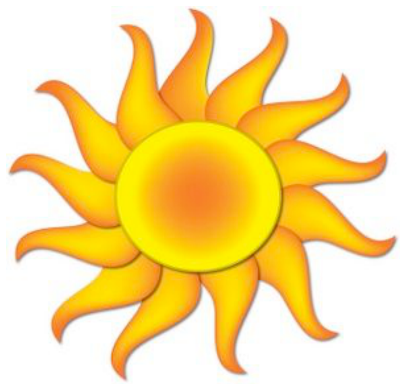
NMSU Astronomy
ASTR 1115G
Lab Manual



ASTR1115G - Dr. Debanjan Sengupta
Spring 2026

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Name:______________________________
Date:_______________________________

1 Tools for Success in ASTR 1115G

1.1 Introduction

Astronomy is a physical science. Just like biology, chemistry, geology, and physics, astronomers collect data, analyze that data, attempt to understand the object/subject they are looking at, and submit their results for publication. Along the way astronomers use all of the mathematical techniques and physics necessary to understand the objects they examine. Thus, just like any other science, a large number of mathematical tools and concepts are needed to perform astronomical research. In today's introductory lab, you will review and learn some of the most basic concepts necessary to enable you to successfully complete the various laboratory exercises you will encounter during this semester. When needed, the weekly laboratory exercise you are performing will refer back to the examples in this introduction—so keep the completed examples you will do today with you at all times during the semester to use as a reference when you run into these exercises later this semester (in fact, on some occasions your TA might have you redo one of the sections of this lab for review purposes).

1.2 A Note About Ratios

You will encounter ratios in many of your classes, cooking, recipes, money transactions, etc.! A ratio simply indicates how many times one number contains the other number. For example, if I had a bowl of fruit with 8 apples and 6 bananas, the ratio of apples to bananas would be eight to six (or we could say 8:6. Which is equal to 4:3). We know this bowl of fruit has 14 total fruit in it. So we know that there is 8 apples out of the total of 14 fruit, or a ratio of 8:14 (which is equal to a ratio of 4:7. Which we are able to get by noting that both "8" and "14" have something in common! They can be divided by 2!).

Additionally, if I take the ratio 8:14 and I divide 8 by 14 I would get 0.57 (or 57%). From knowing the ratio of apples to total number of fruit in the bowl, I know there are 57% apples. Similarly, we said that the ratio of 8:14 was similar to 4:7. If we did the same thing by dividing 4 by 7, we would also get 0.57 (or 57%)! Which makes sense since we said they were equal!!

In fact, a ratio may be considered as an ordered pair of numbers, or a fraction! The first number in a ratio would be the numerator of a fraction. And the second number in the ratio would be the denominator.

Ratios may be quantities of any kind! They can be counts of people or objects! These ratios can be lengths, weights, time, etc.

Practice with ratios:

Remember, a ratio compares two different quantities. Those two quantities can be anything. In your astronomy labs they will most likely be comparing two distances, lengths, or time. The order of a ratio matters!

1. If you drive for 60 miles in 2 hours, how fast were you driving? Show how you figured this out! (**1 points**)

   This is a common use of ratios (and proportions). This is comparing the number of miles (60) to the number of hours it took to drive (2). So the ratio is 60:2 (which we would verbal express as "60 miles in 2 hours").

2. Now let's say you rode your bike at a rate of 10 miles per hour for 4 hours. How many miles did you travel? Show your work with how you solved it. (**2 points**)

   We know our ratio is 10:1 (10 miles per 1 hour). So that tells us that in 4 hours, we will have traveled a total of 40 miles.

3. Looking ahead to the scale model lab, we will place all the planets on the Football field with Pluto at the 100 yard line. One of the instructions asks you to figure out how many yards there are per AU based on the fact that Pluto is at the 100 yard line (an AU is an Astronomical Unit which is the average distance between the sun and Earth). We know that Pluto is 40 AU away in space. So if we were to "scale" down the distance to yards on a football field, we know that there would be a ratio of 100 yards to AU. Similar to the miles per hour example above, how many yards per AU is there in a "Scale Model" of the solar system? (**2 points**)

1.3 The Metric System

Like all other scientists, astronomers use the metric system. The metric system is based on powers of 10, and has a set of measurement units analogous to the English system we use in everyday life here in the US. In the metric system the main unit of length (or distance) is the *meter*, the unit of mass is the *kilogram*, and the unit of liquid volume is the *liter.* A meter is approximately 40 inches, or about 4" longer than the yard. Thus, 100 meters is about 111 yards. A liter is slightly larger than a quart (1.0 liter = 1.101 qt). On the Earth's surface, a kilogram = 2.2 pounds.

As you have almost certainly learned, the metric system uses prefixes to change scale. For example, one thousand meters is one "kilometer." One thousandth of a meter is a "millimeter." The prefixes that you will encounter in this class are listed in Table 1.3.

Table 1.1: Metric System Prefixes

Prefix Name	**Prefix Symbol**	**Prefix Value**
Giga	G	1,000,000,000 (one billion)
Mega	M	1,000,000 (one million)
kilo	k	1,000 (one thousand)
centi	c	0.01 (one hundredth)
milli	m	0.001 (one thousandth)
micro	μ	0.0000001 (one millionth)
nano	n	0.0000000001 (one billionth)

In the metric system, 3,600 meters is equal to 3.6 kilometers; 0.8 meter is equal to 80 centimeters, which in turn equals 800 millimeters, etc. In the lab exercises this semester we will encounter a large range in sizes and distances. For example, you will measure the sizes of some objects/things in class in millimeters, talk about the wavelength of light in nanometers, and measure the sizes of features on planets that are larger than 1,000 kilometers.

1.4 Beyond the Metric System

When we talk about the sizes or distances to objects beyond the surface of the Earth, we begin to encounter very large numbers. For example, the average distance from the Earth to the Moon is 384,000,000 meters or 384,000 kilometers (km). The distances found in astronomy are usually so large that we have to switch to a unit of measurement that is much larger than the meter, or even the kilometer. In and around the solar system, astronomers use "Astronomical Units." An Astronomical Unit is the mean (average) distance between the Earth and the Sun. One Astronomical Unit (AU) = 149,600,000 km. For example, Jupiter is about 5 AU from the Sun, while Pluto's average distance from the Sun is 39 AU. With this change in units, it is easy to talk about the distance to other planets. It is more convenient to say that Saturn is 9.54 AU away than it is to say that Saturn is 1,427,184,000 km from Earth.

1.5 Changing Units and Scale Conversion

Changing units (like those in the previous paragraph) and/or scale conversion is something you must master during this semester. You already do this in your everyday life whether you know it or not (for example, if you travel to Mexico and you want to pay for a Coke in pesos), so **do not panic!** Let's look at some examples (**2 points each**):

1. Convert 34 meters into centimeters:

   Answer: Since one meter = 100 centimeters, 34 meters = 3,400 centimeters.

2. Convert 34 kilometers into meters:

3. If one meter equals 40 inches, how many meters are there in 400 inches?

4. How many centimeters are there in 400 inches?

5. In August 2003, Mars made its closest approach to Earth for the next 50,000 years. At that time, it was only about .373 AU away from Earth. How many km is this?

1.5.1 Map Exercises

One technique that you will use this semester involves measuring a photograph or image with a ruler, and converting the measured number into a real unit of size (or distance). One example of this technique is reading a road map. Figure 1.1 shows a map of the state of New Mexico. Down at the bottom left hand corner of the map is a scale in both miles and kilometers.

Use a ruler to determine (**2 points each**):

6. How many kilometers is it from Las Cruces to Albuquerque?

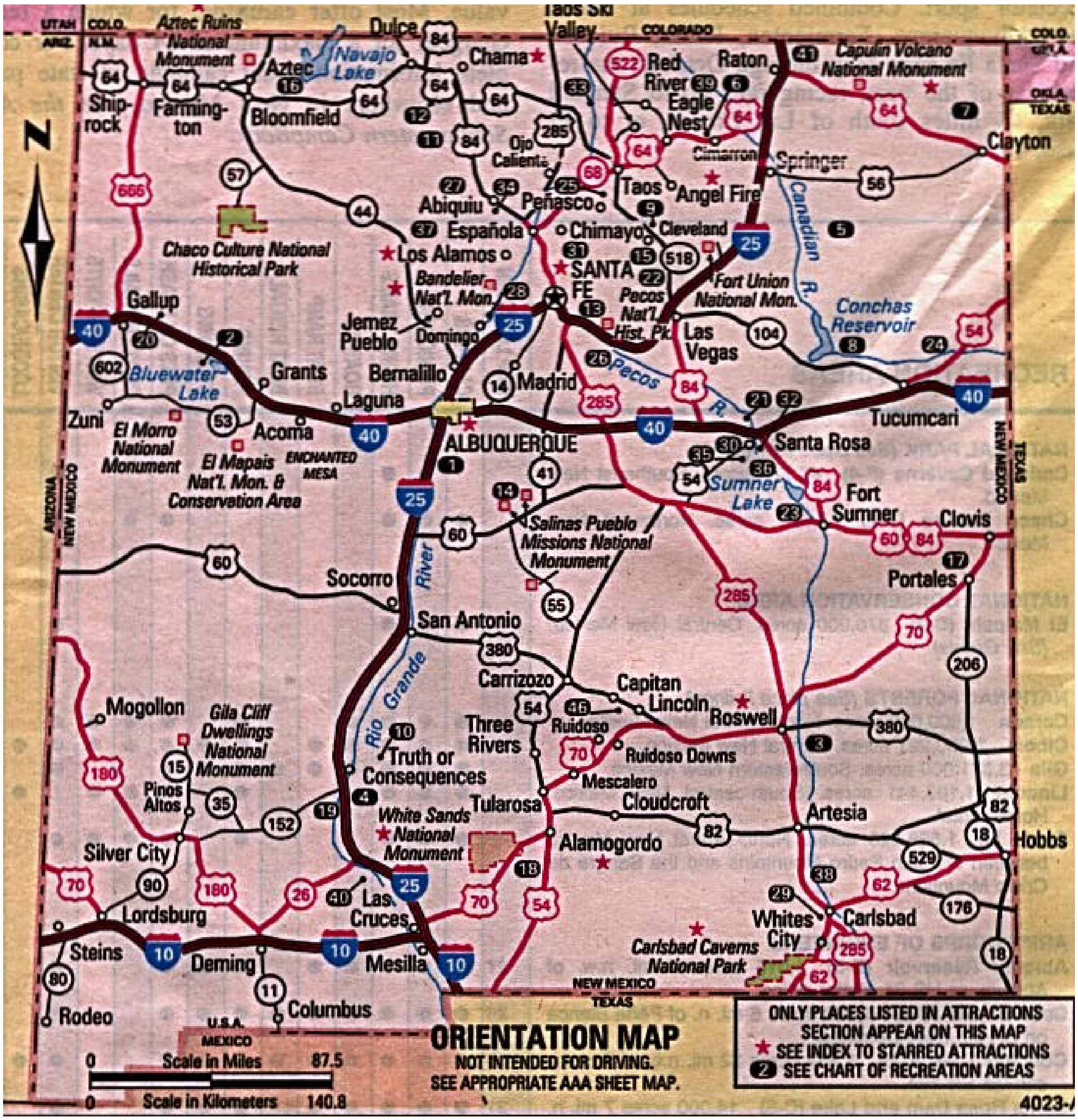


Figure 1.1: Map of New Mexico.

7. What is the distance in miles from the border with Arizona to the border with Texas if you were to drive along I-40?

8. If you were to drive 100 km/hr (kph), how long would it take you to go from Las Cruces to Albuquerque?

9. If one mile = 1.6 km, how many miles per hour (mph) is 100 kph?

1.6 Squares, Square Roots, and Exponents

In several of the labs this semester you will encounter squares, cubes, and square roots. Let us briefly review what is meant by such terms as squares, cubes, square roots and exponents. The square of a number is simply that number times itself: $3 \times 3 = 3^2 = 9$. The *exponent* is the little number "2" above the three. $5^2 = 5 \times 5 = 25$. The exponent tells you how many times to multiply that number by itself: $8^4 = 8 \times 8 \times 8 \times 8 = 4096$. The square of a number simply means the exponent is 2 (three squared = 3^2), and the cube of a number means the exponent is three (four cubed = 4^3). Here are some examples:

- $7^2 = 7 \times 7 = 49$
- $7^5 = 7 \times 7 \times 7 \times 7 \times 7 = 16{,}807$
- The cube of 9 (or "9 cubed") = $9^3 = 9 \times 9 \times 9 = 729$
- The exponent of 12^{16} is 16
- $2.56^3 = 2.56 \times 2.56 \times 2.56 = 16.777$

Your turn (2 points each):

10. $6^3 =$

11. $4^4 =$

12. $3.1^2 =$

The concept of a square root is fairly easy to understand, but is much harder to calculate (we usually have to use a calculator). The square root of a *number* is that number whose square is the *number*: the square root of 4 = 2 because 2 × 2 = 4. The square root of 9 is 3 (9 = 3 × 3). The mathematical operation of a square root is usually represented by the symbol "$\sqrt{\ }$", as in $\sqrt{9} = 3$. But mathematicians also represent square roots using a *fractional* exponent of one half: $9^{1/2} = 3$. Likewise, the cube root of a number is represented as $27^{1/3} = 3$ (3 × 3 × 3 = 27). The fourth root is written as $16^{1/4}$ (= 2), and so on. Here are some example problems:

- $\sqrt{100} = 10$

- $10.5^3 = 10.5 \times 10.5 \times 10.5 = 1157.625$

- Verify that the square root of 17 ($\sqrt{17} = 17^{1/2}$) = 4.123

1.7 Scientific Notation

The range in numbers encountered in Astronomy is enormous: from the size of subatomic particles, to the size of the entire universe. You are certainly comfortable with numbers like ten, one hundred, three thousand, ten million, a billion, or even a trillion. But what about a number like one million trillion? Or, four thousand one hundred and fifty six million billion? Such numbers are too cumbersome to handle with words. Scientists use something called "Scientific Notation" as a short hand method to represent very large and very small numbers. The system of scientific notation is based on the number 10. For example, the number $100 = 10 \times 10 = 10^2$. In scientific notation the number 100 is written as 1.0×10^2. Here are some additional examples:

- Ten = $10 = 1 \times 10 = 1.0 \times 10^1$
- One hundred = $100 = 10 \times 10 = 10^2 = 1.0 \times 10^2$
- One thousand = $1{,}000 = 10 \times 10 \times 10 = 10^3 = 1.0 \times 10^3$
- One million = $1{,}000{,}000 = 10 \times 10 \times 10 \times 10 \times 10 \times 10 = 10^6 = 1.0 \times 10^6$

Ok, so writing powers of ten is easy, but how do we write 6,563 in scientific notation? 6,563 = 6563.0 = 6.563×10^3. To figure out the exponent on the power of ten, we simply count the numbers to the *left* of the decimal point, but do not include the left-most number. Here are some more examples:

- 1,216 = 1216.0 = 1.216×10^3
- 8,735,000 = 8735000.0 = 8.735000×10^6
- 1,345,999,123,456 = 1345999123456.0 = $1.345999123456 \times 10^{12} \approx 1.346 \times 10^{12}$

Note that in the last example above, we were able to eliminate a lot of the "unnecessary" digits in that very large number. While $1.345999123456 \times 10^{12}$ is technically correct as the scientific notation representation of the number 1,345,999,123,456, we do not need to keep **all** of the digits to the right of the decimal place. We can keep just a few, and approximate that number as 1.346×10^{12}.

