a single leg multiple times, we find that our measurements give 12.0 inches, agreeing to within 0.1 inch. Therefore, we can say that these measurements are precise to 0.1 inch. However, we then find that 12 inches on our ruler really corresponds to 11.75 inches (maybe the ruler has shrunk). This gives us a set of measurements with an accuracy of only 0.25 inch.

If you count the number of people in an ordinary size room, you will probably assign exactly the right number. However, if you measure the length of this page with a ruler, the number you assign to the length will have a small margin of uncertainty. This uncertainty results from your ability to read the ruler the same way each time the measurement is repeated. The precision of the measurement is, in part, limited by the readability of the measuring device. As you will discover, it is not possible to make infinitely precise measurements, hence all physical measurements must be interpreted in light of their uncertainty.

The amount of uncertainty, or error, is either explicitly specified or implied by the number of digits in the number assigned during the measurement (i.e., the number of **significant digits**). Thus it is implied that a measurement of length expressed as 1.000 meters is more precise than a length expressed as 1.00 meters. If, for example, we were measuring lengths with a meter stick having a scale marked only with hundredths of a meter, it would not make sense to assign a length 1.000 meters. The third zero is meaningless since we cannot measure precisely enough to differentiate between 1.000 and 1.001 meters. We can however differentiate between 1.00 and 1.01 meters in length. We would therefore assign 1.00 meters to our measurement.

Precision and accuracy are quantities that can be measured. The **accuracy** of an individual measurement, i.e., the difference between the measurement and the true value, is expressed as a percentage, is given by:

$$\%\ \text{error} \equiv \%\boldsymbol{E} = \left(\frac{M - M_{std}}{M_{std}}\right) \times 100\% \tag{1}$$

where M is a specific measurement one has made, and M_{std} is the true (standard) value.

The **precision** of an individual measurement, expressed as a percentage, is given by a similar formula:

$$\%\ \text{precision} \equiv \%\boldsymbol{P} = \left(\frac{M - M_{avg}}{M_{avg}}\right) \times 100\% \tag{2}$$

where M_{avg} is the average value of a series of measurements.

In both cases, the goal of any experiment or measurement is to have ***%E*** and ***%P*** as small as possible. We can use the **average precision, *%P*** —

In both cases, the goal of any experiment or measurement is to have ***%E*** and ***%P*** as small as possible. We can use the **average precision,** $\%\boldsymbol{P}_{avg}$**,** to characterize the general uncertainty in a set of measurements. $\%\boldsymbol{P}_{avg}$ is simply the average of the absolute values of the ***%P***'s for a set of measurements and reflects the size of the overall scatter of a set of measurements about their mean value. So, if you wanted to tell someone how long this page was, you would measure it several times and report M_{avg} with an average relative uncertainty of $\%\boldsymbol{P}_{avg}$.

There is a good reason for measuring the page several times and taking an average value. When we use tools to assign a number to a physical quantity, some error is introduced into the measurement. If the error introduced has a pattern, it is called ***systematic***. If it has no pattern, it is called ***random*** error. For example, if your bathroom scale reads 5 lbs when no one is standing on it, a systematic error will be introduced into measurements made with the scale, since each measurement would be 5 lbs too large. If you were to measure the length of a candle flame in a drafty room, some of your measurements would be too large, and some too small. These random errors, introduced by the flickering of the flame, can be minimized from the data by taking an average of a series of measurements. During the averaging process, the measurements that are too small will cancel those that are too large. As more and more measurements are made, the average value converges to the true value. Note that averaging will not cancel systematic errors.

Lab Procedure

Go to the experiment station that has the least number of people waiting. Follow the instructions for that station, given below, and measure each item five times. Make your measurements to the highest precision that your measuring device will allow. Record your results in your Excel spreadsheet or in the Data Tables at the end of the lab writeup. Continue moving to different stations until you have finished all four experiments.

After you have recorded your measurements from all the stations, compute the average values and insert them in the Data Table. Next, compute the precision ***%P*** of each of the individual measurements, using Equation 2 above, and record these values. Finally, compute the mean precision $\%P_{avg}$ of the measurements for each of the stations, using the absolute values of ***%P*** and insert them in the Table

Station 1 - Reaction Time I: The time it takes to respond to a stimulus is called reaction time. Human reaction time can be measured in a variety of ways. A simple method to determine human reaction time uses the principles of uniformly accelerated motion of a falling object. In the seventeenth century Galileo showed that the distance an object falls at the Earth's surface is directly related to the square of its time in the air, if the object started at rest. The formula is:

$$t = \sqrt{\frac{2d}{980}} \quad seconds \qquad (3)$$

Where the distance d is expressed in cm. You will use this consistent behavior of motion on Earth to determine your reaction time.

This measurement requires you to work with a lab partner. You will, however, have your own set of reaction times to work with each. Have your lab partner hold the top of a ruler so that it is vertical. At the lower edge of the ruler – at 0 cm place your index finger and thumb as if you are attempting to grab it. As soon as your partner releases the ruler, grab it as fast as you can. Measure the distance the ruler has fallen. Do this at least 5 times. Make your measurements using the centimeter/millimeter scale and measure to the nearest millimeter. Record your drop distances in Data Table 1 and use Galileo's formula above to compute the drop distance into drop times. Transfer the Drop Times to Data Table 2 in the lines designated for Station 1. ***To get a good estimate of your reaction time, your lab partner should try not to telegraph his/her intentions to drop the ruler. Also, the "catcher" should have his/her arm resting on the edge of the table and keep it there. This will prevent the hand from jerking up or down – which would invalidate the measurement***

Station 2 - Reaction Time II: The station for this reaction time test is your computer. You won't need a lab partner. On your computer open a browser window and navigate to the Human Benchmark website at http://www.humanbenchmark.com/tests/reactiontime/ . Read the description on the web page. The test is simple. You will stare at a red block and, when it turns green, left-click the mouse. Your reaction time is the delay between the block turning green and you clicking on the mouse. Perform 5 trials, recording each reaction time in the appropriate box in Data Table 2. Record your reaction time in units of seconds. To convert from milliseconds (which the program uses), simply divide by 1000. ***First do one set of 5 trials to get used to the experimental setup. Then record your results for the second set of trials.***

Station 3 - Length of a Candle Flame: At this station – which is out in the hallway –a candle will be lit. With a *metal* ruler measure the length of the candle flame. Be careful that your do not burn the ruler (or yourself)! Make your measurements using the centimeter/millimeter scale and measure to the nearest millimeter. Make 5 measurements and record then in Data Table 2.

Station 4 - The Diameter of a Hole: An elongated hole is cut out of a piece of cardboard. With a metric ruler measure the diameter of the hole along 5 different directions. Make your measurements using the centimeter/millimeter scale and measure to the nearest millimeter. Record your measurements in Data Table 2.

Questions/Discussion

Question 1: Briefly discuss the possible sources of measurement error at each station. Identify **at least one** (there may be more!) potential source of random error and **at least one** potential source of systematic error for each measurement station:

a) Reaction Time I
b) Reaction Time II
c) Candle Flame
d) Hole Diameter

Question 2: Based on your values for $\%P_{avg}$, which series of measurements at Stations 1–4 was the most precise? What aspect(s) of the experiment do you think contributed to the high precision you obtained? Remember, the smaller the value of $\%P_{avg}$, the more precise the set of measurements.

Question 3: Which series of measurements at Stations 1–4 was the least precise? What aspect(s) of the experiment hindered your ability to make high precision measurements??

Question 4: You used two different techniques to measure your reaction time: Describe your results. Specifically answer the following questions: *How do your two different measurements compare with each other? How does your mean reaction time from Station 2 compare with those of all the other participants in the Human Benchmark test? (Go to* http://www.humanbenchmark.com/tests/reactiontime/stats.php *to see the results for a large group of participants) What is the mean? About what percentage of people are faster than you? What percentage are slower? Which experiment do you think is a more reliable measure of your reaction time? Station 1 or Station 2? Explain why. What do you think you could do to increase the accuracy of your Human Benchmark results? Of your ruler Drop results?*

Question 5: Dick, Jane, Sally, having received degrees in paleontology, each measure the length (in meters) of a dinosaur bone unearthed by their team leader Spot. Their results are:

Dick	Jane	Sally
2.0	7.3	7.0
2.1	9.4	7.3
1.9	5.1	7.2
2.0	7.5	7.5

They were confused by these results and weren't sure who had gotten the right answer, so they called in Spot. Spot, being a world-renowned expert in bones, quickly determined that the true length of the bone was 7.3 meters.

Among Dick, Jane, and Sally:

a) Whose measurements are both accurate and precise? Explain your answer
b) Whose measurements are precise but inaccurate? Explain
c) Whose measurements are accurate but imprecise? Explain
d) Whose measurements are probably affected by a systematic error? Explain

Question 6: Which is affected by a systematic error: precision or accuracy? Explain.

Data Table 1: Ruler Drop Experiment

Trial #	Drop Distance (cm)	Drop Time (sec)
1		
2		
3		
4		
5		

Data Table 2: Experimental Results

Station	Measurements	%P	ABS(%P)
Reaction Time I (sec)			
Average = ________			
$\%P_{avg}$ = ________			
Reaction Time II (sec)			
Average = ________			
$\%P_{avg}$ = ________			
Candle Flame (cm)			
Average = ________			
$\%P_{avg}$ = ________			
Hole Diameter (cm)			
Average = ________			
$\%P_{avg}$ = ________			

Lab Report Cover Page

Astronomy Laboratory - Planets
Mendel Science Experience 2150
Fall 2019

Lab B
<u>Measurments and Experimental Uncertainty</u>

Student Name: ____

Lab Section: __________

Date: __________

Lab C
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.

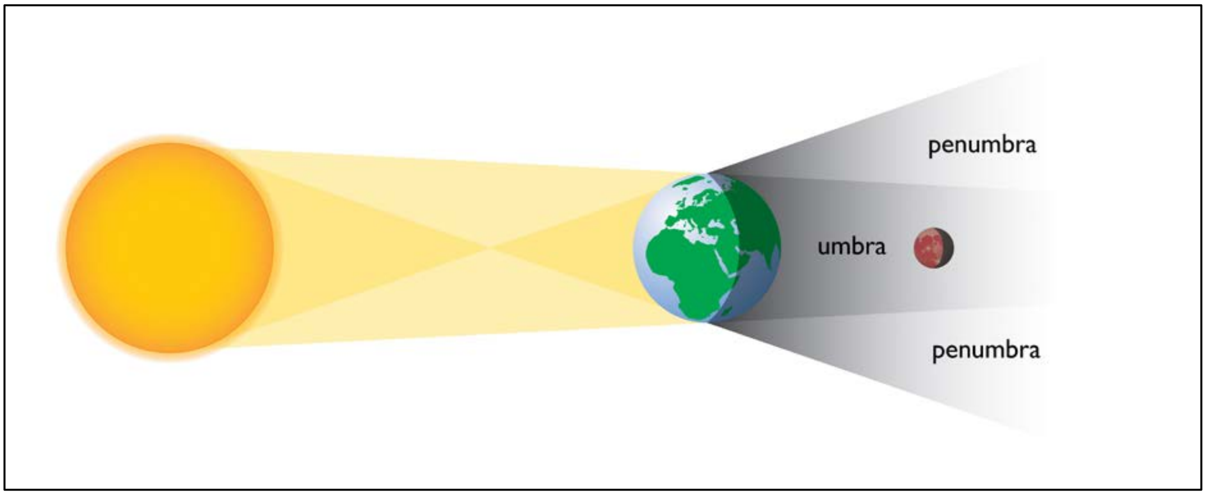


Figure 1: The geometry of a lunar eclipse. The figure is NOT drawn to scale. Source: Megapixl.com

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?*

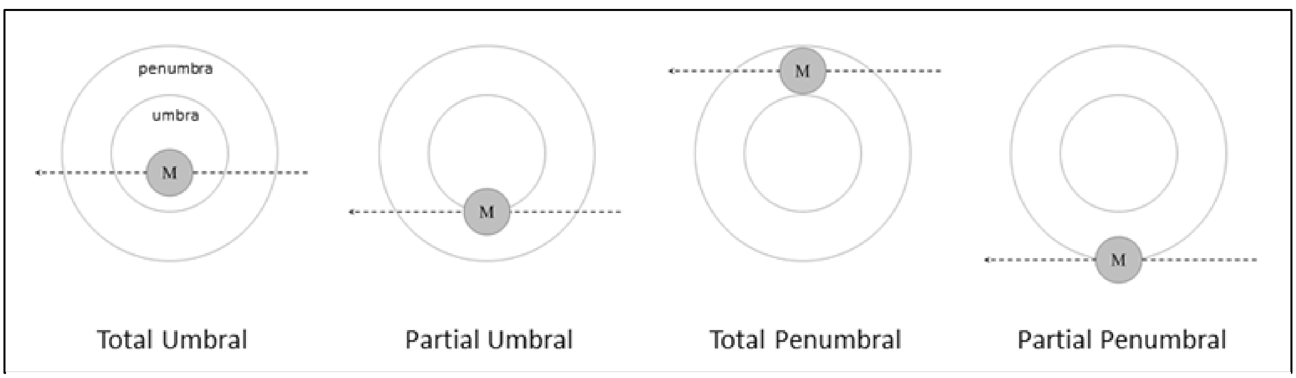


Figure 2: The different types of lunar eclipses

Observing Eclipses with *Starry Night College*

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!

Step 1: Starting up Starry Night College

Launch the *Starry Night College* program by double-clicking the *SN7* icon that appears on your lab computer's Desktop. The program opens with a view of the sky as seen from the roof of the Mendel Science Center, facing towards the south. The tool bars across the top of the image contains the date and time corresponding to your view of the sky and a number of drop-down menus allowing you to access the many options available in the program. (See **Appendix II** at the end of the Lab Manual.)

Step 2: Getting Ready for the First Eclipse

We will begin this lab by examining a recent set of Lunar Eclipses. Click **Favorites, MSE 2150, Lunar Eclipse Lab.** You should now see a nearly full Moon in the middle of the screen at midnight on August 7, 2017. 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.

Step 3: Measuring the Contact Times

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 Time Step 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 **Table 1**, in the "ECLIPSE A1" column. *Note that there will be no values for CT_2 and CT_3 unless the eclipse type is Partial or Total Umbral!*

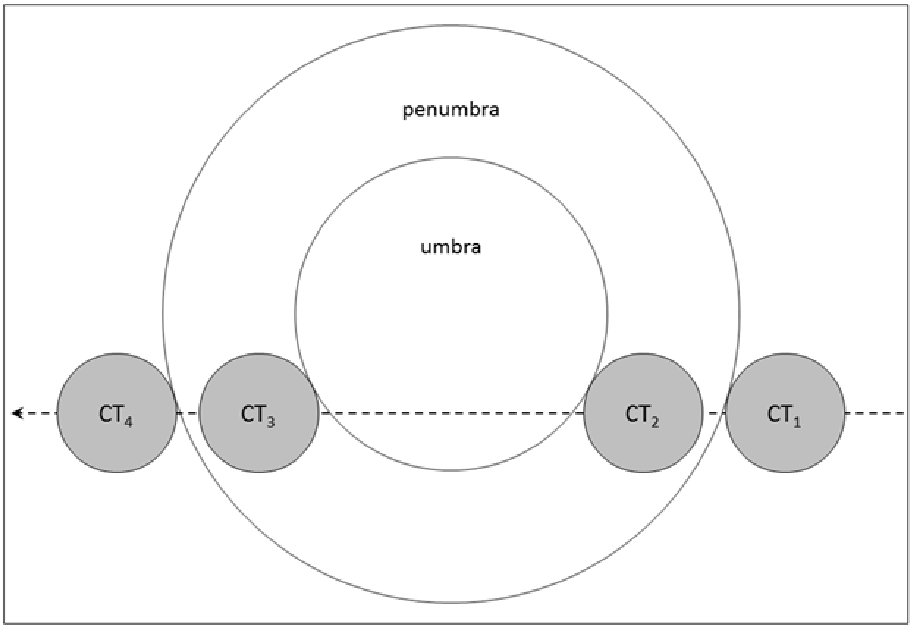


Figure 3: Eclipse Contact Times

Step 4: 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. We will use this fact to examine two more eclipses.

Use the Time Step menu to set the time step to 177 days, then step ahead *once*. 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**.

Now let's do one more eclipse. Once again, jump ahead by 177 days, find the shadow target and measure the eclipse times. Record all the data in the "ECLIPSE A3" column of **Table 1**.

Step 5: Characterizing the Eclipses

You should now have Contact Time data for three eclipses in **Table 1**. Compute the Duration of each eclipse (in 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. Now compute the Julian Date of the midpoints of the eclipses and enter in **Table 1**. The midpoint of an eclipse is simply the average of your 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 each of the midpoint dates. If you have done your calculations correctly, the Moon should be halfway through each eclipse. On **Figure X** ("Eclipse Set A"), draw an image of the Moon showing its location within the umbra or penumbra at the midpoint. Also, draw an arrow showing the path of the Moon across the shadow. Label these arrows "A1", "A2", and "A3" to identify each eclipse. **Make your drawings carefully and accurately. Draw the Moon in the correct scale relative to the**

shadow. (It should be about the size of a Quarter.) Your drawings should look something like one of the panels in **Figure 2** (except with 3 moons!).

Based on your observations, what types of eclipses did you observe? Record the types in **Table 1**.

> ***Question 3****: From an examination of the altitudes you recorded for your 3 eclipses, were any of them visible from Villanova? If so, how much of the eclipse will was 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 noticed that almost 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

Set up *Starry Night College* for the date and the mid-eclipse time for the first eclipse you viewed above (ECLIPSE A1). Change the field of view to about 60°, and the Time Step to 18 years. Step ahead *once*. Now change the Time Step to 1 day and begin to step ahead until you see the Earth’s shadows approach the Moon. ***Caution! If you’ve stepped ahead by more than 20 days without seeing the Earth’s shadow target, something is wrong! Go back and try again!***

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 Table 2 in the column labeled “ECLIPSE B1”.

Now jump ahead 177 days, find the next eclipse, and repeat your measurements. Record in **Table 2** (“ECLIPSE B2”).

Finally, jump ahead another 177 days 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****: Examine Tables 1 and 2 and Figures X and Y. Comment on the eclipse patterns you’ve observed. Are all lunar eclipses alike? Do all have the same duration? Now compare the pattern you observed in Eclipse Set A with that in Eclipse Set B. Are the patterns the same? Are the durations the same? 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			
Mid-Eclipse (JD)			
Duration (Hours)			
Mid-Eclipse (Calendar)			
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			
Mid Eclipse (JD)			
Duration (Hours)			
Mid-Eclipse (Calendar)			
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

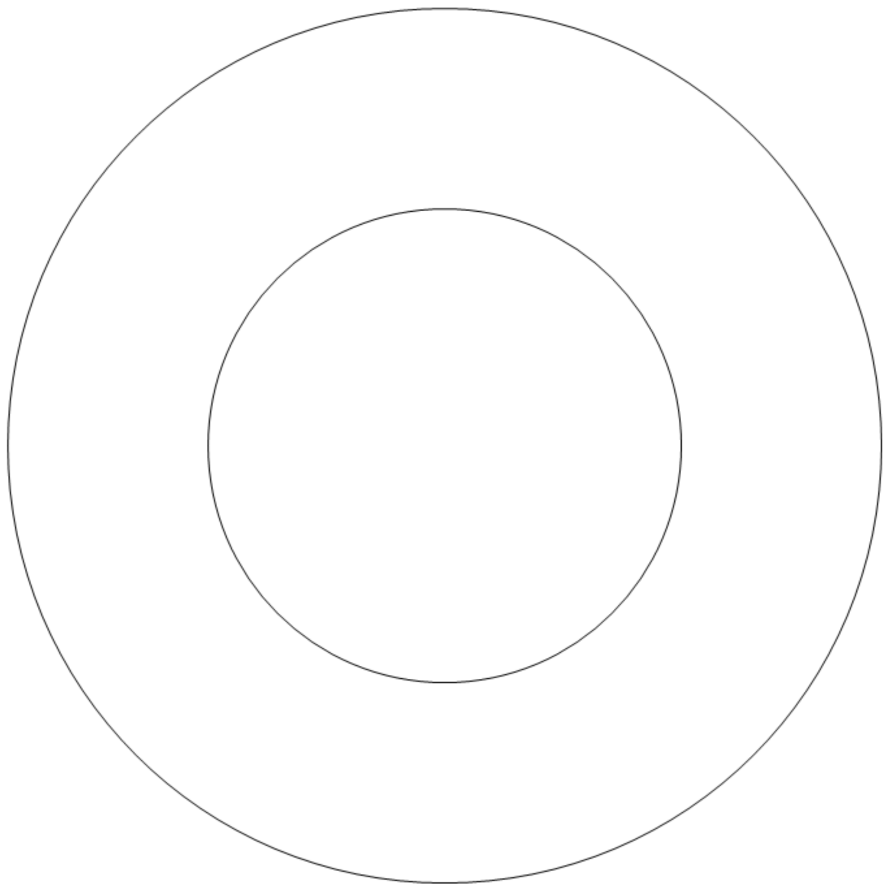
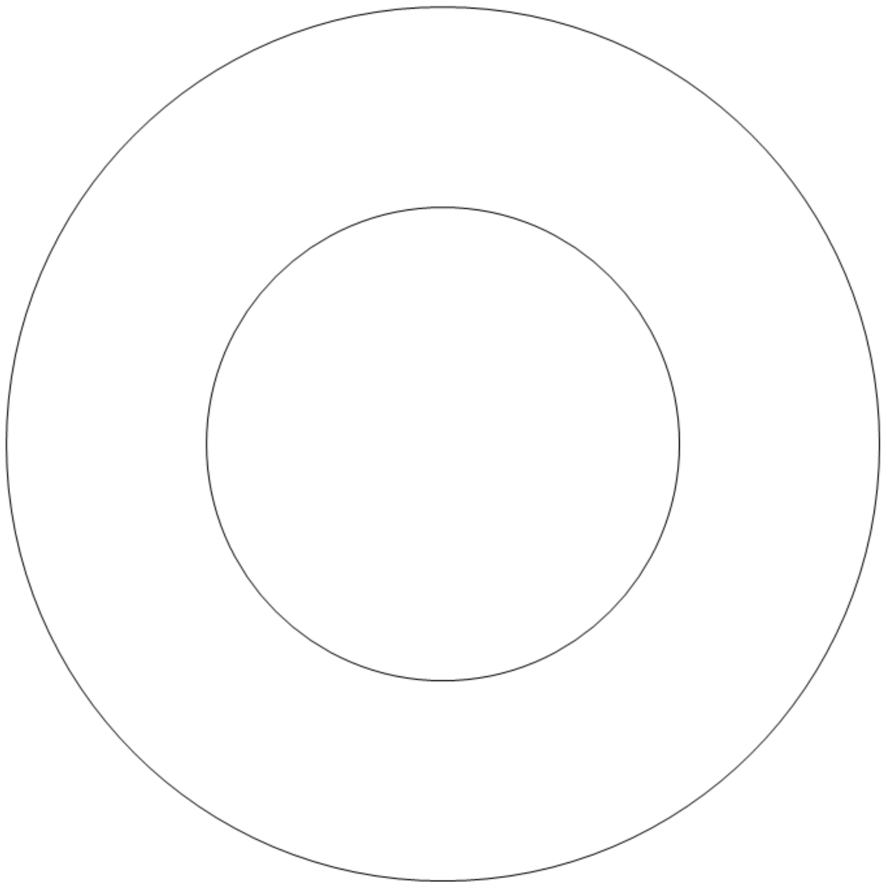