Your turn! Work the following examples (2 points each):

13. 121 = 121.0 =

14. 735,000 =

15. 999,563,982 =

Now comes the sometimes confusing issue: writing very small numbers. First, lets look at powers of 10, but this time in fractional form. The number $0.1 = \frac{1}{10}$. In scientific notation we would write this as 1×10^{-1}. The negative number in the exponent is the way we write the fraction $\frac{1}{10}$. How about 0.001? We can rewrite 0.001 as $\frac{1}{10} \times \frac{1}{10} \times \frac{1}{10} = 0.001 = 1 \times 10^{-3}$. Do you see where the exponent comes from? Starting at the decimal point, we simply count over to the *right* of the first digit that isn't zero to determine the exponent. Here are some examples:

- $0.121 = 1.21 \times 10^{-1}$
- $0.000735 = 7.35 \times 10^{-4}$

- $0.0000099902 = 9.9902 \times 10^{-6}$

Your turn (2 points each):

16. $0.0121 =$

17. $0.0000735 =$

18. $0.0000000999 =$

19. $-0.121 =$

There is one issue we haven't dealt with, and that is *when* to write numbers in scientific notation. It is kind of silly to write the number 23.7 as 2.37×10^1, or 0.5 as 5.0×10^{-1}. You use scientific notation when it is a more compact way to write a number to insure that its value is quickly and easily communicated to someone else. For example, if you tell someone the answer for some measurement is 0.0033 meter, the person receiving that information has to count over the zeros to figure out what that means. It is better to say that the measurement was 3.3×10^{-3} meter. But telling someone the answer is 215 kg, is much easier than saying 2.15×10^2 kg. It is common practice that numbers bigger than 10,000 or smaller than 0.01 are best written in scientific notation.

1.8 Calculator Issues

Since you will be using calculators in nearly all of the labs this semester, you should become familiar with how to use them for functions beyond simple arithmetic.

1.8.1 Scientific Notation on a Calculator

Scientific notation on a calculator is usually designated with an "E." For example, if you see the number 8.778046E11 on your calculator, this is the same as the number 8.778046×10^{11}. Similarly, 1.4672E-05 is equivalent to 1.4672×10^{-5}.

Entering numbers in scientific notation into your calculator depends on layout of your calculator; we cannot tell you which buttons to push without seeing your specific calculator. However, the "E" button described above is often used, so to enter 6.589×10^7, you may need to type 6.589 "E" 7.

Verify that you can enter the following numbers into your calculator:

- 7.99921×10^{21}

- 2.2951324×10^{-6}

1.8.2 Order of Operations

When performing a complex calculation, the order of operations is extremely important. There are several rules that need to be followed:

i. Calculations must be done from left to right.

ii. Calculations in brackets (parenthesis) are done first. When you have more than one set of brackets, do the inner brackets first.

iii. Exponents (or radicals) must be done next.

iv. Multiply and divide in the order the operations occur.

v. Add and subtract in the order the operations occur.

If you are using a calculator to enter a long equation, when in doubt as to whether the calculator will perform operations in the correct order, apply parentheses.

Use your calculator to perform the following calculations **(2 points each):**

20. $\frac{(7+34)}{(2+23)} =$

21. $(4^2 + 5) - 3 =$

22. $20 \div (12 - 2) \times 3^2 - 2 =$

1.9 Graphing and/or Plotting

Now we want to discuss graphing data. You probably learned about making graphs in high school. Astronomers frequently use graphs to plot data. You have probably seen all sorts of graphs, such as the plot of the performance of the stock market shown in Fig. 1.2. A plot like this shows the history of the stock market versus time. The "x" (horizontal) axis represents time, and the "y" (vertical) axis represents the value of the stock market. Each place on the curve that shows the performance of the stock market is represented by two numbers, the date (x axis), and the value of the index (y axis). For example, on May 10 of 2004, the Dow Jones index stood at 10,000.

Plots like this require two data points to represent each point on the curve or in the plot. For comparing the stock market you need to plot the value of the stocks versus the date. We call data of this type an "ordered pair." Each data point requires a value for x (the date)

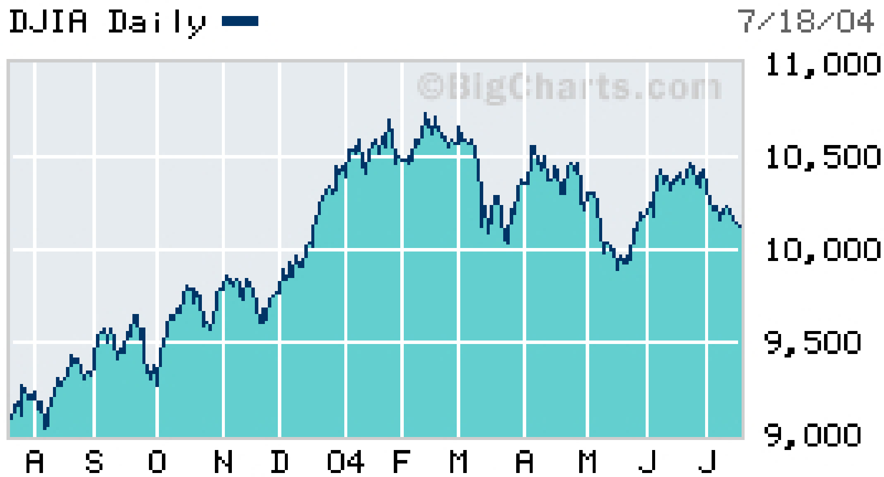


Figure 1.2: The change in the Dow Jones stock index over one year (from April 2003 to July 2004).

Table 1.2: Temperature vs. Altitude

Altitude (feet)	Temperature °F
0	59.0
2,000	51.9
4,000	44.7
6,000	37.6
8,000	30.5
10,000	23.3
12,000	16.2
14,000	9.1
16,000	1.9

and y (the value of the Dow Jones index).

Table 1.2 contains data showing how the temperature changes with altitude near the Earth's surface. As you climb in altitude, the temperature goes down (this is why high mountains can have snow on them year round, even though they are located in warm areas). The data points in this table are plotted in Figure 1.3.

1.9.1 The Mechanics of Plotting

When you are asked to plot some data, there are several things to keep in mind.

First of all, the plot axes **must be labeled.** This will be emphasized throughout the

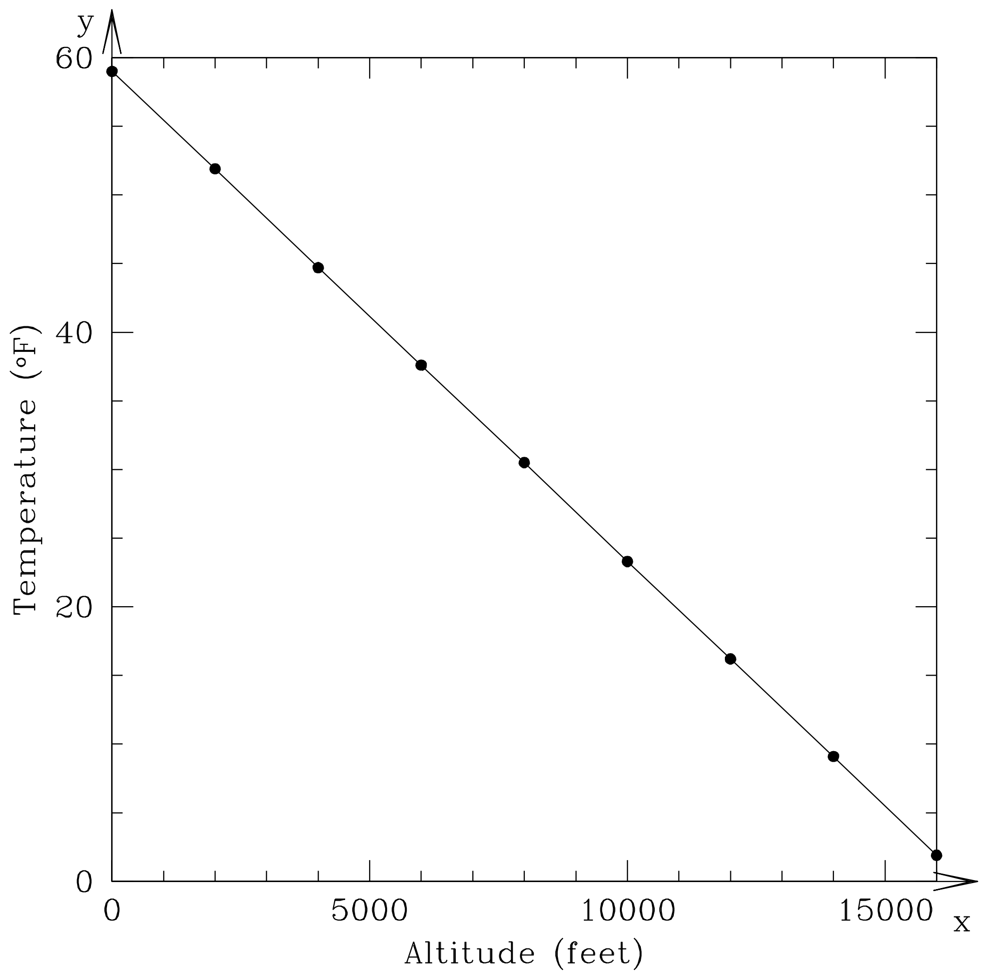


Figure 1.3: The change in temperature as you climb in altitude with the data from Table 1.2. At sea level (0 ft altitude) the surface temperature is 59°F. As you go higher in altitude, the temperature goes down.

semester. In order to quickly look at a graph and determine what information is being conveyed, it is imperative that both the x-axis and y-axis have labels.

Secondly, if you are creating a plot, choose the numerical range for your axes such that the data fit nicely on the plot. For example, if you were to plot the data shown in Table 1.2, with altitude on the y-axis, you would want to choose your range of y-values to be something like 0 to 18,000. If, for example, you drew your y-axis going from 0 to 100,000, then all of the data would be compressed towards the lower portion of the page. It is important to choose your *ranges* for the x and y axes so they bracket the data points.

1.9.2 Plotting and Interpreting a Graph

Table 1.3 contains hourly temperature data on January 19, 2006, for two locations: Tucson and Honolulu.

Table 1.3: Hourly Temperature Data from 19 January 2006

Time hh:mm	Tucson Temp. °F	Honolulu Temp. °F
00:00	49.6	71.1
01:00	47.8	71.1
02:00	46.6	71.1
03:00	45.9	70.0
04:00	45.5	72.0
05:00	45.1	72.0
06:00	46.0	73.0
07:00	45.3	73.0
08:00	45.7	75.0
09:00	46.6	78.1
10:00	51.3	79.0
11:00	56.5	80.1
12:00	59.0	81.0
13:00	60.8	82.0
14:00	60.6	81.0
15:00	61.7	79.0
16:00	61.7	77.0
17:00	61.0	75.0
18:00	59.2	73.0
19:00	55.0	73.0
20:00	53.4	72.0
21:00	51.6	71.1
22:00	49.8	72.0
23:00	48.9	72.0
24:00	47.7	72.0

23. On the blank sheet of graph paper in Figure 1.4, plot the hourly temperatures measured for Tucson and Honolulu on 19 January 2006. (**10 points**)

24. Which city had the highest temperature on 19 January 2006? (**2 points**)

25. Which city had the highest *average* temperature? (**2 points**)

26. Which city heated up the fastest in the morning hours? (**2 points**)

While straight lines and perfect data show up in science from time to time, it is actually quite rare for *real* data to fit perfectly on top of a line. One reason for this is that all

Figure 1.4: Graph paper for plotting the hourly temperatures in Tucson and Honolulu.

measurements have *error*. So even though there might be a perfect relationship between x and y, the uncertainty of the measurements introduces small deviations from the line. In other cases, the data are *approximated* by a line. This is sometimes called a *best-fit* relationship for the data.

1.10 Does it Make Sense?

This is a question that you should be asking yourself after *every* calculation that you do in this class!

One of our primary goals this semester is to help you develop intuition about our solar system. This includes recognizing if an answer that you get "makes sense." For example, you may be told (or you may eventually know) that Mars is 1.5 AU from Earth. You also know that the Moon is a lot closer to the Earth than Mars is. So if you are asked to calculate the

Earth-Moon distance and you get an answer of 4.5 AU, this should alarm you! That would imply that the Moon is **three times** farther away from Earth than Mars is! And you know that's not right.

Use your intuition to answer the following questions. In addition to just giving your answer, state *why* you gave the answer you did. (**5 points each**)

27. Earth's diameter is 12,756 km. Jupiter's diameter is about 11 times this amount. Which makes more sense: Jupiter's diameter being 19,084 km or 139,822 km?

28. Sound travels through air at roughly 0.331 kilometers per second. If BX 102 suddenly exploded, which would make more sense for when people in Mesilla (almost 5 km away) would hear the blast? About 14.5 seconds later, or about 6.2 minutes later?

29. Water boils at 100 °C. Without knowing anything about the planet Pluto other than the fact that is roughly 40 times farther from the Sun than the Earth is, would you expect the surface temperature of Pluto to be closer to -100° or 50°?

1.11 Putting it All Together

We have covered a lot of tools that you will need to become familiar with in order to complete the labs this semester. Now let's see how these concepts can be used to answer real questions about our solar system. *Remember, ask yourself* **does this make sense?** *for each answer that you get!*

30. To travel from Las Cruces to New York City by car, you would drive 3585 km. What is this distance in AU? (**10 points**)

31. The Earth is 4.5 billion years old. The dinosaurs were killed 65 million years ago due to a giant impact by a comet or asteroid that hit the Earth. If we were to compress the history of the Earth from 4.5 billion years into one 24-hour day, at what time would the dinosaurs have been killed? (**10 points**)

32. When it was launched towards Pluto, the New Horizons spacecraft was traveling at approximately 20 kilometers per second. How long did it take to reach Jupiter, which is roughly 4 AU from Earth? [Hint: see the definition of an AU in Section 1.3 of this lab.] (**7 points**)

Name(s):______________________________
Date:____________________________________

2 The Origin of the Seasons

2.1 Introduction

The origin of the science of Astronomy owes much to the need of ancient peoples to have a practical system that allowed them to predict the seasons. It is critical to plant your crops at the right time of the year—too early and the seeds may not germinate because it is too cold, or there is insufficient moisture. Plant too late and it may become too hot and dry for a sensitive seedling to survive. In ancient Egypt, they needed to wait for the Nile to flood. The Nile river would flood every July, once the rains began to fall in Central Africa.

Thus, the need to keep track of the annual cycle arose with the development of agriculture, and this required an understanding of the motion of objects in the sky. The first devices used to keep track of the seasons were large stone structures (such as Stonehenge) that used the positions of the rising Sun or Moon to forecast the coming seasons. The first recognizable calendars that we know about were developed in Egypt, and appear to date from about 4,200 BC. Of course, all a calendar does is let you know what time of year it was, it does not provide you with an understanding of *why* the seasons occur! The ancient people had a variety of models for why seasons occurred, but thought that everything, including the Sun and stars, orbited around the Earth. Today, you will learn the real reason *why* there are seasons.

- *Goals:* To learn why the Earth has seasons.
- *Materials:* a meter stick, a mounted plastic globe, an elevation angle apparatus, string, a halogen lamp, and a few other items

2.2 The Seasons

Before we begin today's lab, let us first talk about the seasons. In New Mexico we have rather mild Winters, and hot Summers. In the northern parts of the United States, however, the winters are much colder. In Hawaii, there is very little difference between Winter and Summer. As you are also aware, during the Winter there are fewer hours of daylight than in the Summer. In Table 2.1 we have listed seasonal data for various locations around the world. Included in this table are the average January and July maximum temperatures, the latitude of each city, and the length of the daylight hours in January and July. We will use this table in Exercise #2.

In Table 2.1, the "N" following the latitude means the city is in the northern hemisphere of the Earth (as is all of the United States and Europe) and thus *North* of the equator. An "S" following the latitude means that it is in the southern hemisphere, *South* of the Earth's

Table 2.1: **Season Data for Select Cities**

City	Latitude (Degrees)	January Ave. Max. Temp.	July Ave. Max. Temp.	January Daylight Hours	July Daylight Hours
Fairbanks, AK	64.8N	-2	72	3.7	21.8
Minneapolis, MN	45.0N	22	83	9.0	15.7
Las Cruces, NM	32.5N	57	96	10.1	14.2
Honolulu, HI	21.3N	80	88	11.3	13.6
Quito, Ecuador	0.0	77	77	12.0	12.0
Apia, Samoa	13.8S	80	78	11.1	12.7
Sydney, Australia	33.9S	78	61	14.3	10.3
Ushuaia, Argentina	54.6S	57	39	17.3	7.4

equator. What do you think the latitude of Quito, Ecuador (0.0^o) means? Yes, it is right on the equator. Remember, latitude runs from 0.0^o at the equator to $\pm 90^o$ at the poles. If north of the equator, we say the latitude is XX degrees north (or sometimes "+XX degrees"), and if south of the equator we say XX degrees south (or "−XX degrees"). We will use these terms shortly.