Figure Y: Eclipse Set B



Lab Report Cover Page

Astronomy Laboratory - Planets
Mendel Science Experience 2150
Fall 2019

Lab C
<u>Lunar Eclipses and the Saros Cycle</u>

Name: ____

Lab Section: __________

Date: __________

Lab D
The Next North American Total Solar Eclipse

PURPOSE:

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

EQUIPMENT:

Starry Night College computer program.

Solar 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'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 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.

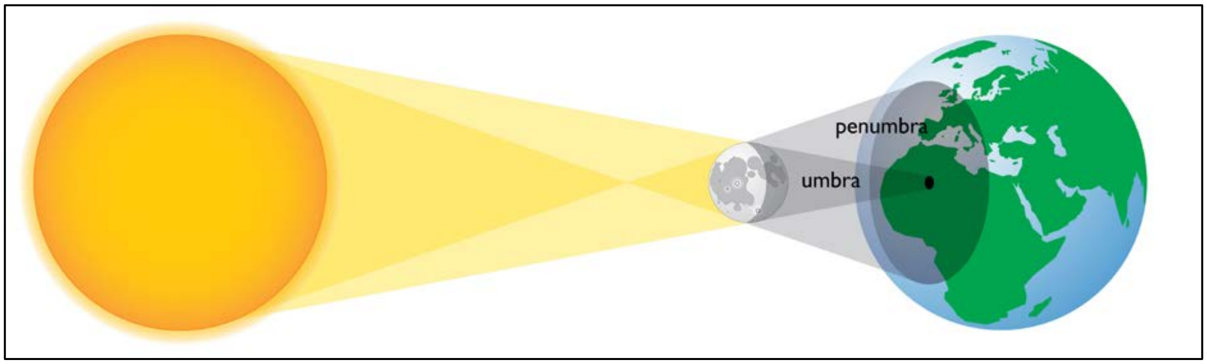


Figure 2: The geometry of a solar eclipse. The figure is NOT drawn to scale. Source: Megapixl.com

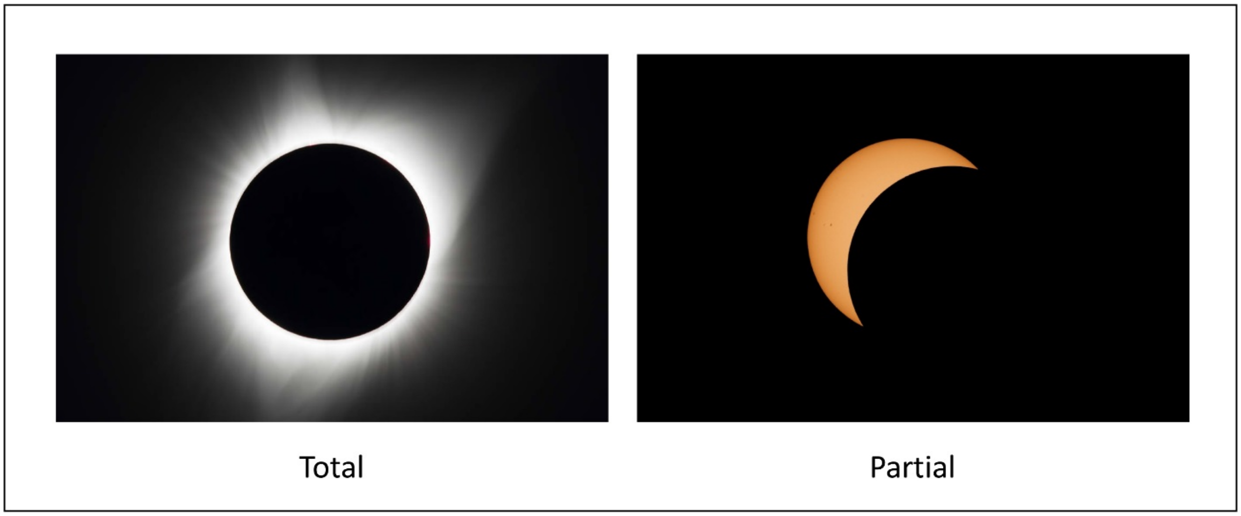


Figure 1: The Different Types of Solar Eclipses

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 Next 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 has scheduled a repeat performance on April 8, 2024. In this lab you will use *Starry Night College* to examine this upcoming eclipse, and have the opportunity to view it from the surface of the Earth, the surface of the Moon, and the surface of the Sun.

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 will enter the U.S. in Texas, travel diagonally across the country, and exit in Maine. As you just learned above, viewing this eclipse will require 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 prepare for the trip to Niagara Falls, first 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. To go to Niagara Falls, click **Favorites, MSE2150, Solar Eclipse Lab, Solar Eclipse from Niagara-1**. 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.

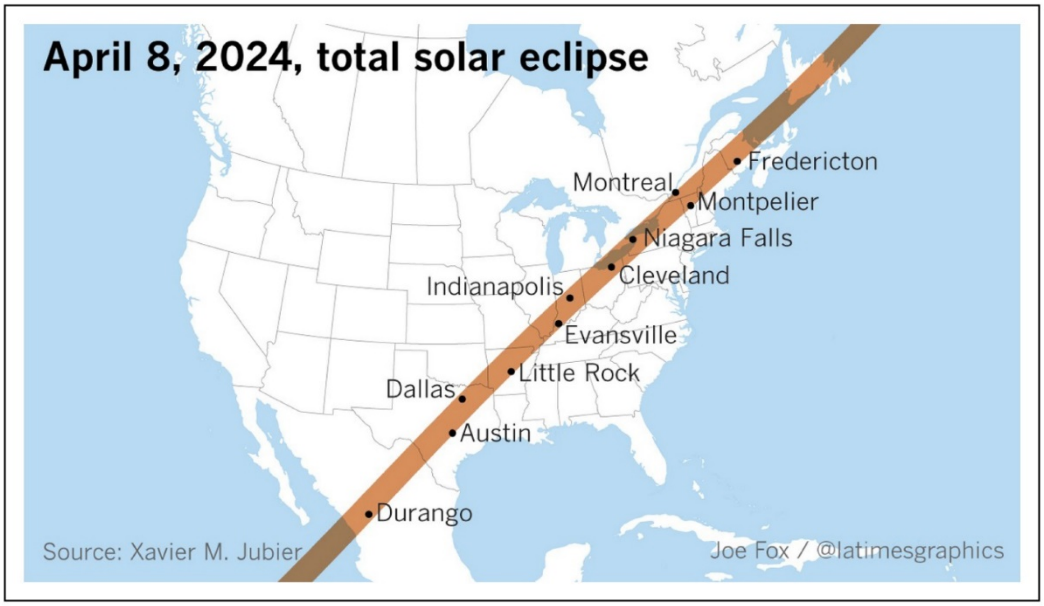


Figure 3: April 2024 Eclipse Path of Totality

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? 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? How long did this phase of the eclipse last? (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?*

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 4****: 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 5****: What is the total duration of the Total Eclipse (in 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 6****: About how fast is the umbra moving across the Earth's surface? 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 the 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.*

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, 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 7****: 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 2019

Lab D
<u>The Next North American Total Solar Eclipse</u>

Name: ____

Lab Section: __________

Date: __________

Lab E
Planetary Motion

PURPOSE:

To observe the motions of the planets across the sky.

EQUIPMENT:

Starry Night College computer program, calculator or Excel spreadsheet

The "Inferior" Planets

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 lab, 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 next March 1st 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.

Venus and Mercury should be clearly visible on the screen (as well as some of the other planets). The Time Step should already be set to 6 hours. Let time run freely forward by clicking the "play" button ("▶"). Carefully watch the motions of the Sun and the two inferior planets Venus and Mercury. They will 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.) 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 have to wait a few moments. 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 in **Table 1**.

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. 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.*

Question 4: *Now imagine that Venus and Mercury are at their respective GWE's. When would be the best time to observe them? In what direction would you look?*

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 1**, 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 opportunity to measure their orbital radii with simple naked-eye observations. The positions of the Earth and the inferior planet in Figure 1 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

$$r_I = r_{Earth} \sin\theta \qquad (1)$$

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 is determined in units of AU. Note that the same measurement and calculation could be made with the planet at GWE.

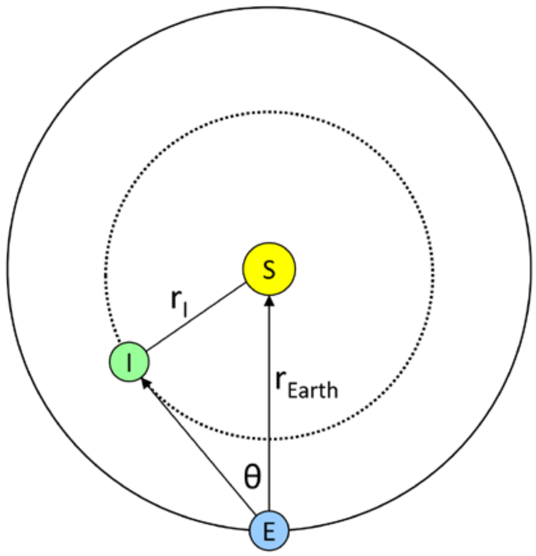


Figure 1: Relative positions of the Sun (S), the Earth (E) and an Inferior planet (I) during GEE.

Question 5: *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 1), 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?*

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. 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. 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 6:*** *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 7: *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 5? 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 2019

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

Kepler's Method

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.