Now, if you were to walk into the Mesilla Valley Mall and ask a random stranger "why do we have seasons"? The most common answer you would get is "because we are closer to the Sun during Summer, and further from the Sun in Winter". This answer suggests that the general public (and most of your classmates) correctly understand that the Earth orbits the Sun in such a way that at some times of the year it is closer to the Sun than at other times of the year. As you have (or will) learn in your lecture class, the orbits of all planets around the Sun are ellipses. As shown in Figure 2.1 an ellipse is sort of like a circle that has been squashed in one direction. For most of the planets, however, the orbits are only very slightly elliptical, and closely approximate circles. But let us explore this idea that the distance from the Sun causes the seasons.

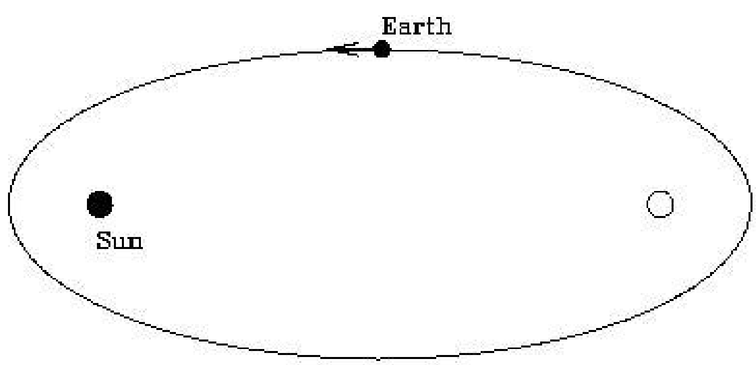


Figure 2.1: An ellipse with the two "foci" identified. The Sun sits at one focus, while the other focus is empty. The Earth follows an elliptical orbit around the Sun, but not nearly as exaggerated as that shown here!

Exercise #1. In Figure 2.1, we show the locations of the two "foci" of an ellipse (foci is the plural form of focus). We will ignore the mathematical details of what foci are for now, and simply note that the Sun sits at one focus, while the other focus is empty (see the Kepler Law lab for more information if you are interested). A planet orbits around the Sun in an elliptical orbit. So, there are times when the Earth is closest to the Sun ("perihelion"), and times when it is furthest ("aphelion"). When closest to the Sun, at perihelion, the distance from the Earth to the Sun is 147,056,800 km ("147 million kilometers"). At aphelion, the distance from the Earth to the Sun is 152,143,200 km (152 million km).

With the meter stick handy, we are going to examine these distances. Obviously, our classroom is not big enough to use kilometers or even meters so, like a road map, we will have to use a reduced scale: 1 cm = 1 million km. Now, stick a piece of tape on the table and put a mark on it to set the starting point (the location of the Sun!). Carefully measure out the two distances (along the same direction) and stick down two more pieces of tape, one at the perihelion distance, one at the aphelion distance (put small dots/marks on the tape so you can easily see them).

1) Do you think this change in distance is big enough to cause the seasons? Explain your logic. (**3 points**)

2) Take the ratio of the aphelion to perihelion distances: ____________. (**1 point**)

Given that *we know* objects appear bigger when we are closer to them, let's take a look at the two pictures of the Sun you were given as part of the materials for this lab. One image was taken on January 23^{rd}, 1992, and one was taken on the 21^{st} of July 1992 (as the "date stamps" on the images show). Using a ruler, *carefully* measure the diameter of the Sun in each image:

Sun diameter in January image = ____________ mm.

Sun diameter in July image = ____________ mm.

3) Take the ratio of bigger diameter / smaller diameter, this = ____________. (**1 point**)

4) How does this ratio compare to the ratio you calculated in question #2? (**2 points**)

5) So, if an object appears bigger when we get closer to it, in what month is the Earth

closest to the Sun? (**2 points**)

6) At that time of year, what season is it in Las Cruces? What do you conclude about the statement "the seasons are caused by the changing distance between the Earth and the Sun"? (**4 points**)

Exercise #2. Characterizing the nature of the seasons at different locations. For this exercise, we are going to be exclusively using the data contained in Table 2.1. First, let's look at Las Cruces. Note that here in Las Cruces, our latitude is $+32.5^{o}$. That is we are about one third of the way from the equator to the pole. In January our average high temperature is 57°F, and in July it is 96°F. It is hotter in Summer than Winter (duh!). Note that there are about 10 hours of daylight in January, and about 14 hours of daylight in July.

7) Thus, for Las Cruces, the Sun is "up" longer in July than in January. Is the same thing true for all cities with northern latitudes: Yes or No ? (**1 point**)

Ok, let's compare *Las Cruces with Fairbanks, Alaska.* Answer these questions by filling in the blanks:

8) Fairbanks is ________________________ the North Pole than Las Cruces. (**1 point**)

9) In January, there are more daylight hours in ________________________. (**1 point**)

10) In July, there are more daylight hours in ________________________. (**1 point**)

Now let's compare *Las Cruces with Sydney, Australia.* Answer these questions by filling in the blanks:

12) While the latitudes of Las Cruces and Sydney are similar, Las Cruces is ____________ of the Equator, and Sydney is ____________ of the Equator. (**2 points**)

13) In January, there are more daylight hours in ________________________. (**1 point**)

14) In July, there are more daylight hours in ________________________. (**1 point**)

15) **Summarizing:** During the Wintertime (January) in both Las Cruces and Fairbanks there are fewer daylight hours, *and* it is colder. During July, it is warmer in both Fairbanks

and Las Cruces, *and* there are more daylight hours. Is this also true for Sydney?: ____________. (**1 point**)

16) In fact, it is Wintertime in Sydney during ____________, and Summertime during ____________. (**2 points**)

17) From Table 2.1, I conclude that the times of the seasons in the Northern hemisphere are exactly _______________ to those in the Southern hemisphere. (**1 point**)

From Exercise #2 we learned a few simple truths, but ones that maybe you have never thought about. As you move away from the equator (either to the north or to the south) there are several general trends. The first is that as you go closer to the poles it is *generally* cooler at all times during the year. The second is that as you get closer to the poles, the amount of daylight during the Winter decreases, but the reverse is true in the Summer.

The first of these is not always true because the local climate can be moderated by the proximity to a large body of water, or depend on the elevation. For example, Sydney is milder than Las Cruces, even though they have similar latitudes: Sydney is on the eastern coast of Australia (South Pacific ocean), and has a climate like that of San Diego, California (which has a similar latitude and is on the coast of the North Pacific). Quito, Ecuador has a mild climate even though it sits right on the equator due to its high elevation–it is more than 9,000 feet above sea level, similar to the elevation of Cloudcroft, New Mexico.

The second conclusion (amount of daylight) is always true—as you get closer and closer to the poles, the amount of daylight during the Winter decreases, while the amount of daylight during the Summer increases. In fact, for all latitudes north of 66.5^o, the Summer Sun is up all day (24 hrs of daylight, the so called "land of the midnight Sun") for at least one day each year, while in the Winter there are times when the Sun never rises! 66.5^o is a special latitude, and is given the name "Arctic Circle". Note that Fairbanks is very close to the Arctic Circle, and the Sun is up for just a few hours during the Winter, but is up for nearly 22 hours during the Summer! The same is true for the southern hemisphere: all latitudes south of -66.5^o experience days with 24 hours of daylight in the Summer, and 24 hours of darkness in the Winter. -66.5^o is called the "Antarctic Circle". But note that the seasons in the Southern Hemisphere are exactly opposite to those in the North. During Northern Winter, the North Pole experiences 24 hours of darkness, but the South Pole has 24 hours of daylight.

2.3 The Spinning, Revolving Earth

It is clear from the preceding that your latitude determines both the annual variation in the amount of daylight, and the time of the year when you experience Spring, Summer, Autumn and Winter. To truly understand why this occurs requires us to construct a model. One of the key insights to the nature of the motion of the Earth is shown in the long exposure photographs of the nighttime sky on the next two pages.

Figure 2.2: Pointing a camera to the North Star (Polaris, the bright dot near the center) and exposing for about one hour, the stars appear to move in little arcs. The center of rotation is called the "North Celestial Pole", and Polaris is very close to this position. The dotted/dashed trails in this photograph are the blinking lights of airplanes that passed through the sky during the exposure.

What is going on in these photos? The easiest explanation is that the Earth is spinning, and as you keep your camera shutter open, the stars appear to move in "orbits" around the North Pole. You can duplicate this motion by sitting in a chair that is spinning—the objects in the room appear to move in circles around you. The further they are from the "axis of rotation", the bigger arcs they make, and the faster they move. An object straight above you, exactly on the axis of rotation of the chair, does not move. As apparent in Figure 2.3, the "North Star" Polaris is not perfectly on the axis of rotation at the North Celestial Pole, but it is very close (the fact that there is a bright star near the pole is just random chance). Polaris has been used as a navigational aid for centuries, as it allows you to determine the direction of North.

As the second photograph shows, the direction of the spin axis of the Earth does not change during the year—it stays pointed in the same direction *all* of the time! If the Earth's spin axis moved, the stars would not make perfect circular arcs, but would wander

Figure 2.3: Here is a composite of many different exposures (each about one hour in length) of the night sky over Vienna, Austria taken throughout the year (all four seasons). The images have been composited using a software package like Photoshop to demonstrate what would be possible if it stayed dark for 24 hrs, and you could actually obtain a 24 hour exposure (which can only be truly done north of the Arctic circle). Polaris is the smallest circle at the very center.

around in whatever pattern was being executed by the Earth's axis.

Now, as shown back in Figure 2.1, we said the Earth orbits ("revolves" around) the Sun on an ellipse. We could discuss the evidence for this, but to keep this lab brief, we will just assume this fact. So, now we have two motions: the spinning and revolving of the Earth. It is the combination of these that actually give rise to the seasons, as you will find out in the next exercise.

Exercise #3: In this part of the lab, we will be using the mounted plastic globe, a piece of string, a ruler, and the halogen desklamp. **Warning: while the globe used here is made of fairly inexpensive parts, it is very time consuming to make. Please be careful with your globe, as the painted surface can be easily scratched.** Make sure that the piece of string you have is long enough to go slightly more than halfway

around the globe at the equator–if your string is not that long, ask your TA for a longer piece of string. As you may have guessed, this plastic globe is a model of the Earth. The spin axis of the Earth is actually tilted with respect to the plane of its orbit by 23.5°.
Set up the experiment in the following way. Place the halogen lamp at one end of the table (shining towards the closest wall so as to not affect your classmates), and set the globe at a distance of 1.5 meters from the lamp. After your TA has dimmed the classroom lights, turn on the halogen lamp to the highest setting (depending on the lamp, there may be a dim, and a bright setting). Note these lamps get very hot, so be careful. For this lab, we will define the top of the globe as the Northern hemisphere, and the bottom as the Southern hemisphere.

First off, it will be helpful to know the length of the entire arc at the 4 latitudes at which you'll be measuring later. Using the piece of string, measure the length of the arc at each latitude and note it below.

Table 2.2: Total Arc Length

Latitude	**Total Length of Arc**
Arctic Circle	
45°N	
Equator	
Antarctic Circle	

Experiment #1: For the first experiment, *arrange the globe so the axis of the "Earth"is pointed at a right angle (90°) to the direction of the "Sun"*. Use your best judgement. Now adjust the height of the desklamp so that the light bulb in the lamp is at the same approximate height as the equator.

There are several colored lines on the globe that form circles which are concentric with the axis, and these correspond to certain latitudes. The red line is the equator, the black line is 45° North, while the two blue lines are the Arctic (top) and Antarctic (bottom) circles.

Note that there is an illuminated half of the globe, and a dark half of the globe. The line that separates the two is called the "terminator". It is the location of sunrise or sunset. Using the piece of string, we want to measure the length of each arc that is in "daylight", and the length that is in "night". This is kind of tricky, and requires a bit of judgement as to exactly where the terminator is located. So make sure you have a helper to help keep the string *exactly* on the line of constant latitude, and get the advice of your lab partners of where the terminator is (and it is probably best to do this more than once!). Fill in the following table (**4 points**):

As you know, the Earth rotates once every 24 hours (= 1 Day). Each of the lines of constant latitude represents a full circle that contains 360°. But note that these circles get smaller in radius as you move away from the equator. The circumference of the Earth at the

Table 2.3: Position #1: Equinox Data Table

Latitude	**Length of Daylight Arc**	**Length of Nightime Arc**
Arctic Circle		
45°N		
Equator		
Antarctic Circle		

equator is 40,075 km (or 24,901 miles). At a latitude of 45°, the circle of constant latitude has a circumference of 28,333 km. At the arctic circles, the circle has a circumference of only 15,979 km. This is simply due to our use of two coordinates (longitude and latitude) to define a location on a sphere.

Since the Earth is a solid body, all of the points on Earth rotate once every 24 hours. Therefore, the sum of the daytime and nighttime arcs you measured equals 24 hours! So, fill in the following table (**2 points**):

Table 2.4: Position #1: Length of Night and Day

Latitude	**Daylight Hours**	**Nighttime Hours**
Arctic Circle		
45°N		
Equator		
Antarctic Circle		

18) The caption for Table 2.3 was "Equinox data". The word Equinox means "equal nights", as the length of the nighttime is the same as the daytime. While your numbers in Table 2.4 may not be exactly perfect, what do you conclude about the length of the nights and days for *all* latitudes on Earth in this experiment? Is this result consistent with the term Equinox? (**3 points**)

Experiment #2: Now we are going to *re-orient the globe so that the (top) polar axis points exactly away from the Sun* and repeat the process of Experiment #1. Fill in the following two tables (**4 points**):

19) Compare your results in Table 2.6 for +45° latitude with those for Minneapolis in Table 2.1. Since Minneapolis is at a latitude of +45°, what season does this orientation of the globe correspond to? (**2 points**)

Table 2.5: Position #2: Solstice Data Table

Latitude	**Length of Daylight Arc**	**Length of Nightime Arc**
Arctic Circle		
45°N		
Equator		
Antarctic Circle		

Table 2.6: Position #2: Length of Night and Day

Latitude	**Daylight Hours**	**Nighttime Hours**
Arctic Circle		
45°N		
Equator		
Antarctic Circle		

20) What about near the poles? In this orientation what is the length of the nighttime at the North pole, and what is the length of the daytime at the South pole? Is this consistent with the trends in Table 2.1, such as what is happening at Fairbanks or in Ushuaia? (**4 points**)

Experiment #3: Now we are going to approximate the Earth-Sun orientation six months after that in Experiment #2. To do this correctly, the globe and the lamp should now switch locations. Go ahead and do this if this lab is confusing you—or you can simply *rotate the globe apparatus by 180° so that the North polar axis is tilted exactly towards the Sun*. Try to get a good alignment by looking at the shadow of the wooden axis on the globe. Since this is six months later, it easy to guess what season this is, but let's prove it! Complete the following two tables (**4 points**):

Table 2.7: Position #3: Solstice Data Table

Latitude	**Length of Daylight Arc**	**Length of Nightime Arc**
Arctic Circle		
45°N		
Equator		
Antarctic Circle		

21) As in question #19, compare the results found here for the length of daytime and

Table 2.8: Position #3: Length of Night and Day

Latitude	**Daylight Hours**	**Nighttime Hours**
Arctic Circle		
45°N		
Equator		
Antarctic Circle		

nighttime for the +45° degree latitude with that for Minneapolis. What season does this appear to be? (**2 points**)

22) What about near the poles? In this orientation, how long is the daylight at the North pole, and what is the length of the nighttime at the South pole? Is this consistent with the trends in Table 2.1, such as what is happening at Fairbanks or in Ushuaia? (**2 points**)

23) Using your results for all three positions (Experiments #1, #2, and #3) can you explain what is happening at the Equator? Does the data for Quito in Table 2.1 make sense? Why? Explain. (**3 points**)

We now have discovered the driver for the seasons: the Earth spins on an axis that is inclined to the plane of its orbit (as shown in Figure 2.4). *But the spin axis always points to the same place in the sky* (towards Polaris). Thus, as the Earth orbits the Sun, the amount of sunlight seen at a particular latitude varies: the amount of daylight and nighttime hours change with the seasons. In Northern Hemisphere Summer (approximately June 21^{st}) there are more daylight hours, at the start of the Autumn (∼ Sept. 20^{th}) and Spring (∼ Mar. 21^{st}) the days are equal to the nights. In the Winter (approximately Dec. 21^{st}) the nights are long, and the days are short. We have also discovered that the seasons in the Northern and Southern hemispheres are exactly opposite. If it is Winter in Las Cruces, it is Summer in Sydney (and vice versa). This was clearly demonstrated in our experiments, and is shown in Figure 2.4.