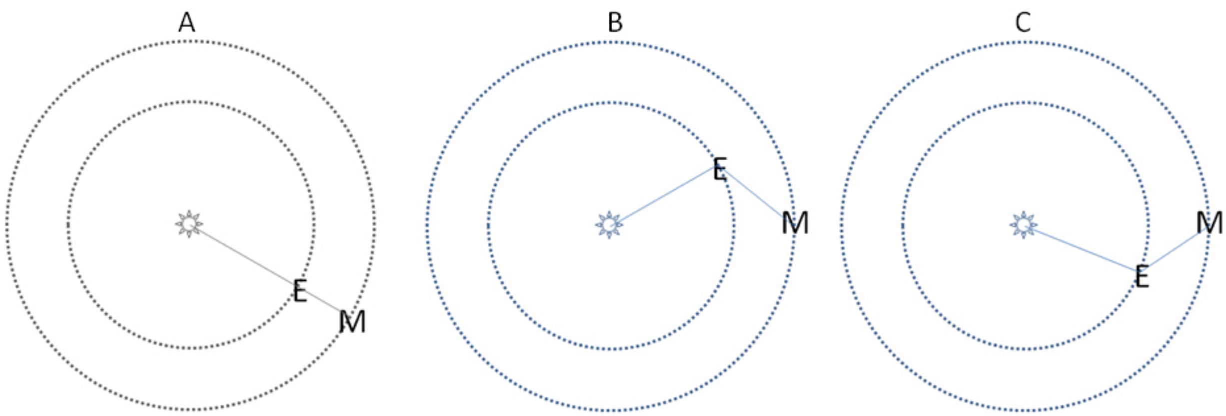


Figure 1: The relative positions of the Sun, Earth, and Mars in Kepler's Method

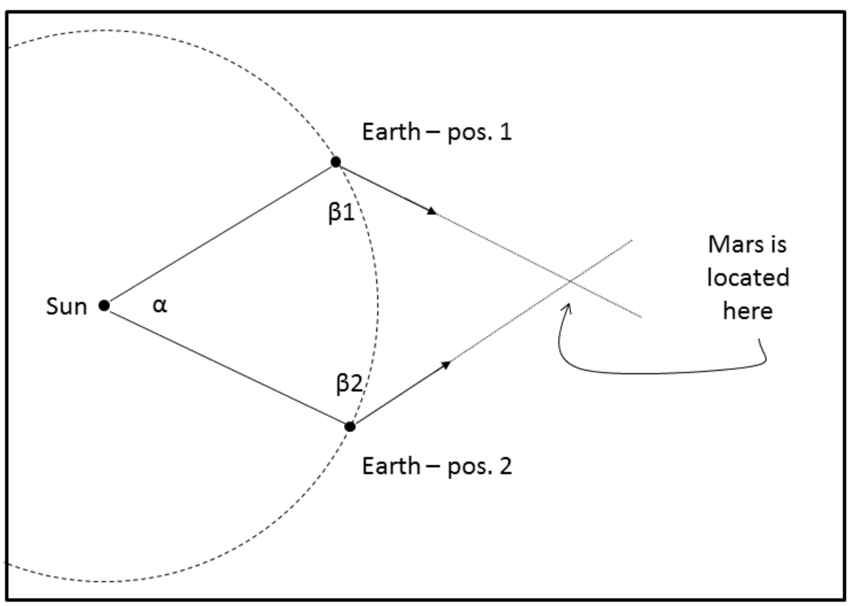


Figure 2: A graphical solution to the distance of Mars

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 September 1, 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 our location at the top of the Mendel Science Center. 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 +/– six 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.)

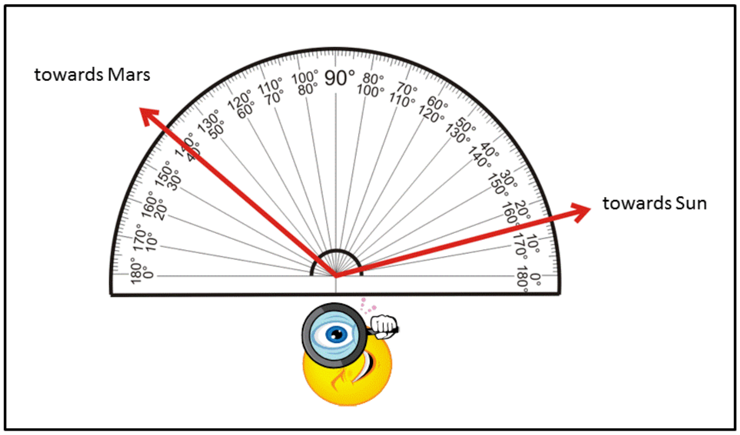


Figure 3: Measuring the Mars-Earth-Sun separation angle on the sky

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 the last page 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. Show all your measurements on the drawing.

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**. 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**.

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 really 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* <u>*exact*</u> *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 in part B - using triangulation - with the distance given by Starry Night Pro above? Did you get the same answer? To answer this question, you have to 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 − 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

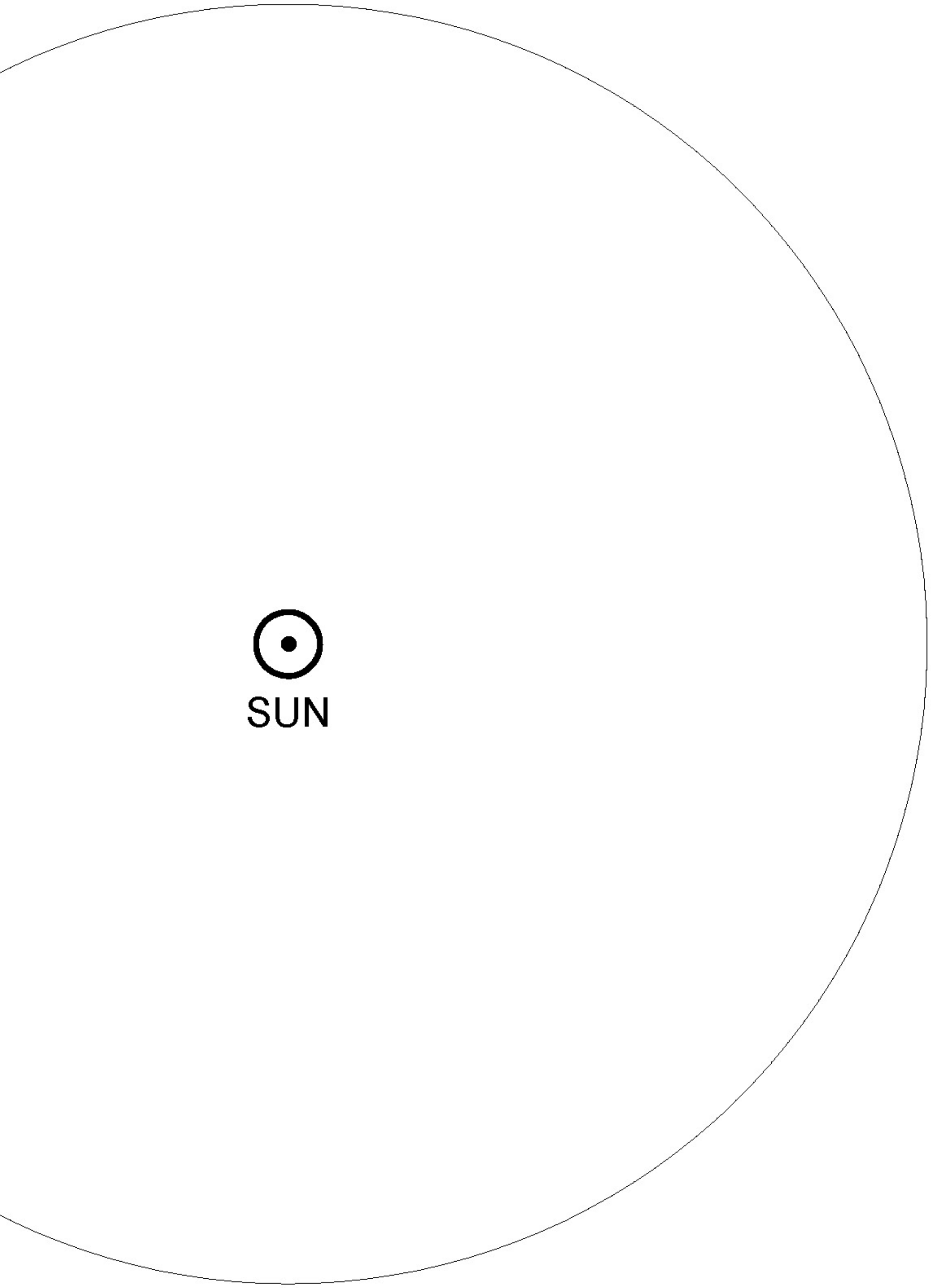
Mars-Sun distance (mm)	
Earth-Sun distance (mm)	
Mars-Sun distance (AU)	

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

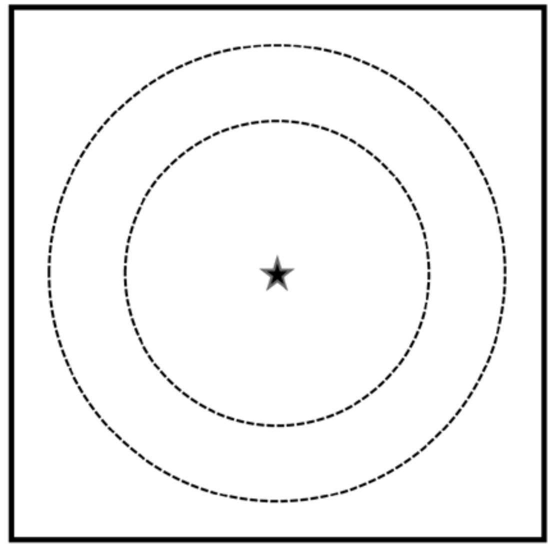
Calendar Date (mm/dd/yyyy)	
Mars-Sun distance (AU)	

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

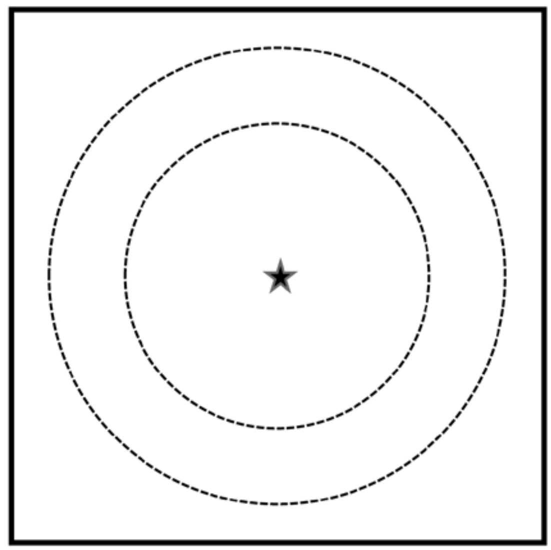
Minimum Mars-Sun distance (AU)	
Maximum Mars-Sun distance (AU)	
Percentage Change (Max-Min)/Average*100%	


SUN

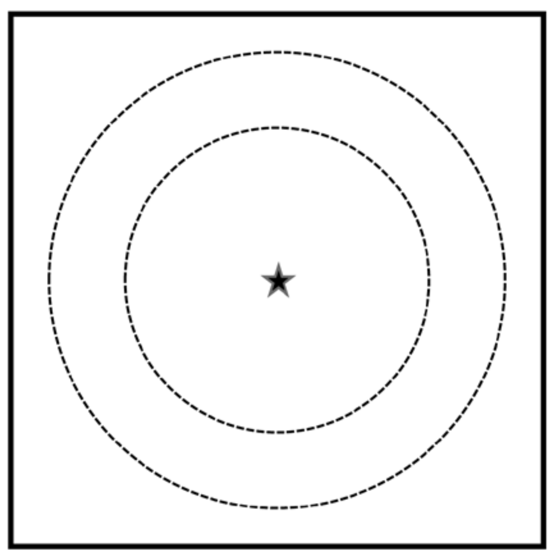
Question 1 Sketch:



Question 2 Sketch:



Question 3 Sketch:



Lab Report Cover Page

Astronomy Laboratory - Planets
Mendel Science Experience 2150
Fall 2019

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 motion of objects under the influence of gravity. Upon completion of this lab, you will be able to:

a) explain what is meant by "down" in terms of gravity
b) describe the role of mass in gravitational acceleration
a) describe the shape of orbits
b) describe the variations in orbital speed with position in the orbit
c) describe the relationship of orbital speed versus semi-major axis
d) construct a plot of period versus semi-major axis for an orbit

EQUIPMENT:

PhET interactive simulation program *My Solar System*; EXCEL spreadsheet

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 15th and 16th 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.