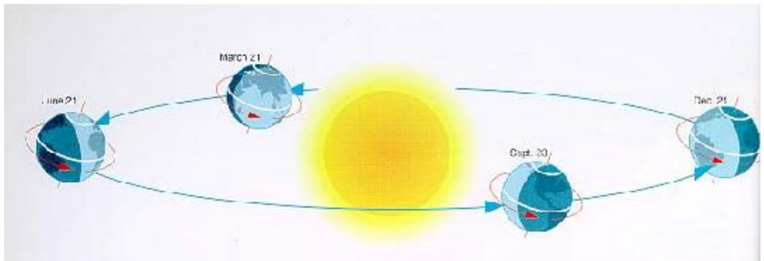


Figure 2.4: The Earth's spin axis always points to one spot in the sky, *and* it is tilted by 23.5° to its orbit. Thus, as the Earth orbits the Sun, the illumination changes with latitude: sometimes the North Pole is bathed in 24 hours of daylight, and sometimes in 24 hours of night. The exact opposite is occurring in the Southern Hemisphere.

The length of the daylight hours is one reason why it is hotter in Summer than in Winter: the longer the Sun is above the horizon the more it can heat the air, the land and the seas. But this is not the whole story. At the North Pole, where there is constant daylight during the Summer, the temperature barely rises above freezing! Why? We will discover the reason for this now.

2.4 Elevation Angle and the Concentration of Sunlight

We have found out part of the answer to why it is warmer in summer than in winter: the length of the day is longer in summer. But this is only part of the story–you would think that with days that are 22 hours long during the summer, it would be hot in Alaska and Canada during the summer, but it is not. The other affect caused by Earth's tilted spin axis is the changing height that the noontime Sun attains during the various seasons. Before we discuss why this happens (as it takes quite a lot of words to describe it correctly), we want to explore what happens when the Sun is higher in the sky. First, we need to define two new terms: "altitude", or "elevation angle". As shown in the diagram in Fig. 2.5.

The Sun is highest in the sky at noon everyday. But how high is it? This, of course, depends on both your latitude and the time of year. For Las Cruces, the Sun has an altitude of 81° on June 21st. On both March 21st and September 20th, the altitude of the Sun at noon is 57.5°. On December 21st its altitude is only 34°. Thus, the Sun is almost straight overhead at noon during near the Summer Solstice, but very low during the Winter Solstice. What difference can this possibly make? We now explore this using the other apparatus, the elevation angle device, that accompanies this lab (the one with the protractor and flashlight).

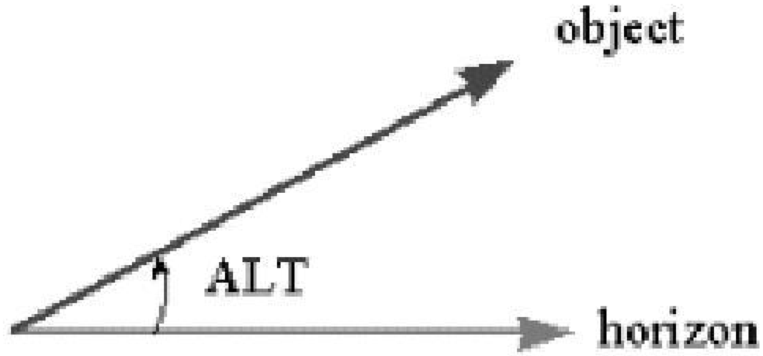


Figure 2.5: Altitude ("Alt") is simply the angle between the horizon, and an object in the sky. The smallest this angle can be is 0°, and the maximum altitude angle is 90°. Altitude is interchangeably known as elevation.

Exercise #4: Using the elevation angle apparatus, we now want to measure what happens when the Sun is at a higher or lower elevation angle. We mimic this by a flashlight mounted on an arm that allows you to move it to just about any elevation angle. It is difficult to exactly model the Sun using a flashlight, as the light source is not perfectly uniform. But here we do as well as we can. Play around with the device.

24) Turn on the flashlight and move the arm to lower and higher angles. How does the illumination pattern change? Does the illuminated pattern appear to change in brightness as you change angles? Explain. (**2 points**)

Ok, now we are ready to begin to quantify this affect. Take a blank sheet of white paper and tape it to the base so we have a more reflective surface. Now arrange the apparatus so the elevation angle is 90°. The illuminated spot should look circular. Measure the diameter of this circle using a ruler.

25) The diameter of the illuminated circle is __________________ cm.

Do you remember how to calculate the area of a circle? Does the formula πR^2 ring a bell? R is the radius, not the diameter, so first you'll need the radius of the circle.

The radius of the illuminated circle is __________________ cm.

The area of the circle of light at an elevation angle of 90° is __________________ cm^2. (**1 point**)

Now, as you should have noticed at the beginning of this exercise, as you move the flashlight to lower and lower elevations, the circle changes to an ellipse. Now adjust the elevation angle to be 45°. Ok, time to introduce you to two new terms: the major axis and minor axis of an ellipse. Both are shown in Fig. 2.6. The minor axis is the smallest diameter, while the major axis is the longest diameter of an ellipse.

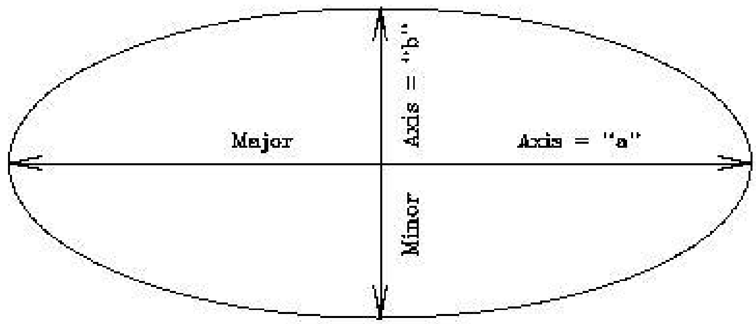


Figure 2.6: An ellipse with the major and minor axes defined.

Ok, now measure the lengths of the major ("a") and minor ("b") axes at 45°:

26) The major axis has a length of a = ____________ cm, while the minor axis has a length of b = ____________ cm.

The area of an ellipse is simply $(\pi \times a \times b)/4$. So, the area of

the ellipse at an elevation angle of 45° is: __________________ cm^2 (**1 point**).

So, why are we making you measure these areas? Note that the black tube restricts the amount of light coming from the flashlight into a cylinder. Thus, there is only a certain amount of light allowed to come out and hit the paper. Let's say there are "one hundred units of light" emitted by the flashlight. Now let's convert this to how many units of light hit each square centimeter at angles of 90° and 45°.

27) At 90°, the amount of light per centimeter is 100 divided by the Area of circle = __________________ units of light per cm^2 (**1 point**).

28) At 45°, the amount of light per centimeter is 100 divided by the Area of the ellipse = __________________ units of light per cm^2 (**1 point**).

29) Since light is a form of energy, at which elevation angle is there more energy per square centimeter? Since the Sun is our source of light, what happens when the Sun is higher in the sky? Is its energy more concentrated, or less concentrated? How about when it is low in the sky? Can you tell this by looking at how bright the ellipse appears versus the circle? (**4 points**)

As we have noted, the Sun never is very high in the arctic regions of the Earth. In fact, at the poles, the highest elevation angle the Sun can have is 23.5°. Thus, the light from the Sun is spread out, and cannot heat the ground as much as it can at a point closer to the equator. That's why it is always colder at the Earth's poles than elsewhere on the planet.

You are now finished with the in-class portion of this lab. To understand why the Sun appears at different heights at different times of the year takes a little explanation (and the following can be read at home unless you want to discuss it with your TA). Let's go back and take a look at Fig. 2.3. Note that Polaris, the North Star, barely moves over the course of a night or over the year—it is always visible. If you had a telescope and could point it accurately, you could see Polaris during the daytime too. Polaris never sets for people in the Northern Hemisphere since it is located very close to the spin axis of the Earth. Note that as we move away from Polaris the circles traced by other stars get bigger and bigger. But all of the stars shown in this photo are *always* visible—they never set. We call these stars "circumpolar". For every latitude on Earth, there is a set of circumpolar stars (the number decreases as you head towards the equator).

Now let us add a new term to our vocabulary: the "Celestial Equator". The Celestial Equator is the projection of the Earth's Equator onto the sky. It is a great circle that spans the night sky that is directly overhead for people who live on the Equator. As you have now learned, the lengths of the days and nights at the equator are nearly always the same: 12 hours. But we have also learned that during the Equinoxes, the lengths of the days and the nights *everywhere* on Earth are also twelve hours. Why? Because during the equinoxes, the Sun is *on the Celestial Equator*. That means it is straight overhead (at noon) for people who live in Quito, Ecuador (and everywhere else on the equator). Any object that is on the Celestial Equator is visible for 12 hours per night from everywhere on Earth. To try to understand this, take a look at Fig. 2.7. In this figure is shown the celestial geometry explicitly showing that the Celestial Equator is simply the Earth's equator projected onto the sky (left hand diagram). But the Earth is large, and to us, it appears flat. Since the objects in the sky are very far away, we get a view like that shown in the right hand diagram: we see one hemisphere of the sky, and the stars, planets, Sun and Moon rise in the east, and set in the west. But note that the Celestial Equator exactly intersects East and West. Only objects located on the Celestial Equator rise exactly due East, and set exactly due West. All other objects rise in the northeast or southeast and set in the northwest or the southwest. Note that in this diagram (for a latitude of 40°) all stars that have latitudes (astronomers call them "Declinations", or "dec") above 50° never set–they are circumpolar.

What happens is that during the year, the Sun appears to move above and below the Celestial Equator. On, or about, March 21st the Sun is on the Celestial Equator, and each day after this it gets higher in the sky (for locations in the Northern Hemisphere) until June 21st. After which it retraces its steps until it reaches the Autumnal Equinox (September 20th), after which it is South of the Celestial Equator. It is lowest in the sky on December 21st. This is simply due to the fact that the Earth's axis is tilted with respect to its orbit, and this tilt does not change. You can see this geometry by going back to the illuminated globe model used in Exercise #3. If you stick a pin at some location on the globe away from the equator, turn on the halogen lamp, and slowly rotate the entire apparatus around (while

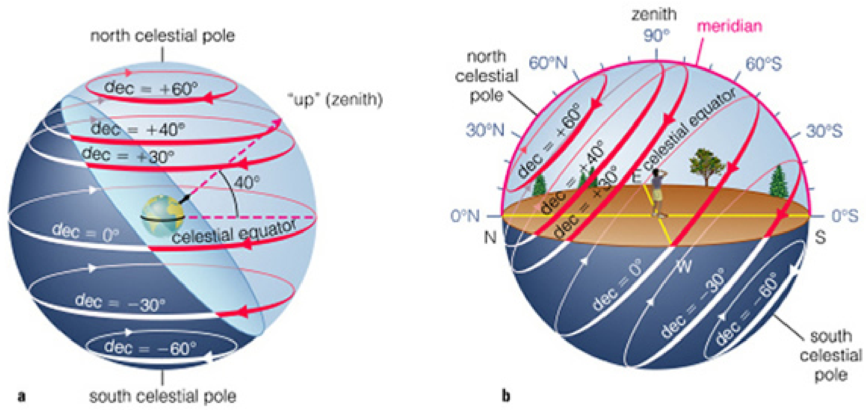


Figure 2.7: The Celestial Equator is the circle in the sky that is straight overhead ("the zenith") of the Earth's equator. In addition, there is a "North Celestial" pole that is the projection of the Earth's North Pole into space (that almost points to Polaris). But the Earth's spin axis is tilted by 23.5° to its orbit, and the Sun appears to move above and below the Celestial Equator over the course of a year.

keeping the pin facing the Sun) you will notice that the shadow of the pin will increase and decrease in size. This is due to the apparent change in the elevation angle of the "Sun".

Name:____________________________
Date:____________________________

2.5 Take Home Exercise (35 total points)

On a clean sheet of paper, answer the following questions:

1. Why does the Earth have seasons?
2. What is the origin of the term "Equinox"?
3. What is the origin of the term "Solstice"?
4. Most people in the United States think the seasons are caused by the changing distance between the Earth and the Sun. Why do you think this is?
5. What type of seasons would the Earth have if its spin axis was *exactly* perpendicular to its orbital plane? Make a diagram like Fig. 2.4.
6. What type of seasons would the Earth have if its spin axis was *in* the plane of its orbit? (Note that this is similar to the situation for the planet Uranus.)
7. What do you think would happen if the Earth's spin axis wobbled randomly around on a monthly basis? Describe how we might detect this.

2.6 Possible Quiz Questions

1) What does the term "latitude" mean?
2) What is meant by the term "Equator"?
3) What is an ellipse?
4) What are meant by the terms perihelion and aphelion?
5) If it is summer in Australia, what season is it in New Mexico?

2.7 Extra Credit (make sure to ask your TA for permission before attempting, 5 points)

We have stated that the Earth's spin axis constantly points to a single spot in the sky. This is actually not true. Look up the phrase "precession of the Earth's spin axis". Describe what is happening and the time scale of this motion. Describe what happens to the timing of the seasons due to this motion. Some scientists believe that precession might help cause ice ages. Describe why they believe this.

Name(s): ____________________
Date: ____________________

3 Phases of the Moon

3.1 Introduction

Every once in a while, your teacher or TA is confronted by a student with the question "Why can I see the Moon today, is something wrong?". Surprisingly, many students have never noticed that the Moon is visible in the daytime. The reason they are surprised is that it confronts their notion that the shadow of the Earth is the cause of the phases–it is obvious to them that the Earth cannot be causing the shadow if the Moon, Sun and Earth are simultaneously in view! Maybe you have a similar idea. You are not alone, surveys of science knowledge show that the idea that the shadow of the Earth causes lunar phases is one of the most common misconceptions among the general public. Today, you will learn why the Moon has phases, the names of these phases, and the time of day when these phases are visible.

Even though they adhered to a "geocentric" (Earth-centered) view of the Universe, it may surprise you to learn that the ancient Greeks completely understood why the Moon has phases. In fact, they noticed during lunar eclipses (when the Moon *does* pass through the Earth's shadow) that the shadow was curved, and that the Earth, like the Moon, must be spherical. The notion that Columbus feared he would fall of the edge of the flat Earth is pure fantasy—it was not a flat Earth that was the issue of the time, *but how big the Earth actually was* that made Columbus' voyage uncertain.

The phases of the Moon are cyclic, in that they repeat every month. In fact the word "month", is actually an Old English word for the Moon. That the average month has 30 days is directly related to the fact that the Moon's phases recur on a 29.5 day cycle. Note that it only takes the Moon 27.3 days to orbit once around the Earth, but the changing phases of the Moon are due to the relative to positions of the Sun, Earth, and Moon. Given that the Earth is moving around the Sun, it takes a few days longer for the Moon to get to the same *relative* position each cycle.

Your textbook probably has a figure showing the changing phases exhibited by the Moon each month. Generally, we start our discussion of the changing phases of the Moon at "New Moon". During New Moon, the Moon is invisible because it is in the same direction as the Sun, and cannot be seen. Note: because the orbit of the Moon is tilted with respect to the Earth's orbit, the Moon rarely crosses in front of the Sun during New Moon. When it does, however, a spectacular "solar eclipse" occurs.

As the Moon continues in its orbit, it becomes visible in the western sky after sunset a few days after New Moon. At this time it is a thin "crescent". With each passing day, the crescent becomes thicker, and thicker, and is termed a "waxing" crescent. About seven days after New Moon, we reach "First Quarter", a phase when we see a half moon. The visible, illuminated portion of the Moon continues to grow ("wax") until fourteen days after New Moon when we reach "Full Moon". At Full Moon, the entire, visible surface of the Moon is illuminated, and we see a full circle. After Full Moon, the illuminated portion of the Moon declines with each passing day so that at three weeks after New Moon we again see a half Moon which is termed "Third" or "Last" Quarter. As the illuminated area of the Moon is getting smaller each day, we refer to this half of the Moon's monthly cycle as the "waning" portion. Eventually, the Moon becomes a waning crescent, heading back towards New Moon to begin the cycle anew. Between the times of First Quarter and Full Moon, and between Full Moon and Third Quarter, we sometimes refer to the Moon as being in a "gibbous" phase. Gibbous means "hump-backed". When the phase is increasing towards Full Moon, we have a "waxing gibbous" Moon, and when it is decreasing, the "waning gibbous" phases.