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

<u>Experimenting With Gravity</u>

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 the mid-point between Accurate and Fast
- Number of bodies set to 2

<u>*PART A: BODIES OF EQUAL MASS*</u>

Set up the simulation as follows:

- Mass for both bodies = 200
- Position for body 1: X= -200, Y=0
- Position for 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 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?*

<u>*PART B: BODIES OF UNEQUAL MASS*</u>

Set up the simulation as follows:

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

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

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 100, then 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 for body 1 = 500 (Earth)
- Mass for body 2 = 0.01 (the thing you're dropping)
- Position for body 1: X= -200, Y=0
- Position for 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
- Star location: X = 0, Y=0
- Star velocity: X=0, Y=0
- Planet location: X=100, 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 precise 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)?*

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 precisely 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 larger 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

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

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.

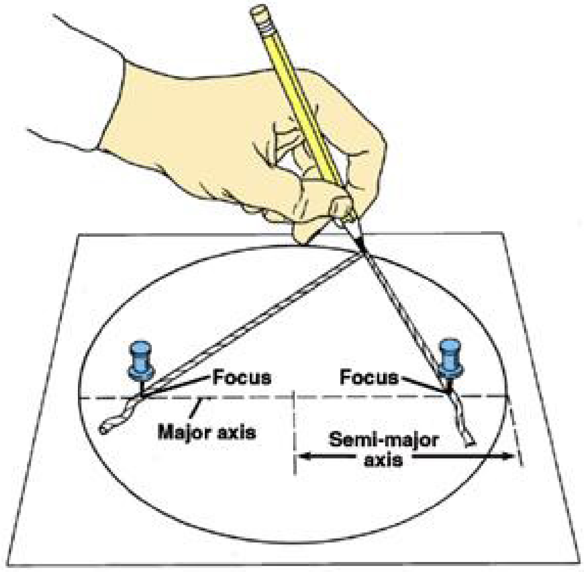


Figure 1

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?*

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

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
- Star location: X = 0, Y=0
- Star velocity: X=0, Y=0
- Planet location (X, Y) = (100, 0)
- Planet Y-velocity ~ 35 or 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?*

Kepler's Third Law:

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.)

In the simulation, set the (X, Y) position of the planet to (50, 0). For each X position in the table below, determine the precise Y-velocity for a circular orbit 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:

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

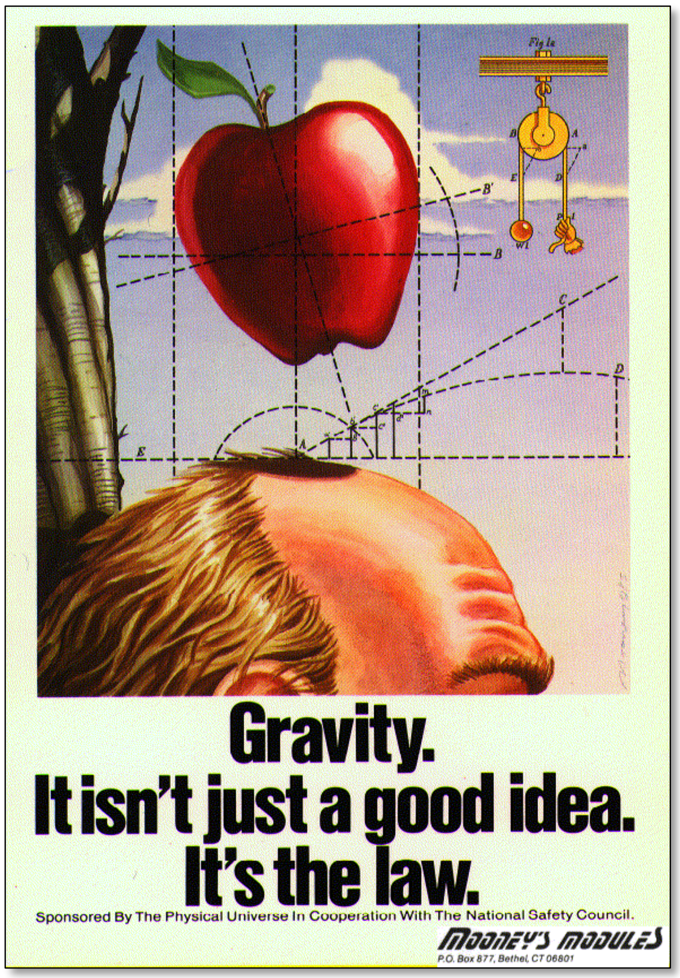
which can be simplified to:

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

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 size 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.)*


Gravity.
It isn't just a good idea.
It's the law.
Sponsored By The Physical Universe In Cooperation With The National Safety Council.
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Lab Report Cover Page

Astronomy Laboratory – Planets
Mendel Science Experience 2150
Fall 2019

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:

$$P^2 = C \times a^3 \qquad (1)$$

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:

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

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:

$$P^2 = \frac{4\pi}{GM_1} a^3 \qquad (3)$$

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:

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

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.

<u>Jupiter's Moons</u>

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 E*at *G*reen *C*arrots.") 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 perpendicular, or projected, distance of the moon to the line of sight between the Earth and Jupiter. The situation looks like this:

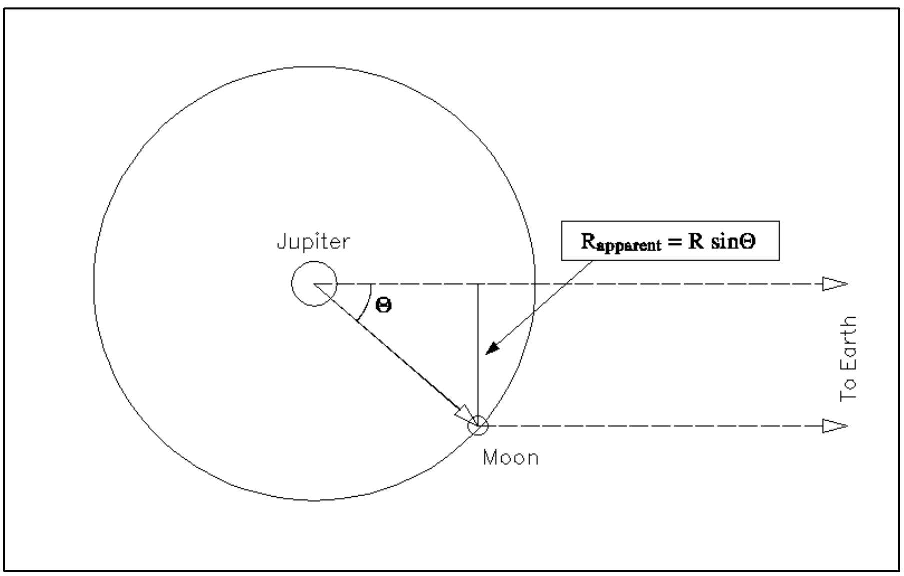


Figure 2: View of Jupiter and one of its moons from "above."

Therefore, the projected distance of the moon from Jupiter should be a sinusoidal curve if you plot it versus time. **By taking enough measurements of the observed – i.e., projected – 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

This lab could, in principle, be done by anyone with a set of binoculars or a small telescope. You will obtain data from at least 24 clear observing sessions making observations twice per evening, spaced 12 hours apart. (Such observations are possible only in the winter time when the nights are long.) However, the computer simulation program Revolution of the Moons of Jupiter will replace the actual outdoor observing sessions. The computer simulation is based on the actual orbital data for each satellite. As a matter of fact, 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 the observatory. On the computer screen, Jupiter and its moons will look much like they would through a telescope, with west to the right and east to the left. The program will allow you to measure the projected distance of each of the moons from the center of Jupiter in units of Jupiter diameters (D_J).

SETTING UP THE PROGRAM:

Launch the Revolution of the Moons of Jupiter program by double clicking on its icon. The program simulates the operation of an automatically controlled telescope with a charge coupled device (CCD) camera that provides a video image to a computer screen. It has a sophisticated computer program that allows convenient measurements to be made at the computer console and you can adjust the telescope's magnification as well. The computer 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.

Click **File, Log In...** to enter the STUDENT ACCOUNTING screen. Enter your name. Do not use punctuation marks. When all the information has been entered to your satisfaction, click **OK** to continue. A set of start-up values are needed by the computer to establish your initial observation session. Each person will perform and analyze a *different* set of observations based on the date of your birth. First, click on **File, Run…** and 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. Next, click **File, Timing…** and set the **Observation Step** to 12.0 hours.

After you have entered this information into the computer (and pressed **OK**), it will display a screen like **Figure 3** below.

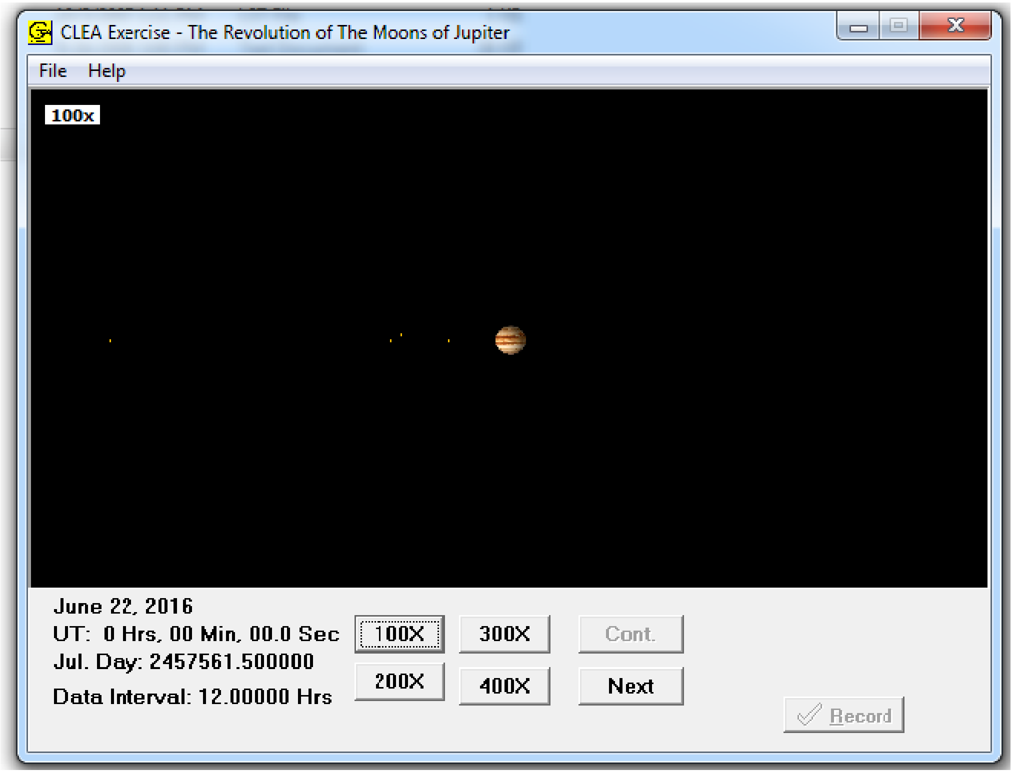


Figure 3: The Main Telescope Screen

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.

Now, center the 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.

TAKING DATA:

Now, 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 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.

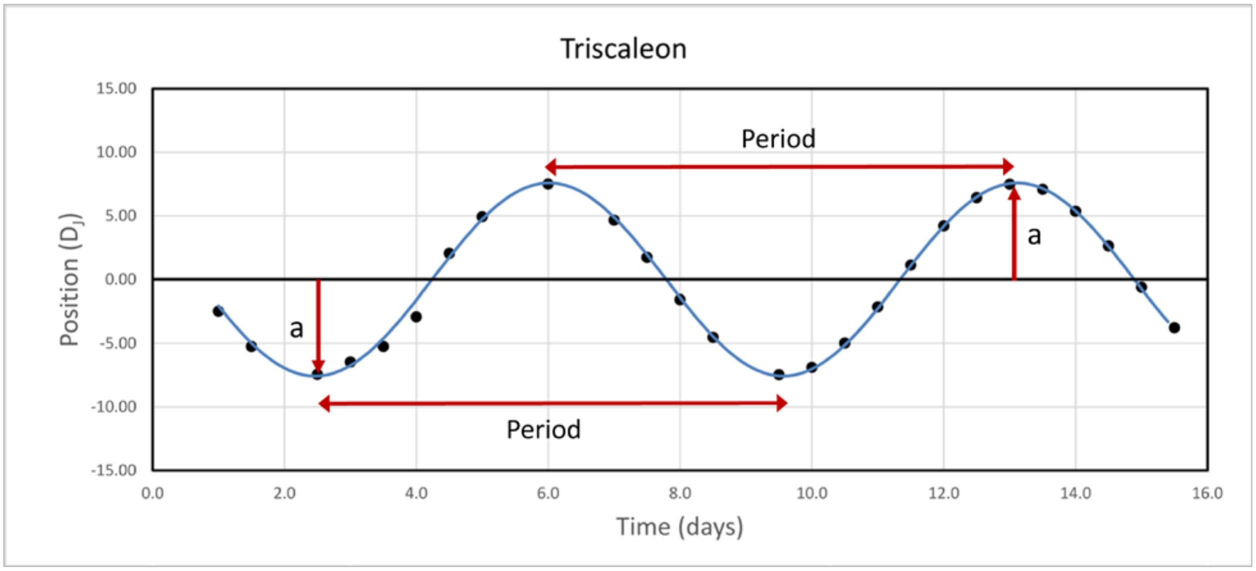


Figure 5: Measurements for the imaginary moon Triscaleon

Analyzing YOUR Data

Using EXCEL, plot time (from column 1 of the **Table 1**) versus D_J for the moons **Europa** and **Ganymede** on separate graphs. Label the axes in the graphs and put the name of the moon and your name above each graph. Make sure you plot gridlines on your graphs to make it easier to measure *P* and *a* (the more gridlines, the better). Your data should be plotted using the "scatter" option without connecting lines or curves. ***Now print a full-page copy of each plot. (Use landscape mode.) You'll use these plots to measure P and a.***

Using your printed graphs, draw in by hand your estimate of the sine curves that best fit your data. ***Use Figure 5 for reference and follow the "rules" described in the section above for properly drawing the sine curves!***

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*.

REMEMBER!
You must indicate on your graphs exactly how you measured 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:

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

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 M_J, 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. 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:		

Lab Report Cover Page

Astronomy Laboratory – Planets
Mendel Science Experience 2150
Fall 2019

Lab H
<u>Measuring the Mass of Jupiter</u>

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.

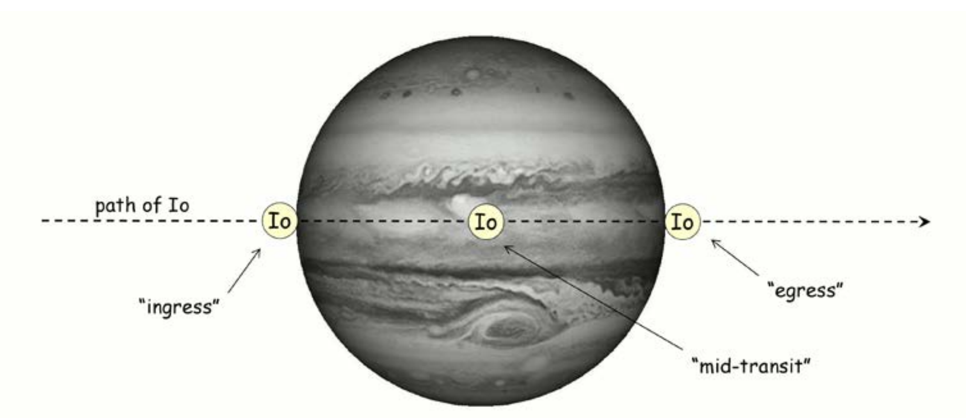


Figure 1: A schematic view of a transit of Io across Jupiter

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.

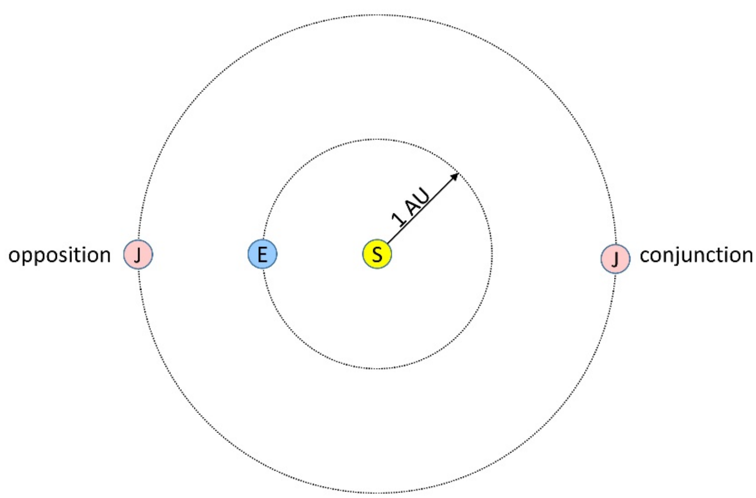


Figure 2: Relative positions of Sun (S), Earth (E), and Jupiter (J) at Opposition and Conjunction

MEASURING IO'S SYNODIC PERIOD:

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. Set the simulation to this time to verify Io's position.

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? We want the Jupiter-Earth distance to be the same at the beginning and end of our measurements, to be sure that there are no errors introduced by different pathlengths traveled by the "ticks" of the clock. This means that we would like to jump ahead to the next Opposition of Jupiter. This event will occur in a little less than 400 days. We have a rough idea (from a recent lab!) that the period of Io's orbit around Jupiter is about 1.77 days. So, a jump of 224 orbits would take about 396.5 days to occur and would return the Jupiter-Earth distance to its current value.

Using the Time Step Menu, step ahead 396 days. 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. Set the simulation to this date and time to verify Io's position at mid-transit.

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 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, because you essentially averaged the results from 224 periods to get your answer.

PREDICTING A FUTURE TRANSIT:

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

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 roughly 200 days, which 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:

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

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:*

$$\%\mathrm{E} = \frac{\text{observed value} - \text{accepted value}}{\text{accepted value}} \times 100\% \tag{1}$$

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 2019

Lab I
<u>Roemer's Measurement of the Speed of Light</u>

Name: ____

Lab Section: __________

Date: __________

Lab J
Comets

Adapted from: *Planet Earth*, Maloney & Maurone

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:

PhET interactive simulation program "*Gravity*" and *Starry Night College* computer program,

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 *my-solar-system_en.jar*[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 30. Start the simulation, noting 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.**

> ***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., ~10%, 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.

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

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
- 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 = [0,30-40]
- For 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? Does the comet "know" that Jupiter is present? What effect does Jupiter have on the comet's orbit?*

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 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!

Now let's 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 will have to measure the separation between the comet and the Earth 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.)*

<u>COMET SWIFT-TUTTLE:</u>

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 <u>very close</u> 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 July 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:*** *What happens every year when Earth runs through Swift-Tuttle's orbital 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?*

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 2019

Lab J
Comets

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.

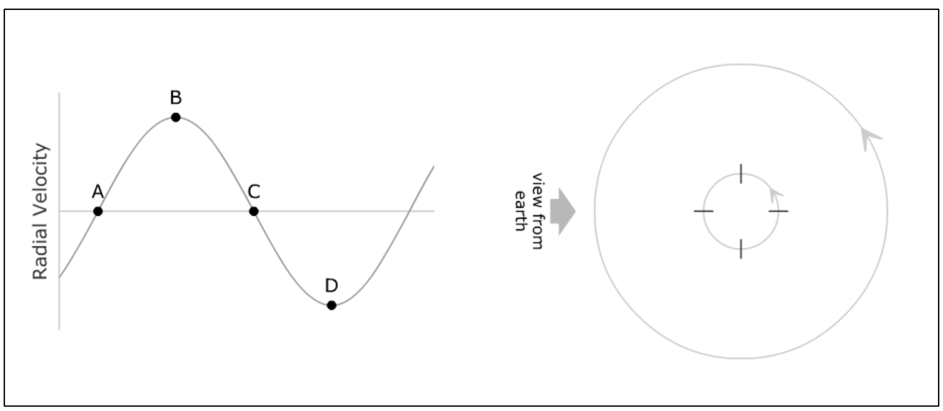
EQUIPMENT:

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

Background Material

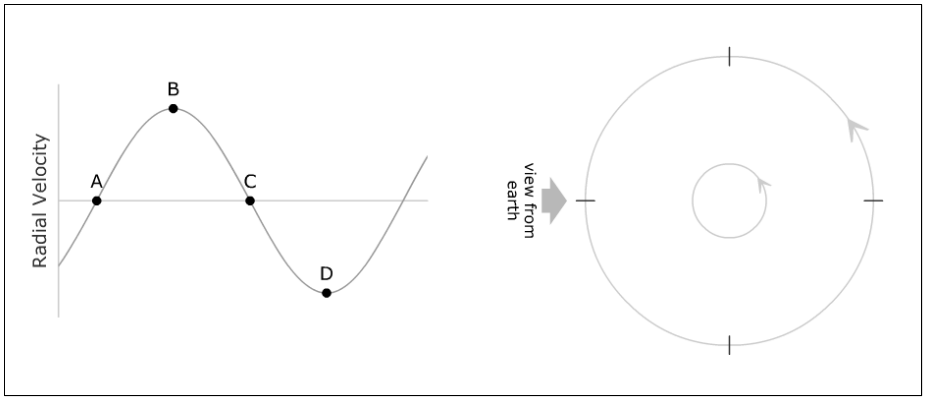
Review the Background pages entitled *Introduction*, *Doppler Shift*, *Center of Mass*, and *ExtraSolar Planet Detection*. Then complete the following two questions. Answer the questions using the larger versions of the figures found on page 9 of the lab write-up.