The objective of this lab is to improve your understanding of the Moon phases [a topic that you WILL see on future exams!]. This concept, the phases of the Moon, involves

1. the position of the Moon in its orbit around the Earth,
2. the illuminated portion of the Moon that is visible from here in Las Cruces, and
3. the time of day that a given Moon phase is at the highest point in the sky as seen from Las Cruces.

You will **finish** this lab by demonstrating to your instructor that you do clearly understand the concept of Moon phases, including an understanding of:

- which direction the Moon travels around the Earth
- how the Moon phases progress from day-to-day
- at what time of the day the Moon is highest in the sky at each phase

Materials

- small spheres (representing the Moon), with two different colored hemispheres. The **dark** hemisphere represents the portion of the Moon not illuminated by the Sun.
- flashlight (representing the Sun)
- yourself (representing the Earth, and your nose Las Cruces!)

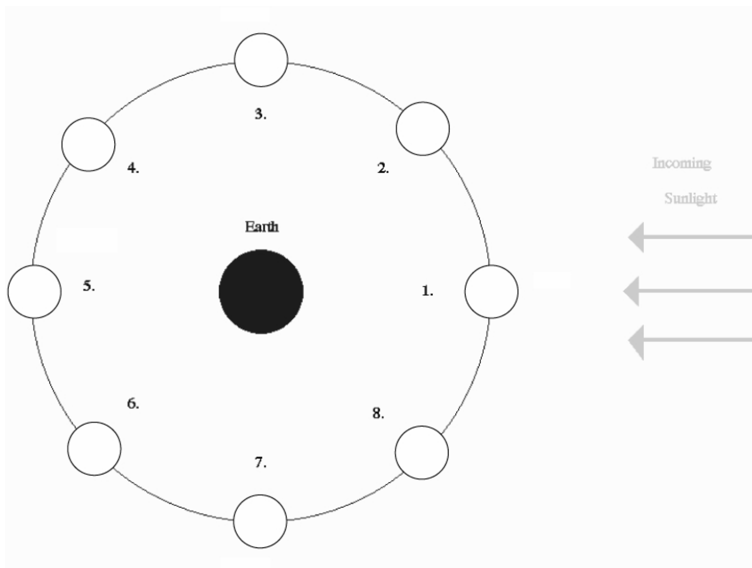
You will use the colored sphere and flashlight as props for this demonstration. Carefully read and thoroughly answer the questions associated with each of the five Exercises on the following pages. [Don't be concerned about eclipses as you answer the questions in these Exercises]. Using the dual-colored sphere to represent the Moon, the flashlight to represent the Sun, and a member of the group to represent the Earth (with that person's nose representing Las Cruces' location), 'walk through' and 'rotate through' the positions indicated in the Exercise figures to fully understand the situation presented.

Note that there are additional questions at the end.

Work in Groups of Three People!

3.2 Exercise 1 (10 points)

The figure below shows a "top view" of the Sun, Earth, and eight different positions (1-8) of the Moon during one orbit around the Earth. Note that the distances shown are **not** drawn to scale.



Ranking Instructions: Rank (from *greatest* to *least*) the amount of the Moon's **entire surface** that is illuminated for the eight positions (1-8) shown.

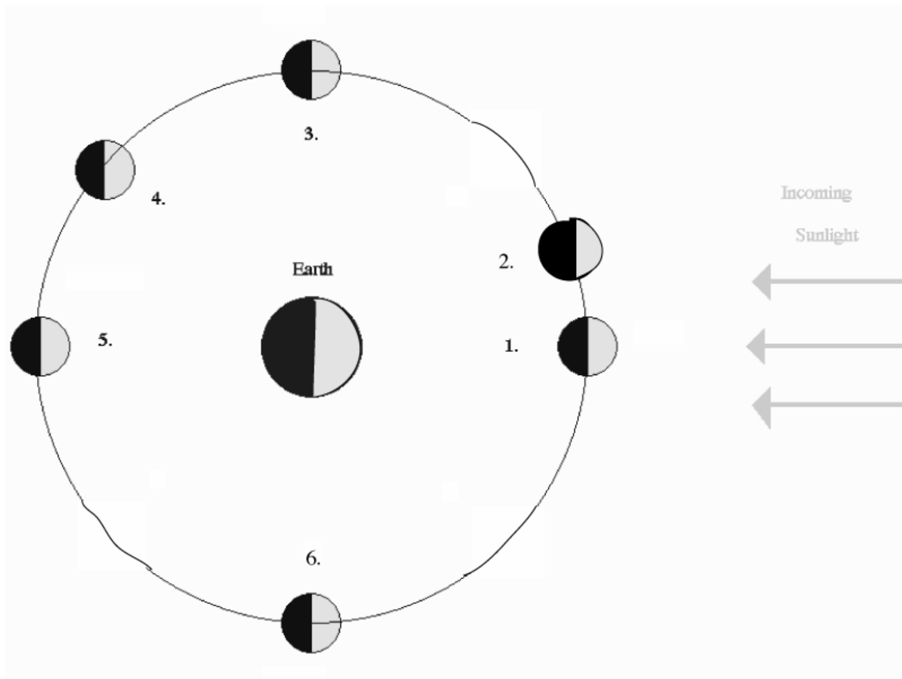
Ranking Order: Greatest A ____B ____C ____D ____E ____F ____G ____H ____Least

Or, the amount of the entire surface of the Moon illuminated by sunlight is the same at all the positions. ______ (indicate with a check mark).

Carefully explain the reasoning for your result:

3.3 Exercise 2 (10 points)

The figure below shows a "top view" of the Sun, Earth, and six different positions (1-6) of the Moon during one orbit of the Earth. Note that the distances shown are **not** drawn to scale.



Ranking Instructions: Rank (from *greatest* to *least*) the amount of the Moon's illuminated surface that is **visible from Earth** for the six positions (1-6) shown.

Ranking Order: Greatest A ______B ______C ______D ______E ______F ______Least

Or, the amount of the Moon's illuminated surface visible from Earth is the same at all the positions. ______ (indicate with a check mark).

Carefully explain the reasoning for your result:

3.4 Exercise 3 (10 points)

Shown below are different phases of the Moon as seen by an observer in the Northern Hemisphere.

A B C D E

Ranking Instructions: Beginning with the *waxing gibbous* phase of the Moon, rank all five Moon phases shown above in the order that the observer would see them over the next four weeks (write both the picture letter and the phase name in the space provided!).

Ranking Order:

1) Waxing Gibbous

2) ____________________

3) ____________________

4) ____________________

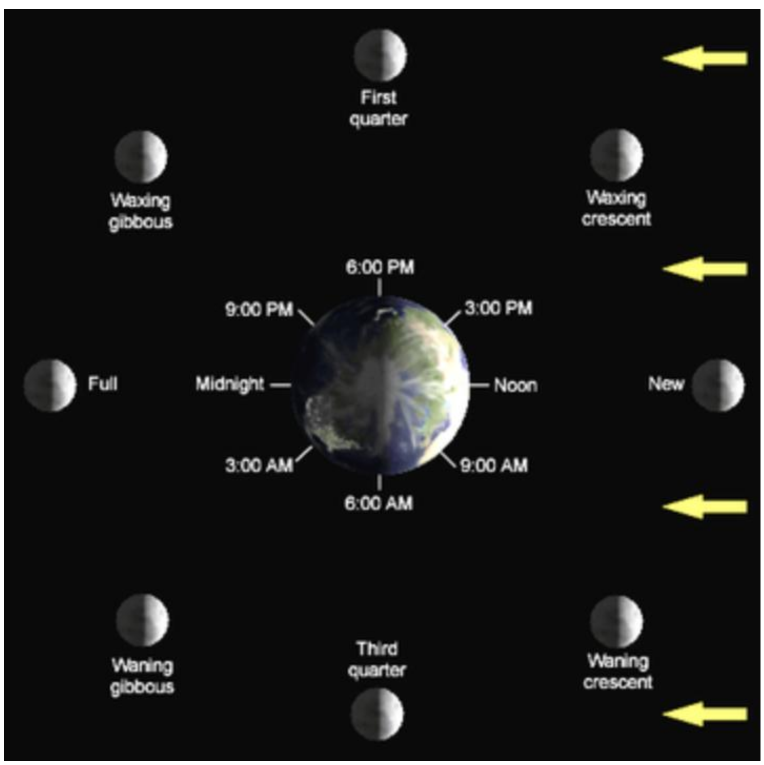
5) ____________________

Or, all of these phases would be visible at the same time: _____ (indicate with a check mark).

3.5 Lunar Phases, and When They Are Observable

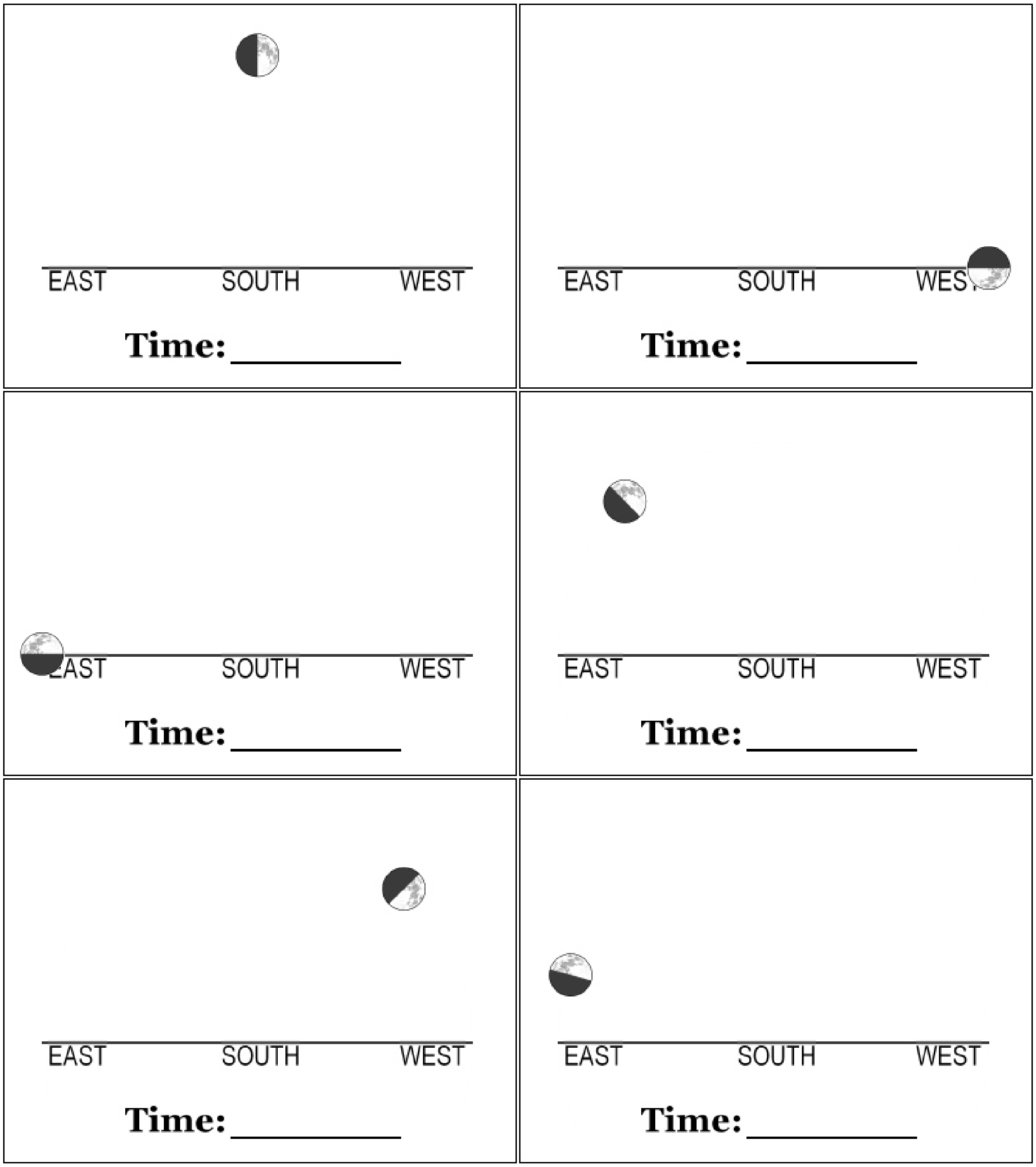
The next three exercises involve determining when certain lunar phases can be observed. Or, alternatively, determining the approximate time of day or night using the position and phase of the Moon in the sky.

In Exercises 1 and 2, you learned about the changing geometry of the Earth-Moon-Sun system that is the cause of the phases of the Moon. When the Moon is in the same direction as the Sun, we call that phase New Moon. During New Moon, the Moon rises with the Sun, and sets with the Sun. So if the Moon's phase was New, and the Sun rose at 7 am, the Moon also rose at 7 am–even though you cannot see it! The opposite occurs at Full Moon: at Full Moon the Moon is in the opposite direction from the Sun. Therefore, as the Sun sets, the Full Moon rises, and vice versa. The Sun reaches its highest point in the sky at noon each day. The Full Moon will reach the highest point in the sky at midnight. At First and Third quarters, the Moon-Earth-Sun angle is a right angle, that is it has an angle of 90° (positions 3 and 6, respectively, in the diagram for exercise #2). At these phases, the Moon will rise or set at either noon, or midnight (it will be up to you to figure out which is which!). To help you with exercises 4 through 6, we include the following figure detailing *when the observed phase is highest* in the sky.



3.6 Exercise 4 (6 points)

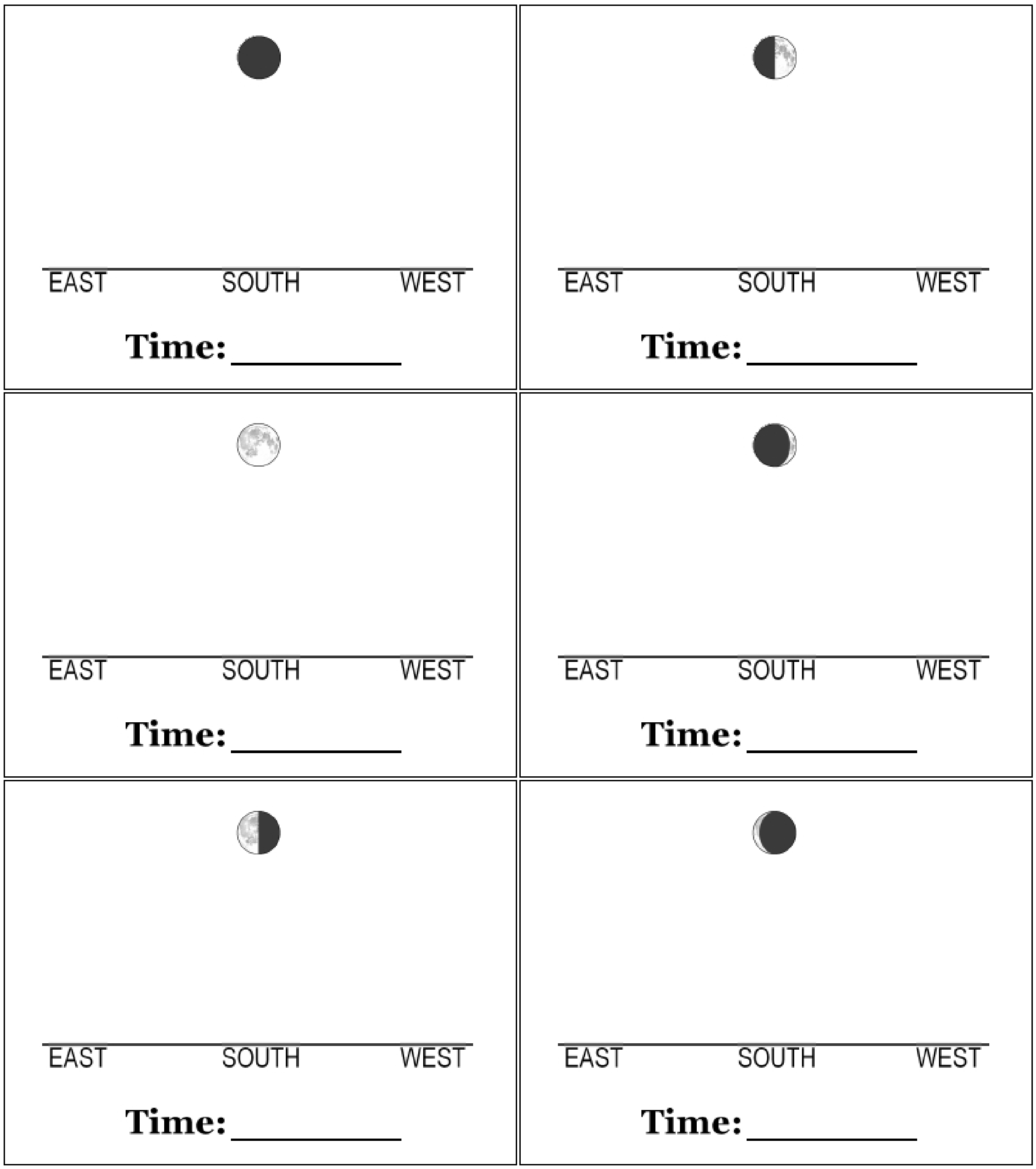
In the set of figures below, the Moon is shown in the first quarter phase at different times of the day (or night). Assume that sunset occurs at 6 p.m. and that sunrise occurs at 6 a.m.



Instructions: Determine the time at which each view of the Moon would be seen, and write it on each panel of the figure.

3.7 Exercise 5 (6 points)

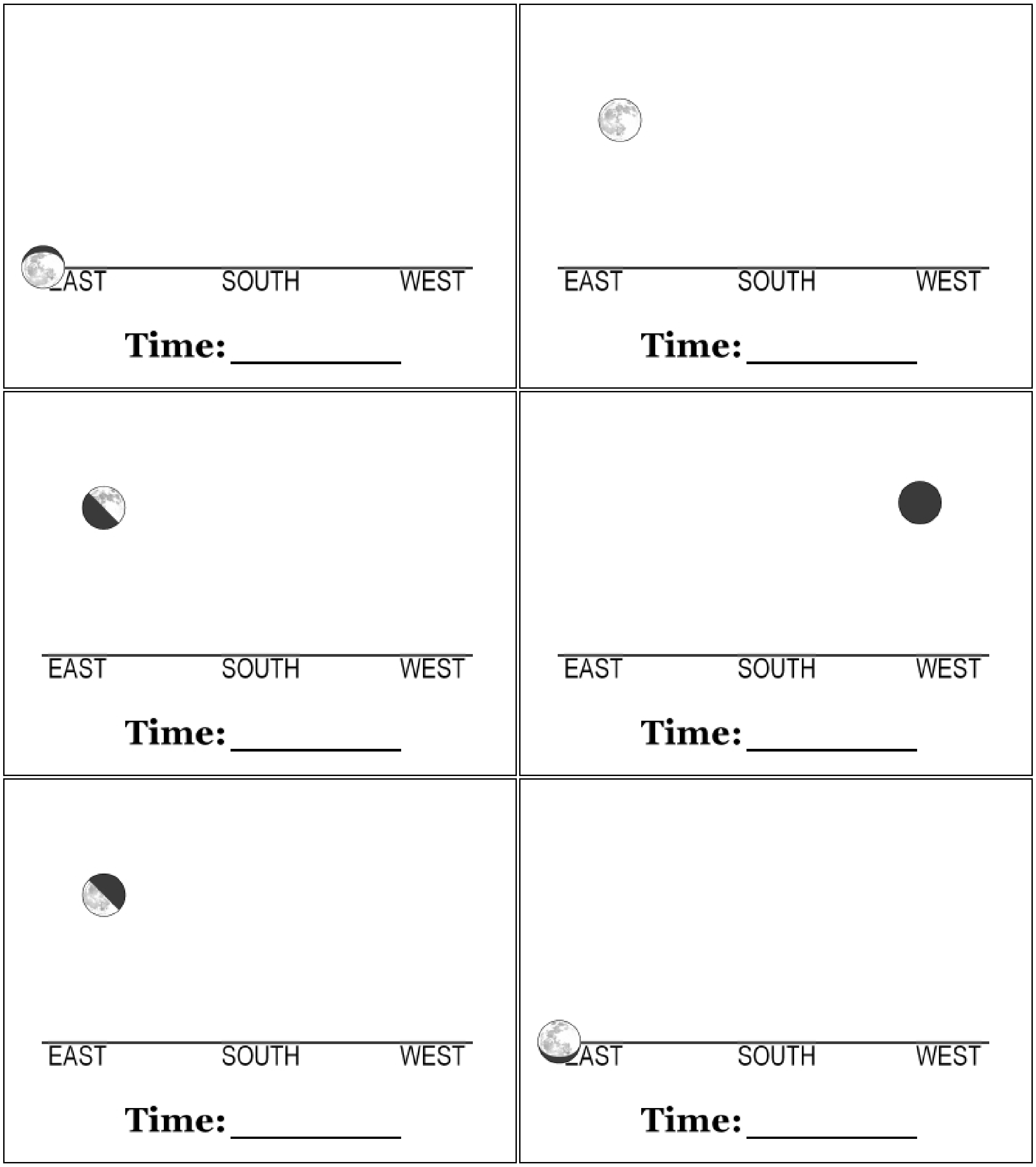
In the set of figures below, the Moon is shown overhead, at its highest point in the sky, but in different phases. Assume that sunset occurs at 6 p.m. and that sunrise occurs at 6 a.m.



Instructions: Determine the time at which each view of the Moon would have been seen, and write it on each panel of the figure.

3.8 Exercise 6 (6 points)

In the two sets of figures below, the Moon is shown in different parts of the sky and in different phases. Assume that sunset occurs at 6 p.m. and that sunrise occurs at 6 a.m.



Instructions: Determine the time at which each view of the Moon would have been seen, and write it on each panel of the figure.

3.9 Demonstrating Your Understanding of Lunar Phases

After you have completed the six Exercises and are comfortable with Moon phases, and how they relate to the Moon's orbital position and the time of day that a particular Moon phase is highest in the sky, you will be verbally quizzed by your instructor (*without the Exercises available*) on these topics. You will use the dual-colored sphere, and the flashlight, and a person representing the Earth to illustrate a specified Moon phase (appearance of the Moon in the sky). You will do this for three different phases. **(17 points)**

Name:______________________________
Date:_______________________________

3.10 Take-Home Exercise (35 points total)

On a separate sheet of paper, answer the following questions:

1. If the Earth was one-half as massive as it actually is, how would the time interval (number of days) from one Full Moon to the next in this 'small Earth mass' situation compare to the actual time interval of 29.5 days between successive Full Moons? Assume that all other aspects of the Earth and Moon system, including the Moon's orbital semi-major axis, the Earth's rotation rate, etc. do not change from their current values. (**15 points**)

2. What (approximate) phase will the Moon be in one week from today's lab? (**5 points**)

3. If you were on Earth looking up at a Full Moon at midnight, and you saw an astronaut at the center of the Moon's disk, what phase would the astronaut be seeing the Earth in? **Draw a diagram to support your answer. (15 points)**

3.11 Possible Quiz Questions

1) What causes the phases of the Moon?
2) What does the term "New Moon" mean?
3) What is the origin of the word "Month"?
4) How long does it take the Moon to go around the Earth once?
5) What is the time interval between successive New Moons?

3.12 Extra Credit (make sure you get permission from your TA before attempting, 5 points)

Write a one page essay on the term "Blue Moon". Describe what it is, and how it got its name.

Name:_________________________________
Date:__________________________________

4 Kepler's Laws

4.1 Introduction

Throughout human history, the motion of the planets in the sky was a mystery: why did some planets move quickly across the sky, while other planets moved very slowly? Even two thousand years ago it was apparent that the motion of the planets was very complex. For example, Mercury and Venus never strayed very far from the Sun, while the Sun, the Moon, Mars, Jupiter and Saturn generally moved from the west to the east against the background stars (at this point in history, both the Moon and the Sun were considered "planets"). The Sun appeared to take one year to go around the Earth, while the Moon only took about 30 days. The other planets moved much more slowly. In addition to this rather slow movement against the background stars was, of course, the daily rising and setting of these objects. How could all of these motions occur? Because these objects were important to the cultures of the time. Being able to predict their motion was considered vital.

The ancient Greeks had developed a model for the Universe in which all of the planets and the stars were embedded in perfect crystalline spheres that revolved around the Earth at uniform, but slightly different speeds. This is the "geocentric", or Earth-centered model. But this model did not work very well, the speed of the planet across the sky changed. Sometimes, a planet even moved backwards! The Egyptian astronomer Ptolemy (85 − 165 AD) finally came up with a model for the motion of the planets that accounted for some of challenges. Ptolemy developed a complicated system to explain the motion of the planets, including "epicycles" and "equants", that in the end worked reasonably well, and no other models for the motions of the planets were considered for 1500 years! While Ptolemy's model worked well, the philosophers of the time did not like this model, their Universe was perfect, and Ptolemy's model suggested that the planets moved in peculiar, imperfect ways.

In the 1540's Nicholas Copernicus (1473 − 1543) published his work suggesting that it was much easier to explain the complicated motion of the planets if the Earth revolved around the Sun, and that the orbits of the planets were circular. While Copernicus was not the first person to suggest this idea, the timing of his publication coincided with attempts to revise the calendar and to fix a large number of errors in Ptolemy's model that had shown up over the 1500 years since the model was first introduced. But the "heliocentric" (Sun-centered) model of Copernicus was slow to win acceptance, since it did not work as well as the geocentric model of Ptolemy.

Johannes Kepler (1571 − 1630) was the first person to truly understand how the planets in our solar system moved. Using the highly precise observations by Tycho Brahe (1546 − 1601) of the motions of the planets against the background stars, Kepler was able to formulate three laws that described how the planets moved. With these laws, he was able to predict the future motion of these planets to a higher precision than was previously possible. Many credit Kepler with the origin of modern physics, as his discoveries were what led Isaac Newton (1643 − 1727) to formulate the law of gravity. Today we will investigate Kepler's laws.

4.2 Gravity

Gravity is the fundamental force governing the motions of astronomical objects. No other force is as strong over as great a distance. Gravity influences your everyday life (ever drop a glass?), and keeps the planets, moons, and satellites orbiting smoothly. Gravity affects everything in the Universe including the largest structures like super clusters of galaxies down to the smallest atoms and molecules.

Experimenting with gravity is difficult to do. You can't just go around in space making extremely massive objects and throwing them together from great distances. But you can model a variety of interesting systems very easily using a computer. By using a computer to model the interactions of massive objects like planets, stars and galaxies, we can study what would happen in just about any situation. All we have to know are the equations which predict the gravitational interactions of the objects.

The orbits of the planets are governed by a single equation formulated by Newton:

$$F_{gravity} = \frac{GM_1M_2}{R^2} \tag{1}$$

A diagram detailing the quantities in this equation is shown in Fig. 4.1. Here $F_{gravity}$ is the gravitational attractive force between two objects whose masses are M_1 and M_2. The distance between the two objects is "R". The gravitational constant G is just a small number that scales the size of the force. **The most important thing about gravity is that the force depends only on the masses of the two objects and the distance between them.** This law is called an Inverse Square Law because the distance between the objects is *squared*, and is in the denominator of the fraction. There are several laws like this in physics and astronomy.

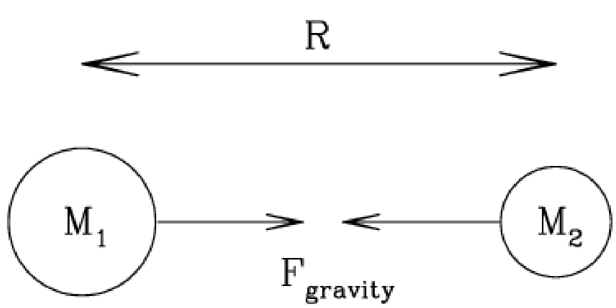


Figure 4.1: The force of gravity depends on the masses of the two objects (M_1, M_2), and the distance between them (R).

4.3 Kepler's Laws

Before you begin the lab, let's state Kepler's three laws, the basic description of how the planets in our Solar System move. Kepler formulated his three laws in the early 1600's, when he finally solved the mystery of how planets moved in our Solar System. These three (empirical) laws are:

I. **The orbits of the planets are ellipses with the Sun at one focus.**

II. **A line from the planet to the Sun sweeps out equal areas in equal intervals of time.**

III. **A planet's orbital period squared is proportional to its average distance from the Sun cubed: $\mathbf{P^2 \propto a^3}$**

In this lab, we will investigate these laws to develop your understanding of them.

Let's look at the first law, and talk about the nature of an ellipse. What is an ellipse? An ellipse is one of the special curves called a "conic section". If we slice a plane through a cone, four different types of curves can be made: circles, ellipses, parabolas, and hyperbolas. This process, and how these curves are created is shown in Fig. 4.2.

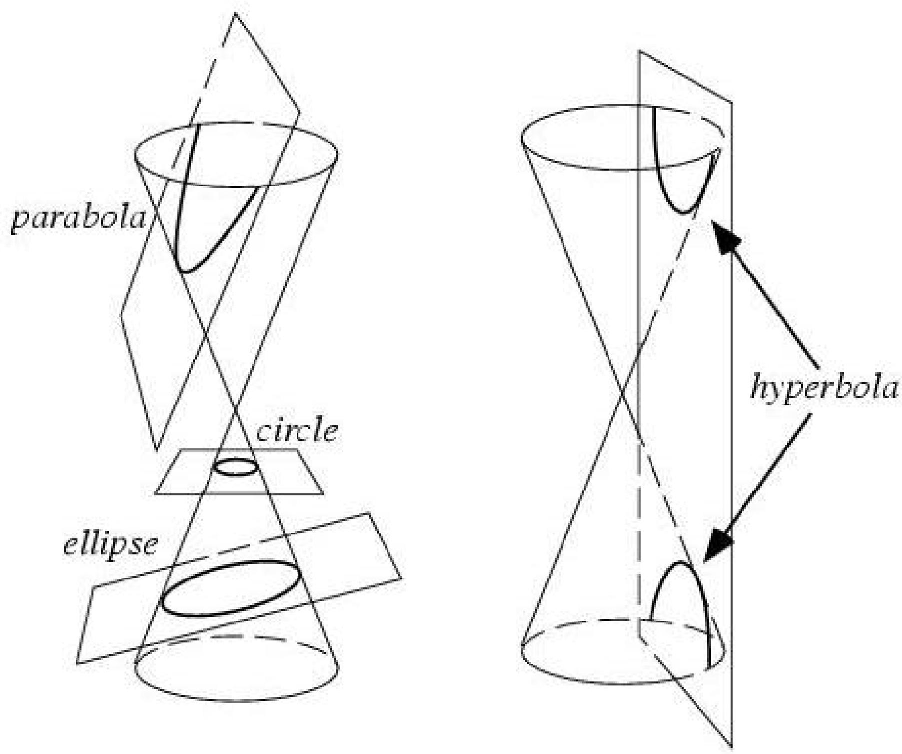


Figure 4.2: Four types of curves can be generated by slicing a cone with a plane: a circle, an ellipse, a parabola, and a hyperbola. Strangely, these four curves are also the allowed shapes of the orbits of planets, asteroids, comets and satellites!