> ***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.*



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

Question 2: *Label the positions on the <u>planet's orbit (i.e., the outer orbit)</u> 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 Exoplanet Radial Velocity Simulator

Open the *Exoplanet Radial Velocity Simulator*. You should note that there are several distinct panels:

- 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 versus phase for the system. 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.

- There are three panels which 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 (effectively, 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}? *Remember that the radial velocity curve you are measuring is that of the star – not the planet.)*

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 (i.e., which would have a radial velocity curve with the largest amplitude): 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?*

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 (i.e., radius) of the planet's orbit? How is the period of the system affected?*

Question8: *Which would be easiest to detect, a planet with a very large orbital radius (and long period) or a planet with a small orbital radius (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* <u>*radial*</u> *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 a combination of planet mass and inclination angle that gives the same maximum amplitude as for the case of 2 M_{Jup} and 30°? What is the mass, inclination angle, and maximum amplitude?*

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 determine the mass of the planet? Are there any limits you can place on the planet's mass?*

<u>*ELLIPTICAL ORBITS:*</u>

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? Explain.*

Now move the "longitude" slider back and forth. Notice the effect this has on the observed radial velocity curve.

Question 14a*: Describe what the longitude parameter means. Is longitude a property of the exoplanetary system? Or a property of the observer? Explain.*

Question 14b*: Describe how changing the longitude affects the shape of the radial velocity curve. Do you think it is possible to infer the longitude from the shape of the radial velocity curve for an elliptical orbit? Explain. Would this work for a circular orbit?*

“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.” 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. **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 15:*** *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 16:*** *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 17:*** *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 of 3 m/s. ***Thus, for a detection to occur, the radial velocity curve must have a sufficiently large amplitude and the orbital period of the planet should be less than the duration of the project.*** (In practice, astronomers usually need to observe several cycles to confirm the existence of the planet.) 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.

__Question 18__: 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?

The Exoplanet Transit Simulator

Open the *Exoplanet Transit Simulator*. 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 19:__ 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 2000 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 20:__ 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.

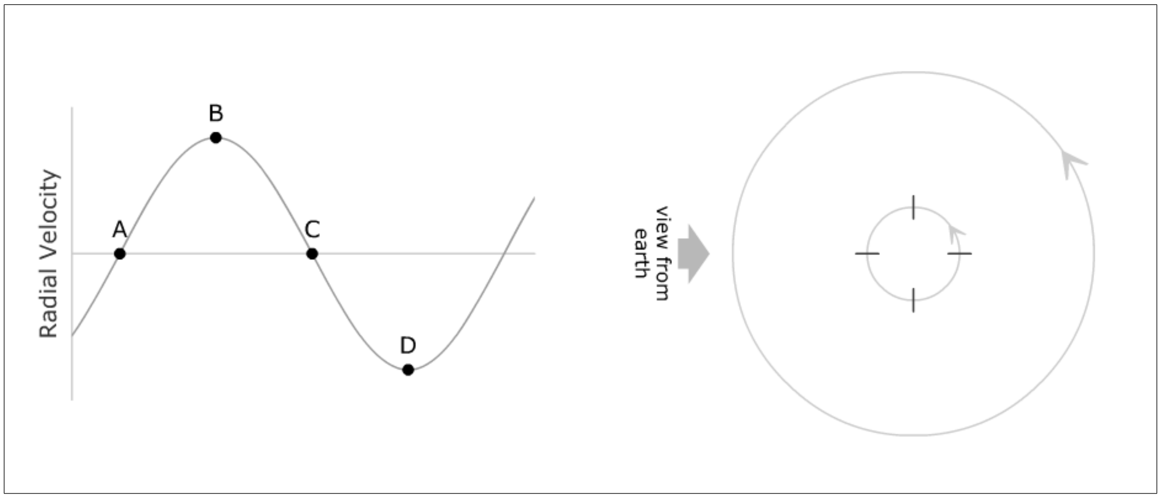
__Question 21:__ How long does the eclipse of an Earth-like planet in an Earth-like orbit around a Sun-like star take? How much time passes between eclipses? What obstacles would a ground-based mission to detect Earth-like planets face?

Data Table 1

Planet's Mass (MJup)	Orbital Radius (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**							

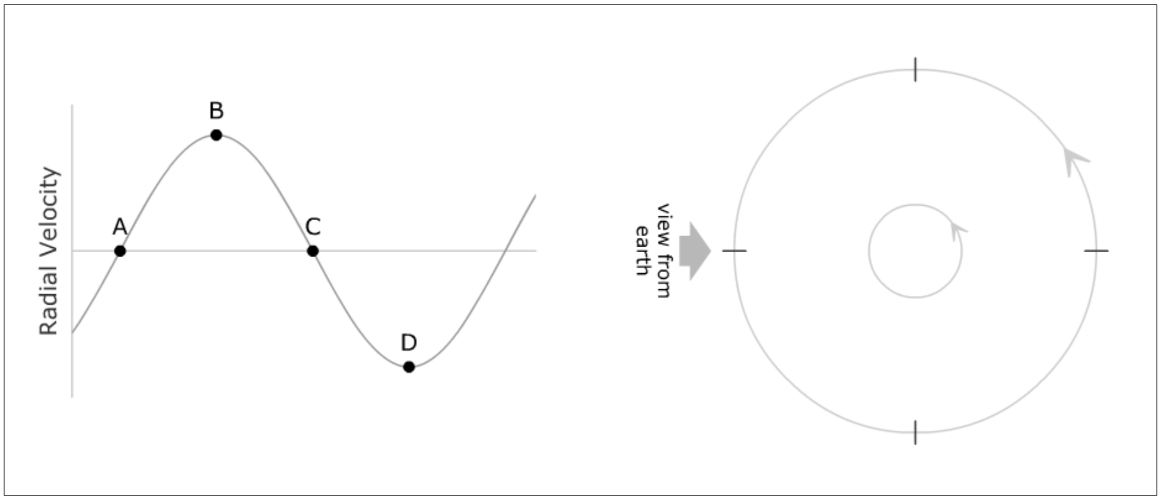
Question 1

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



Lab Report Cover Page

Astronomy Laboratory – Planets
Mendel Science Experience 2150
Fall 2019

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*

Background Material

Read through the Background pages entitled *Life*, *Circumstellar Habitable Zones*, and *The Galactic Habitable Zone* before working on the exercises below.

The Circumstellar Habitable Zone

Open the Circumstellar Zone Simulator (i.e., double-click "*NAAP_StellarHabitableZone.swf*"). There are four main panels in the display screen:

- The top panel simulation displays a visualization of a star and its planets looking down onto the plane of the planetary system. The habitable zone is displayed for the particular star being simulated. One can click in the panel and drag 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 one 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 one 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,

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

sometimes, mass. The changing stellar properties can be followed in the display in the Star and Planet Settings and Properties panel. A number of 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. One can change the planet's distance from the Sun either by dragging it or using the planet distance slider. Try moving it around. Note that the appearance of the planet changes depending upon its location. It appears quite earth-like when inside the circumstellar habitable zone (hereafter CHZ). However, when it is dragged inside of the CHZ it becomes "desert-like" while outside it appears "frozen". Remember that our simple definition of the CHZ is the region around the star within which liquid water could exist on a planet's surface.

SIZE & LOCATION OF THE CHZ:

Now drag the planet to the inner boundary of the CHZ (i.e., the point at which it changes its appearance) and 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 on page **9** of the lab write-up.

Now explore the width of the CHZ for other stars. Complete Data Table 2 on page **9** 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 location of the CHZ for different types of stars?*

Question 2: *Again, using Data Table 2, what general conclusion can be made regarding the width of the CHZ for different types of stars?*

Question 3: *If the likelihood of a planet lying in the habitable zone depended only on the width of the CHZ, then which type of star would most likely have planets in the habitable zone? 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).

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 Table 2. Repeat this experiment a variety of initial stellar masses and record these data in Data Table 2. (Watch out for units! I.e., My vs. Gy.)

> ***Question 4:*** *Based on your data in Table 2, 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 a planet lying in the habitable zone depended only on the length of time a planet could stay in the CHZ, then which type of star would most likely have planets in the habitable zone? 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 white dwarf star and no longer supports fusion)?*

> ***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 mass in its final stages, which reduces its gravitational hold on 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 in to the CHZ. Notice that the planet is shown with a dashed line through its middle. 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 thing for the emergence of life!** (However, a thick atmosphere could theoretically spread the heat around the planet, as happens on Venus. In answering the following questions, please put aside this possibility.)

> ***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 3 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 low enough, 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 Table 2 and 3 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)_________. If the mass of a star is too low, then _________(write the bad thing)_________. The mass range that appear to be "just right" for the presence of complex life is _________."

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.

Open the Milky Way Habitability Explorer (i.e., double-click "*NAAP_MilkyWayHabitability.swf*"). Each of the two factors described above are 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?*
>
> ***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?*
>
> ***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 _________."