Before we describe an ellipse, let's examine a circle, as it is a simple form of an ellipse. As you are aware, the circumference of a circle is simply 2πR. The radius, R, is the distance between the center of the circle and any point on the circle itself. In mathematical terms, the

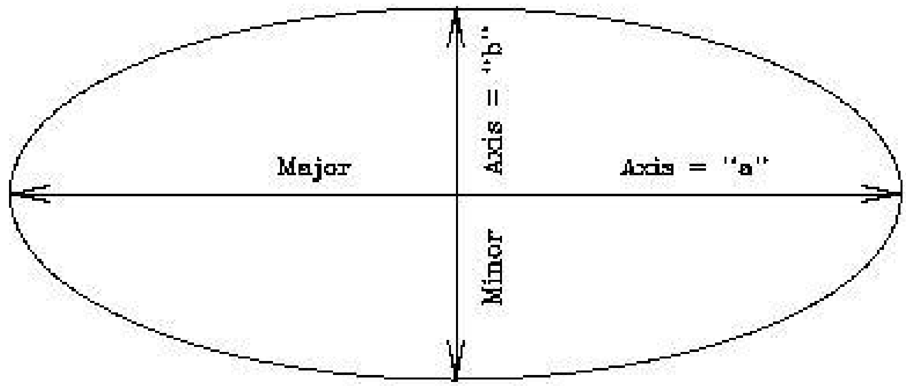


Figure 4.3: An ellipse with the major and minor axes identified.

center of the circle is called the "focus". An ellipse, as shown in Fig. 4.3, is like a flattened circle, with one large diameter (the "major" axis) and one small diameter (the "minor" axis). A circle is simply an ellipse that has identical major and minor axes. Inside of an ellipse, there are two special locations, called "foci" (foci is the plural of focus, it is pronounced "fo-sigh"). The foci are special in that the sum of the distances between the foci and any points on the ellipse are always equal. Fig. 4.4 is an ellipse with the two foci identified, "F_1" and "F_2".

Exercise #1: On the ellipse in Fig. 4.4 are two X's. Confirm that that sum of the distances between the two foci to any point on the ellipse is always the same by measuring the distances between the foci, and the two spots identified with X's. Show your work. (**3 points**)

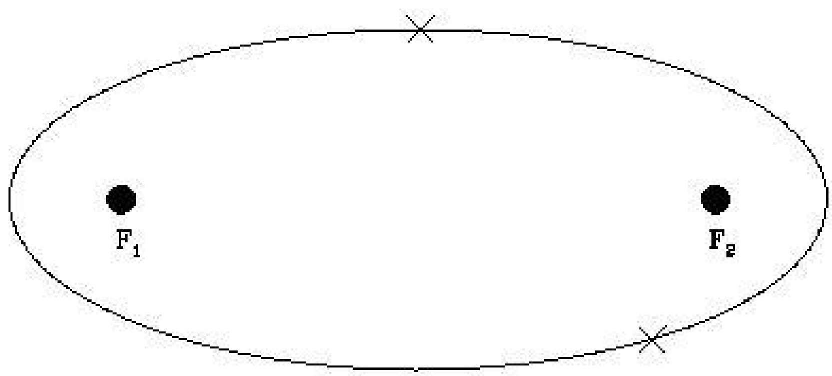


Figure 4.4: An ellipse with the two foci identified.

Exercise #2: In the ellipse shown in Fig. 4.5, two points ("P_1" and "P_2") are identified that are not located at the true positions of the foci. Repeat exercise #1, but confirm that P_1 and P_2 are not the foci of this ellipse. (**3 points**)

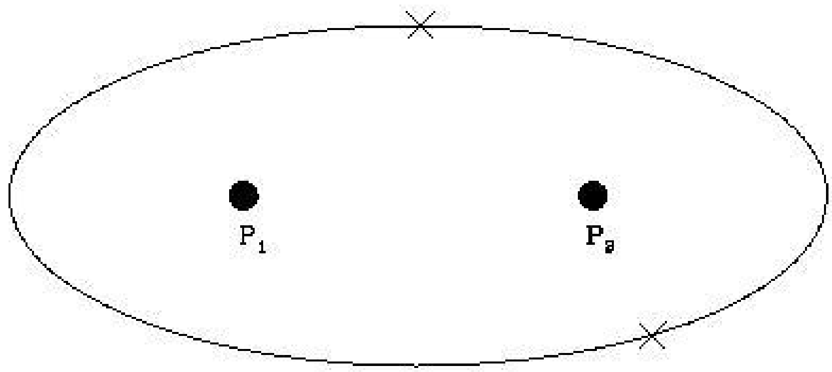


Figure 4.5: An ellipse with two non-foci points identified.

We will now use various online simulators to explore Kepler's Laws of planetary motion

4.4 Simulator

We will be using the NAAP simulators which are located here:

https://astro.unl.edu/naap/pos/animations/kepler.html

4.5 Kepler's 1st Law

If you have not already done so, launch the NAAP Planetary Orbit Simulator.

- Open the Kepler's 1st Law tab if it is not already (it's open by default).
- Enable all 5 check boxes.
- The white dot is the simulated planet. One can click on it and drag it around.
- Change the size of the orbit with the semimajor axis slider. Note how the background grid indicates change in scale while the displayed orbit size remains the same.
- Change the eccentricity and note how it affects the shape of the orbit.

Tip: You can change the value of a slider by clicking on the slider bar or by entering a number in the value box.

Be aware that the ranges of several parameters are limited by practical issues that occur when creating a simulator rather than any true physical limitations. The simulator limits the semi-major axis to 50 AU since that covers most of the objects in which we are interested in our solar system and have limited eccentricity to 0.7 since the ellipses would be hard to fit on the screen for larger values. Note also that the semi-major axis is aligned horizontally for all elliptical orbits created in this simulator, where they are randomly aligned in our solar system.

- Animate the simulated planet. You may need to increase the animation rate for very large orbits or decrease it for small ones.
- The planetary presets set the simulated planet's parameters to those like our solar system's planets. Explore these options.

We will now be using this simulator to answer some questions on Kepler's 1st law.

1. For what eccentricity is the secondary focus (which is usually empty) located at the sun? What is the shape of this orbit? **(2 points)**

2. Create an orbit with a = 20 AU and e = 0. Drag the planet first to the far left of the ellipse and then to the far right. What are the values of r1 and r2 at these locations? **(2 points)**

	r1 (AU)	r2 (AU)
Far Left		
Far Right		

3. Create an orbit with a = 20 AU and e = 0.5. Drag the planet first to the far left of the ellipse and then to the far right. What are the values of r1 and r2 at these locations? **(2 points)**

	r1 (AU)	r2 (AU)
Far Left		
Far Right		

4. What is the value of the sum of r1 and r2 and how does it relate to the ellipse properties? Is this true for all ellipses? **(3 points)**

5. It is easy to create an ellipse using a loop of string and two thumbtacks. The string is first stretched over the thumbtacks which act as foci. The string is then pulled tight using the pencil which can then trace out the ellipse. Assume that you wish to draw an ellipse with a semi-major axis of $a = 20$ cm and an eccentricity of $e = 0.5$. How long would your string need to be? (Hint: think about the case where $e = 0$, i.e., a circle). Given that the eccentricity of an ellipse is c/a, where c is the distance of each focus from the center of the ellipse, how far apart would the thumbtacks (at the focii) need to be? **(4 points)**

4.6 Kepler's 2nd Law

- Use the 'clear optional features' button to remove the 1st Law features.
- Open the Kepler's 2nd Law tab.
- Press the 'start sweeping' button. Adjust the semimajor axis and animation rate so that the planet moves at a reasonable speed.
- Adjust the size of the sweep using the 'adjust size' slider.
- Click and drag the sweep segment around. Note how the shape of the sweep segment changes, but the area does not.
- Add more sweeps. Erase all sweeps with the 'erase sweeps' button.
- The 'sweep continuously' check box will cause sweeps to be created continuously when sweeping. Test this option.

1. Erase all sweeps and create an ellipse with a = 1 AU and e = 0. Set the fractional sweep size to one-twelfth of the period. Drag the sweep segment around. Does its size or shape change? **(2 points)**

2. Leave the semi-major axis at a = 1 AU and change the eccentricity to e = 0.5. Drag the sweep segment around and note that its size and shape change. Where is the sweep segment the widest? Where is it the narrowest? Where is the planet when it is sweeping out each of these segments? What names do astronomers use for these positions? **(4 points)**

3. What eccentricity in the simulator gives the greatest variation of sweep segment shape? **2 points)**

4. Halley's comet has a semimajor axis of about 18.5 AU, a period of 76 years, and an eccentricity of about 0.97 (so Halley's orbit cannot be shown in this simulator.) The orbit of Halley's Comet, the Earth's Orbit, and the Sun are shown in the diagram below (not exactly to scale). Based upon what you know about Kepler's 2nd Law, explain why we can only see the comet for about 6 months every orbit (76 years)? **(4 points)**

4.7 Kepler's 3rd Law

Kepler's third law is:

$$P_{years}^2 = a_{AU}^3 \tag{2}$$

Here is an example of how use this equation to make some predictions. If the average distance of Jupiter from the Sun is about 5 AU, what is its orbital period? Set-up the equation:

$$P(Jupiter)^2 = a(Jupiter)^3 = 5^3 = 5 \times 5 \times 5 = 125 \tag{3}$$

So, for Jupiter, $P^2 = 125$. How do we figure out what P is? We have to take the square root of both sides of the equation, which you can easily do with a calculator.

$$\sqrt{P^2} = P = \sqrt{125} = 11.2 \;\; years \tag{4}$$

The orbital period of Jupiter is approximately 11.2 years.

Similarly, if you are given the period of an orbit, you can find the semimajor axis: just take the square of the period, and then you have to take the cube root of that number:

$$a^3 = P^2 \tag{5}$$

$$a = \sqrt[3]{P^2} \tag{6}$$

You should also be able to do cube roots on your calculator.

Let's investigate Kepler's third law using the simulator.

- Use the 'clear optional features' button to remove the 2nd Law features.
- Open the Kepler's 3rd Law tab.

1. Use the simulator to complete the table below. **(7 points)**

Object	P(years)	a (AU)	e	P^2	a^3
Earth		1.00			
Mars		1.52			
Ceres		2.77	0.08		
Chiron	50.7		0.38		

2. As the size of a planet's orbit increases, what happens to its period? **(2 points)**

3. Start with the Earth's orbit and change the eccentricity to 0.6. Does changing the eccentricity change the period of the planet? **(2 point)**

4. Kepler's third law is $P^2 = a^3$ where P is measured in years, and a is measured in astronomical units. Using this relation, what would the period of an object be if it was an in orbit with a semi-major axis of 4 AU? Show your work. **(3 points)**

5. What would the orbital semimajor axis be for an object that had an orbital period of 10 years? **(3 points)**

If one used units other than years for the period and AU for the semimajor axis, there would be some other numbers in the equation for Kepler's third law, but the basic relation between the square of the period (P^2) and the semimajor axies (a^3) would still be the same. For example, say we measured the semimajor axis in kilometers (km) instead of in AU. We can do a unit conversion (remember those from earlier labs?). Since 1 AU = 1.496×10^8 km, we have:

$$P_{years}^2 = a_{AU}^3 = \left(a_{km} \frac{1AU}{1.496 \times 10^8 km} \right)^3 = 2.99 \times 10^{-25} a_{km}^3 \tag{7}$$

You would get some different number if you used some different units for either the period or the semimajor axis, but you would always see a P^2 on the left side and an a^3 on the right. For this reason, scientist often represent the fundamentally important part of the relation as a *proportionality* rather than as an *equality*, in other words, they would say that P^2 is *proportional to* a^3, which is a statement that is true independent of the units used. This is often written as:

$$P^2 \propto a^3 \tag{8}$$

If you take the square root of both sides, this becomes:

$$P \propto a^{3/2} = a^{1.5} \tag{9}$$

Using proportionalities often makes calculations easier, because you can use ratios of quantities from different objects. For example, if someone says that the semimajor axis of some object is twice that of Jupiter, you can tell them what the period of that object is relative to the period of Jupiter:

$$\left(\frac{P(object)}{P(Jupiter)}\right) = \left(\frac{a(object)}{a(Jupiter)}\right)^{1.5} = 2^{1.5} = 2.82 \text{ times the period of Jupiter} \tag{10}$$

without ever needing to know what the semimajor axis or the period of Jupiter is at all!

1. The *proportionality* part of Kepler's third law holds for all orbiting objects, although the equality does not. Imagine we discovered another system of planets around another star, and found that a planet located at 1 AU from the star took 2 years to go around (this would happen if the star was less massive than our Sun). How long would it take a planet that was located at 4 AU from that star to orbit the star? Use equation 10 and explain your reasoning. **(5 points)**

4.8 Take Home Exercise (35 points total):

On a clean sheet of paper, please summarize the important concepts of this lab. Use complete sentences, and proofread your summary before handing in the lab. Your response should include:

- Describe the Law of Gravity and what happens to the gravitational force as *a)* as the masses increase, and *b)* the distance between the two objects increases
- Describe Kepler's three laws *in your own words*, and describe how you tested each one of them.
- Mention some of the things which you have learned from this lab
- Astronomers think that finding life on planets in binary systems is unlikely. Why do they think that? Use your simulation results to strengthen your argument.

4.9 Possible Quiz Questions

1. Describe the difference between an ellipse and a circle.
2. List Kepler's three laws.
3. How quickly does the strength ("pull") of gravity get weaker with distance?
4. Describe the major and minor axes of an ellipse.

Name:________________________________

Date:________________________________

5 Optics

5.1 Introduction

Unlike other scientists, astronomers are far away from the objects they want to examine. Therefore astronomers learn everything about an object by studying the light it emits. Since objects of astronomical interest are far away, they appear very dim and small to us. Thus astronomers must depend upon telescopes to gather more information. Lenses and mirrors are used in telescopes which are the instruments astronomers use to observe celestial objects. Therefore it is important for us to have a basic understanding of optics in order to optimize telescopes and interpret the information we receive from them.

The basic idea of optics is that mirrors or lenses can be used to change the direction which light travels. Mirrors change the direction of light by *reflecting* the light, while lenses redirect light by *refracting*, or bending the light.

The theory of optics is an important part of astronomy, but it is also very useful in other fields. Biologists use microscopes with multiple lenses to see very small objects. People in the telecommunications field use fiber optic cables to carry information at the speed of light. Many people benefit from optics by having their vision corrected with eyeglasses or contact lenses.

This lab will teach you some of the basic principles of optics which will allow you to be able to predict what mirrors and lenses will do to the light which is incident on them. At the observatory you use real telescopes, so the basic skills you learn in this lab will help you understand telescopes better.

- *Goals:* to discuss the properties of mirrors and lenses, and demonstrate them using optics; build a telescope
- *Materials:* optical bench, ray trace worksheet, meterstick

5.2 Discussion

The behavior of light depends on how it strikes the surface of an object. All angles are measured with respect to the **normal** direction. The normal direction is defined as a line which is perpendicular to the surface of the object. The angle between the normal direction and the surface of the object is 90°. Some important definitions are given below. Pay special attention to the pictures in Figure 5.1 since they relate to the reflective (mirrors) and refractive (lenses) optics which will be discussed in this lab.

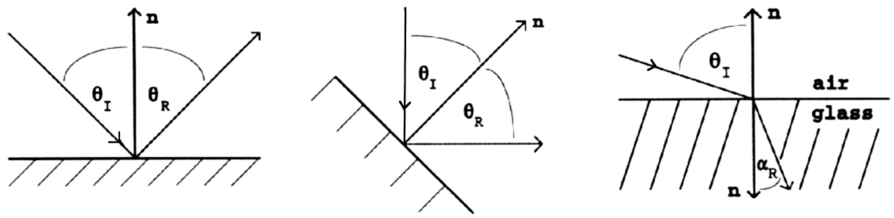


Figure 5.1: The definition of the “normal” direction **n**, and other angles found in optics.

- **n** = line which is always perpendicular to the surface; also called the *normal*
- θ_I = angle of *incidence*; the angle between the *incoming* light ray and the normal to the surface
- θ_R = angle of *reflection*; the angle between the *outgoing* light ray and the normal to the surface
- α_R = angle of *refraction*; the angle between the *transmitted* light ray and the normal direction

5.3 Reflective Optics: Mirrors

How do mirrors work? Let’s experiment by reflecting light off of a simple flat mirror.

As part of the equipment for this lab you have been given a device that has a large wooden protractor mounted in a stand that also has a flat mirror. Along with this set-up comes a “Laser Straight” laser alignment tool. Inside the Laser Straight is a small laser. There is a small black switch which turns the laser on and off. Keep it off, except when performing the following exercise (always be careful around lasers–they can damage your eyes if you stare into them!).

With this set-up, we can explore how light is reflected off of a flat mirror. Turn on the Laser Straight, place it on the wooden part of the apparatus outside the edge of the protractor so that the laser beam crosses across the protractor scale and intercepts the mirror. Align the laser at some angle on the protractor, making sure the laser beam passes through the *vertex* of the protractor. Note how the “incident” laser beam is reflected. Make a sketch of what you observe in the space below.