Data Table 1: Solar System CHZ Properties

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

Data 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)	Time in CHZ (Gy)
0.3					
0.7					
1.0					
2.0					
4.0					
8.0					
15.0					

Data Table 3: Tidal Locking in the CHZ

Star Mass (M_{Sun})	Tidally Locked?
0.3	
0.5	
0.8	
1.0	**No**

Lab Report Cover Page

Astronomy Laboratory – Planets
Mendel Science Experience 2150
Fall 2019

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

Name: ____

Lab Section: __________

Date: __________

Appendix I

Microsoft Excel Tutorial

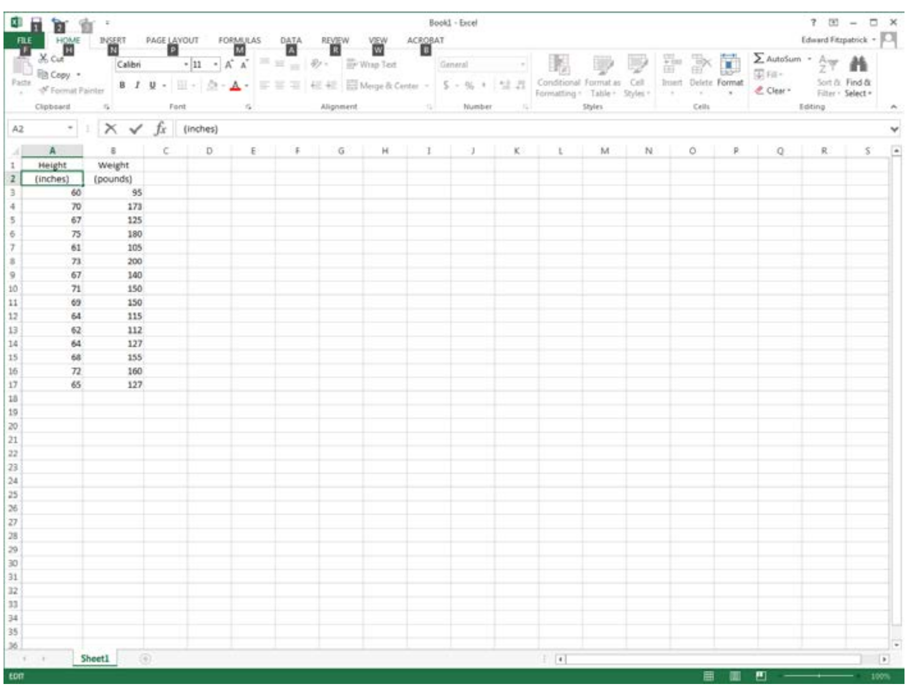
Microsoft Excel Tutorial

Creating a Linear Graph with Regression

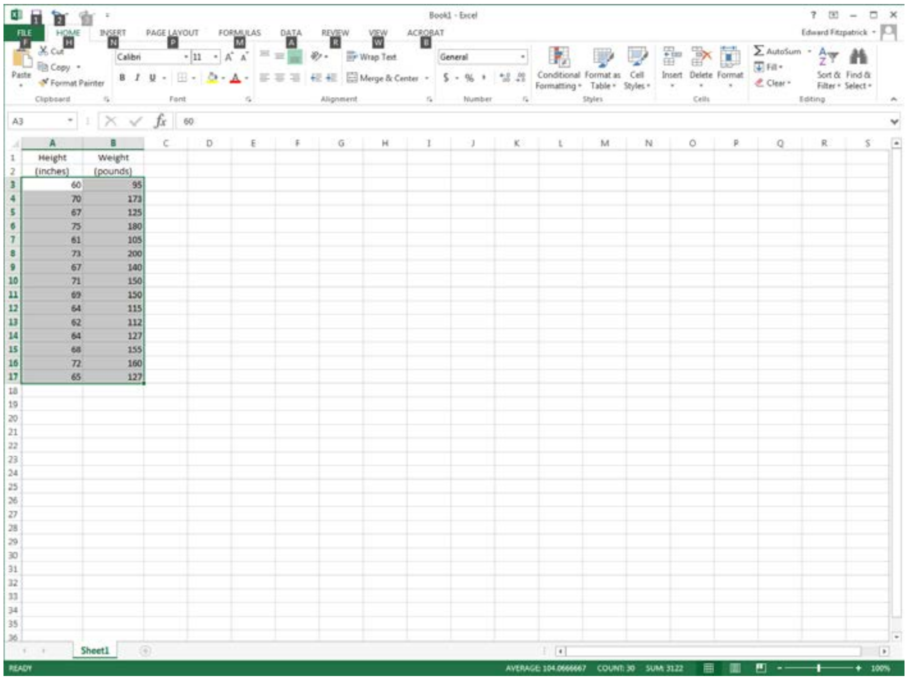
This tutorial is designed to teach you how to create a graph and perform a linear regression using Microsoft Excel. Excel is a spreadsheet program. This is a program that is designed to take data, usually numerical, and perform various operations on it and output those results as numbers or graphs. While 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* page A-2. When entering data, keep the first couple of rows available for column headings.



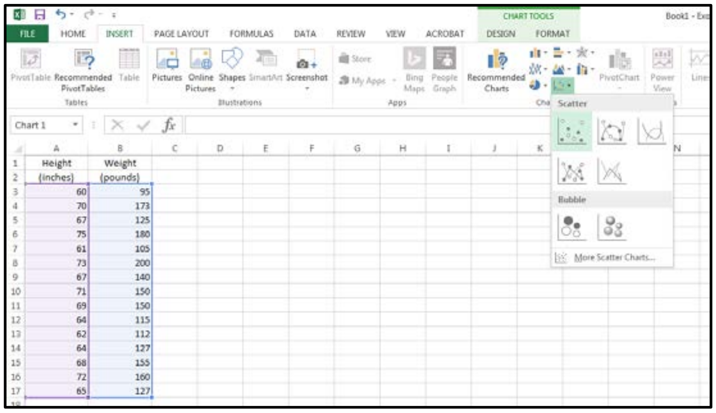
When you've entered all of your data, you can create a graph from it. To select the data that you want to graph, click and hold the left mouse button on the upper left cell, then drag the mouse to the lower right cell while holding the button down. The data will appear highlighted as seen below:



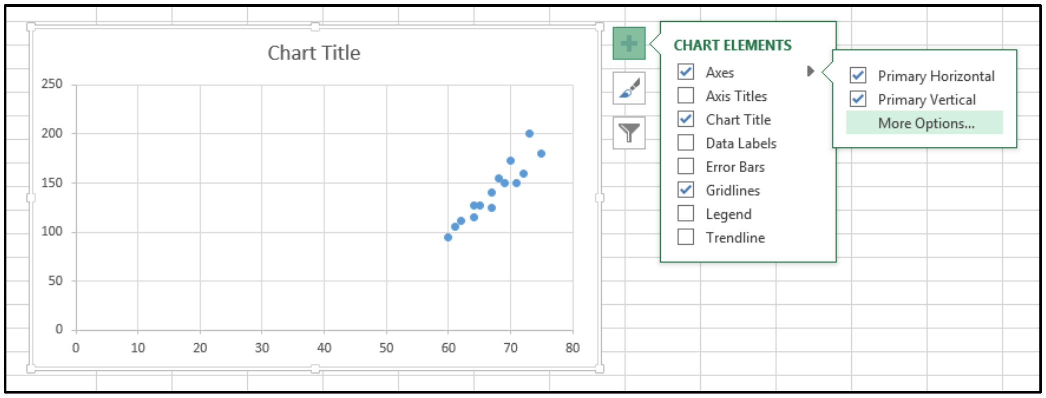
***NOTE*:** To select two column which are not side-by-side, select the first column and then - while holding the CTRL button - select the second column. Both should now appear highlighted. Excel always chooses the leftmost column to be the x-axis of a graph.

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.

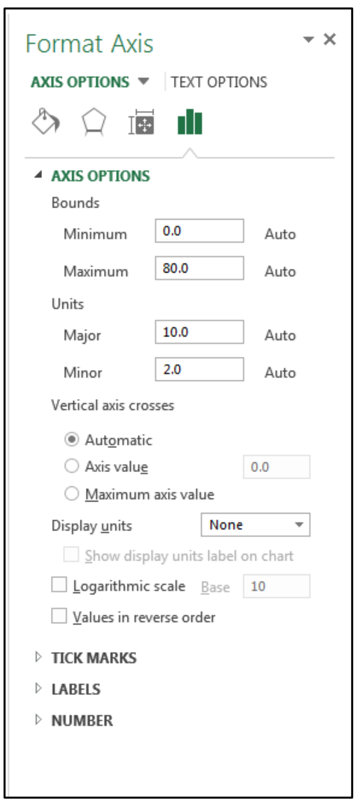
This is the usual style of graph that we will use in this class.



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:

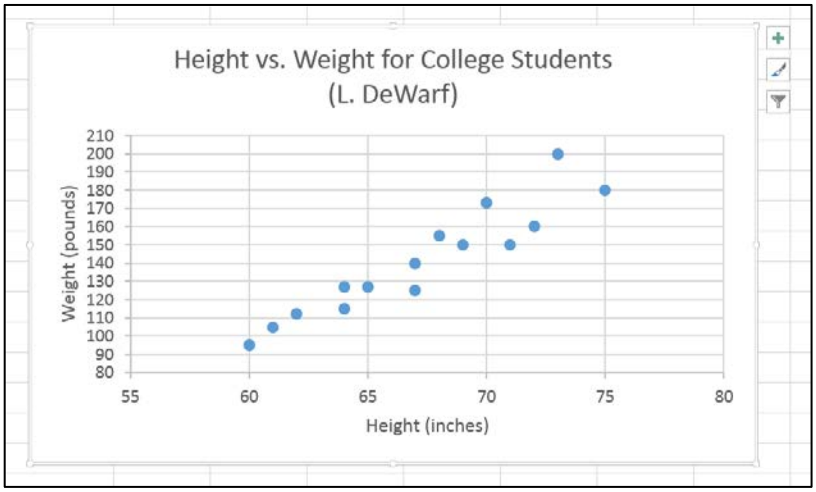


This brings up a number of options which allow you to change the appearance of the chart. To change the range of the graph, click the small arrow next to "Axes" in the "Chart Elements" box and then click "More Options". This brings up the "Format Axis" menu on the right side of the screen:



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.

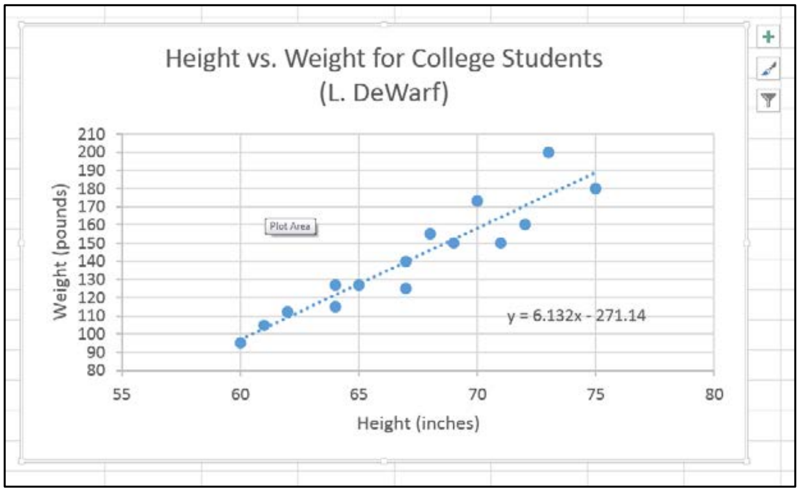
NOTE: After creating a beautiful chart, you may discover that you have entered some of the data incorrectly in the spreadsheet. No worries. Simply change the incorrect value in the spreadsheet and the new results will appear automatically on the chart!

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 a number of 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 that 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.

Appendix II

Starry Night College† Home Screen

†Planetarium simulation program used in Labs C, D, E, I, and J