Table 5.1: Data Table

Angle of Incidence	Angle of Reflection
20º	
30º	
45º	
60º	
75º	
90º	

Now experiment using different angles of incidence by rotating the Laser Straight around the edge of the protractor, always insuring the laser hits the mirror exactly at the vertex of the protractor. Note that an angle of incidence of 90º corresponds to the "normal" defined above (see Fig. 5.1a).

1. Fill in Table 5.1 with the data for angle of incidence vs. angle of reflection. (**3 pts**)

2. What do you conclude about how light is reflected from a mirror? (**2 pts**)

The law governing the behavior of light when it strikes a mirror is known as the **Law of Reflection**:

angle of incidence = angle of reflection

$$\theta_I = \theta_R$$

3. OK, now what happens if you make the mirror curved? First let's consider a *concave* mirror, one which is curved *away* from the light source. Try to think about the curved mirror as being made up of lots of small subsections of flat mirrors, and make a prediction for what you will see if you put a curved mirror in the light path. You might try to make a drawing in the space below:

   At the front of the classroom is in fact just such a device: A curved wooden base to which are glued a large number of flat mirrors, along with a metal stand that has three lasers mounted in it, and the "disco5000" smoke machine. Have your TA turn on the lasers, align them onto the multi-mirror apparatus, and spew some smoke!

4. Was your prediction correct?

   Also at the front of the room are two large curved mirrors. There are two types of curved mirrors, "convex" and "concave". In a convex mirror, the mirror is curved outwards, in a concave mirror, the mirror is curved inwards ("caved" in). Light that is reflected from these two types of mirrors behaves in different ways. In this subsection of the lab, you will investigate how light behaves when encountering a curved mirror.

5. Have your TA place the laser apparatus in front of the convex mirror, and spew some more smoke. **BE CAREFUL NOT TO LET THE LASER LIGHT HIT YOUR EYE.** What happens to the laser beams when they are reflected off of the convex mirror? Make a drawing of how the light is reflected (using the attached work sheet, the diagram labeled "Convex Mirror" in Figure 5.2). (**5 pts**)

6. Now have your TA replace the convex mirror with the concave mirror. Now what happens to the laser beams? Draw a diagram of what happens (using the same worksheet, in the space labeled "Concave Mirror"). (**5 pts**)

7. Note that there are three laser beams. Using a piece of paper, your hand, or some other small opaque item, block out the top laser beam on the stand. Which of the reflected beams disappeared? What happens to the images of the laser beams upon reflection? Draw this result (**5 pts**):

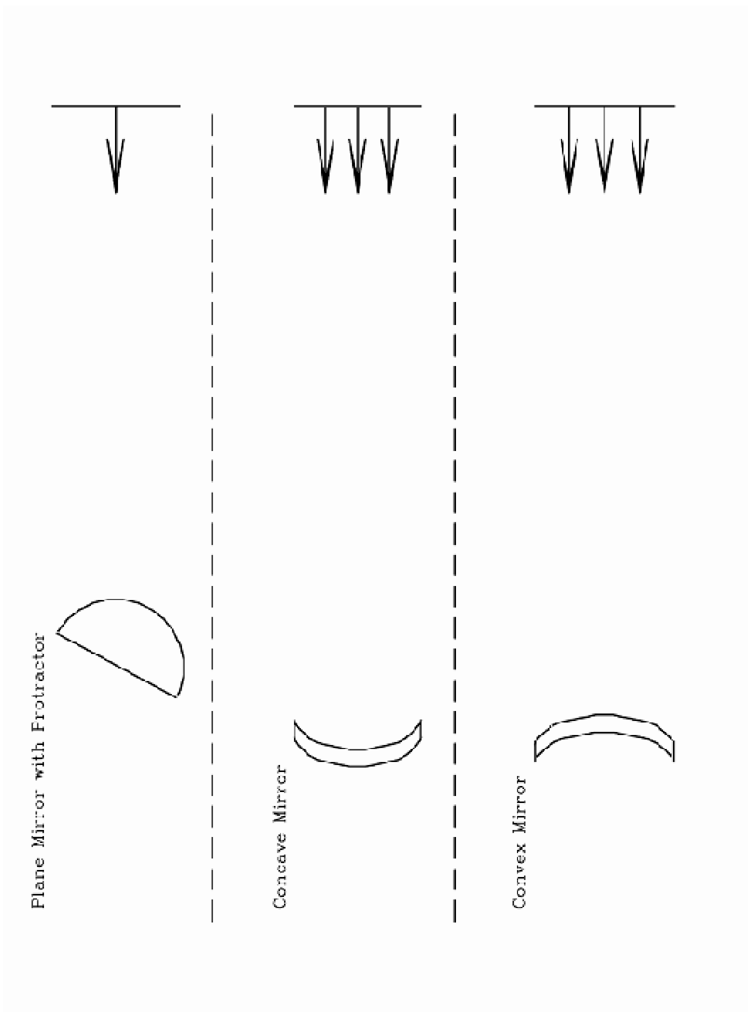


Figure 5.2: The worksheet needed in subsection 3

8. The point where the converging laser beams cross is called the “focus”. From these experiments, we can draw the conclusion that *concave mirrors focus light, convex mirrors diverge light.* Both of the mirrors are 61 cm in diameter. Using a meter stick, how far from the mirror is the convergent point of the reflected light (“where is the best focus achieved”)? (**3 pts**)

   This distance is called the “focal length”. For concave mirrors the focal length is one half of the “radius of curvature” of the mirror. If you could imagine a spherical mirror, cut the sphere in half. Now you have a hemispherical mirror. The radius of the hemisphere is the same as the radius of the sphere. Now, imagine cutting a small cap off of the hemisphere, now you have a concave mirror, but it is a piece of a sphere that has the same radius as before!

9. What is the radius of curvature of the big concave mirror? (**1 pt**)

10. Ok, with the lasers off, look into the concave mirror, is your face larger or smaller? Does a concave mirror appear to magnify, or demagnify your image. How about the convex mirror, does it appear to magnify, or demagnify? (**1 pt**):

5.4 Refractive Optics: Lenses

How about lenses? Do they work in a similar way?

For this subsection of the lab, we will be using an “optical bench” that has a light source on one end, and a projection (imaging) screen on the other end. To start with, there will be three lenses attached mounted on the optical bench. Loosen the (horizontal) thumbscrews and remove the three lenses from the optical bench. Two of the lenses have the same diameter, and one lens is larger. Holding one of the lenses by the steel shaft, examine whether this lens can be used as a “magnifying glass”, that is when you look through it, do objects appear bigger, or smaller? You will find that two of the lenses are “positive” lenses in that they magnify objects, and one is a “negative” lens that acts to “de-magnify” objects. Note how easy it is to decide which lenses are positive and which one is the negative lens.

Now we are going to attempt to measure the “focal lengths” of these lenses. First, remount the smaller positive lens back on the optical bench. Turn on the light by simply connecting the light source to the battery and turning on the switch. Take the smaller *positive* lens move it to the middle of the optical bench (tightening or loosing the vertical clamping screw to allow you to slide it back and forth). At the one end of the optical bench mount the white plastic viewing screen. It is best to mount this at a convenient measurement spot–let's choose to align the plastic screen so that it is right at the 10 cm position on the meter stick. Now slowly move the lens closer to the screen. As you do so, you should see a circle of light that decreases in size until you reach "focus" (for this to work, however, your light source and lens have to be at the same *height* above the meter stick!).

11. Measure the distance between the lens and the plastic screen. Write down this number, we will call it "a".

    The distance "a" = cm (**1 pt**)

12. Now measure the distance between the lens and the front end of the light source.

    Write down this number, we will call it "b":

    The distance "b" = cm (**1 pt**)

    To determine the focal length of a lens ("F"), there is a formula called "the lens maker's formula":

$$\frac{1}{F} = \frac{1}{a} + \frac{1}{b} \tag{11}$$

13. Calculate the focal length of the small positive lens (**2 pts**): F = cm

14. Now replace the positive lens with the small *negative* lens. Repeat the process. Can you find a focus with this lens? What appears to be happening? (**4 pts**)

15. How does the behavior of these two lenses compare with the behavior of mirrors? Draw how light behaves when encountering the two types of lenses using Figure 5.3. Note some similarities and differences between what you have drawn in Fig. 5.2, and what you drew in Fig. 5.3 and write them in the space below. (**5 pts**)

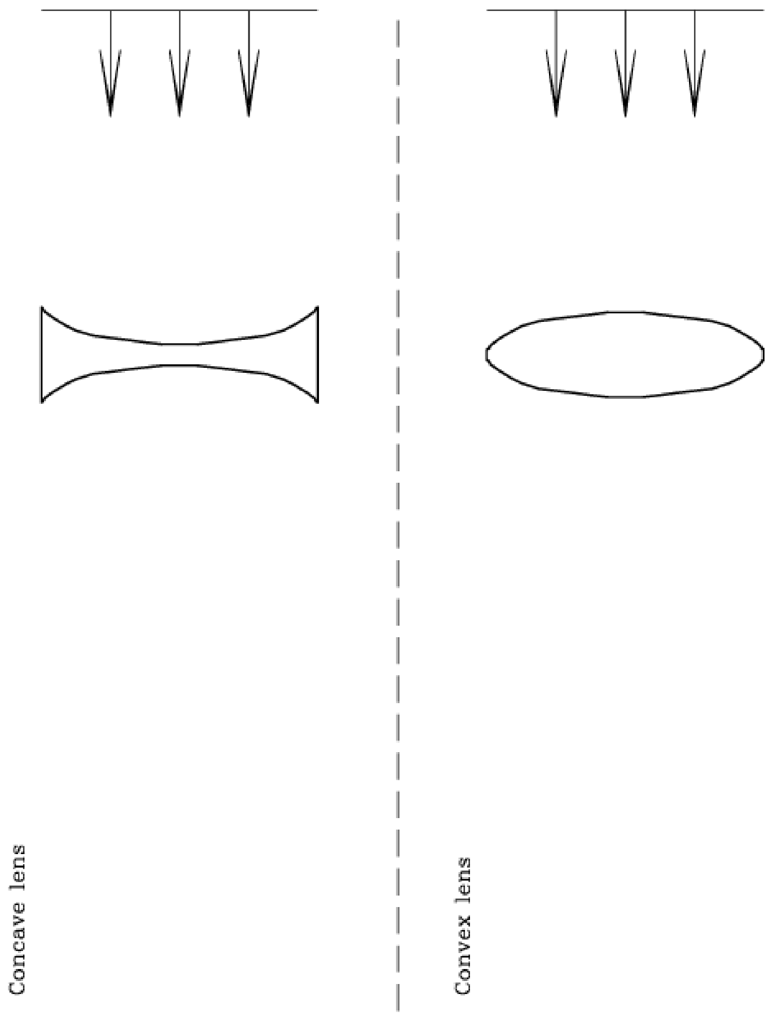


Figure 5.3: The worksheet needed in subsection 4. The positive lenses used in this lab are "double convex" lenses, while the negative lens is a "double concave" lens.

Ok, now let's go back and mount the larger lens on the optical bench. This lens has a very long focal length. Remove the light source from the optical bench. Now mount the big lens exactly 80 cm from the white screen. Holding the light source "out in space", move it back and forth until you can get the best focus (Note that this focus will not be a point, but will be a focused image of the filament in the light bulb and show-up as a small, bright line segment. This is a much higher power lens, so the image is not squished down like occurred with the smaller positive lens). Using the wooden meter stick, have your lab partners measure the distance between the light source and the lens. This is hard to do, but you should get a number that is close to 80 cm.

16. Assuming that $a = b = 80$ cm, use the lens maker's formula to calculate F:

The focal length of the large lens is F = cm (**2 pts**)

5.5 Making a Telescope

As you have learned in class, Galileo is given credit as the first person to point a telescope at objects in the night sky. You are now going to make a telescope just like that used by Galileo. Remove the white screen (and light source) from the optical bench and mount (and lock) the large positive lens at the 10 cm mark on the yardstick scale. Now mount the small *negative* lens about 40 cm away from the big lens. Looking at the "eyechart" mounted in the lab room (maybe go to the back of the room if you are up front–you want to be as far from the eyechart as possible), focus the telescope by moving the little lens backwards or forwards. Once you achieve focus, let your lab partners look through the telescope too. Given that everyone's eyes are different, they may need to re-focus the little lens.

17. Write down the distance "N" between the two lenses:

The distance between the two lenses is N = cm (**2 pts**)

18. Describe what you see when you look through the telescope: What does the image look like? Is it distorted? Are there strange colors? What is the smallest set of letters you can read? Is the image right side up? Any other interesting observations? (**5 pts**):

This is exactly the kind of telescope that Galileo used. Shortly after Galileo's observations became famous, Johannes Kepler built his own telescopes, and described how they worked. Kepler suggested that you could make a better telescope using two *positive* lenses. Let's do that. Remove the small negative lens and replace it with the small positive lens. Like before, focus your telescope on the eyechart, and let everyone in your group do the same. Write down the distance "P" between the two lenses after achieving best focus:

19. The distance between the two lenses is P = cm (**2 pts**)

20. Describe what you see: What does the image look like? Is it distorted? Are there strange colors? What is the smallest set of letters you can read? Is the image right side up? Any other interesting observations? (**5 pts**):

21. Compare the two telescopes. Which is better? What makes it better? Note that Kepler's version of the telescope did not become popular until many years later. Why do you think that is? (**5 pts**):

5.5.1 The Magnifying and Light Collecting Power of a Telescope

Telescopes do two important things: they collect light, and magnify objects. Astronomical objects are very far away, and thus you must magnify the objects to actually see any detail. Telescopes also collect light, allowing you to see fainter objects than can be seen by your eye. It is easy to envision this latter function as two different size buckets sitting out in the rain. The bigger diameter bucket will collect more water than the smaller bucket. In fact, the amount of water collected goes as the area of the top of the bucket. If we have circular buckets, than given that the area of a circle is πR^2, a bucket that is twice the radius, has four times the area, and thus collects four times the rain. The same relationship is at work for your eye and a telescope. The radius of a typical human pupil is 4 mm, while the big lens you have been using has a radius of 20 mm. Thus, the telescopes that you built collect 25 times as much light as your eyes.

Determining the magnification of a telescope is also very simple:

$$M = \frac{F}{f} \tag{12}$$

Where "M" is the magnification, "F" is the focal length of the "objective" lens (the bigger of the two lenses), and "f" is the focal length of the "eyepiece" (the smaller of the two lenses). You have calculated both "F" and "f" in the preceding for the two positive lenses, and thus can calculate the *magnification of the "Kepler" telescope*:

22. The magnification of the Kepler telescope is M = times. (**1 pt**)

Ok, how about the magnification of the Galileo telescope? The magnification for the Galileo telescope is calculated the same way:

$$M = \frac{F}{f} \tag{13}$$

But remember, we could not measure a focal length (f) for the negative lens. How can this be done? With specialized optical equipment it is rather easy to measure the focal length of a negative lens. But since we do not have that equipment, we have to use another technique. In the following two figures we show a "ray diagram" for both the Kepler and Galileo telescopes.

Earlier, we had you make various measurements of the lenses, and measure separations of the lenses in both telescopes once they were focused. If you look at Figure 5.4 and

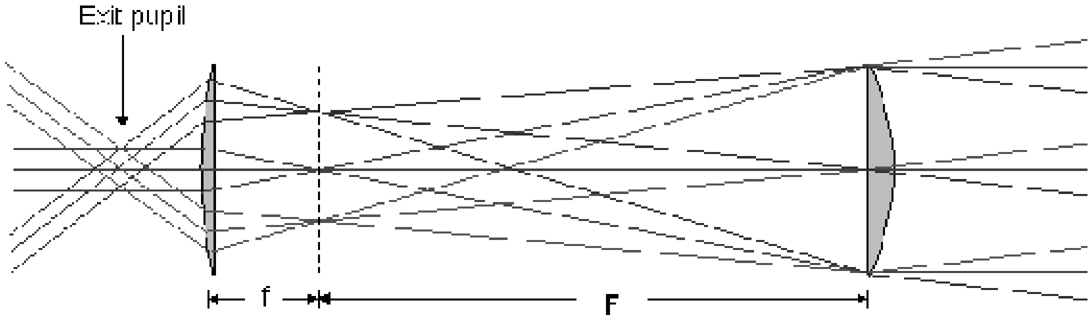


Figure 5.4: The ray diagram for Kepler's telescope.

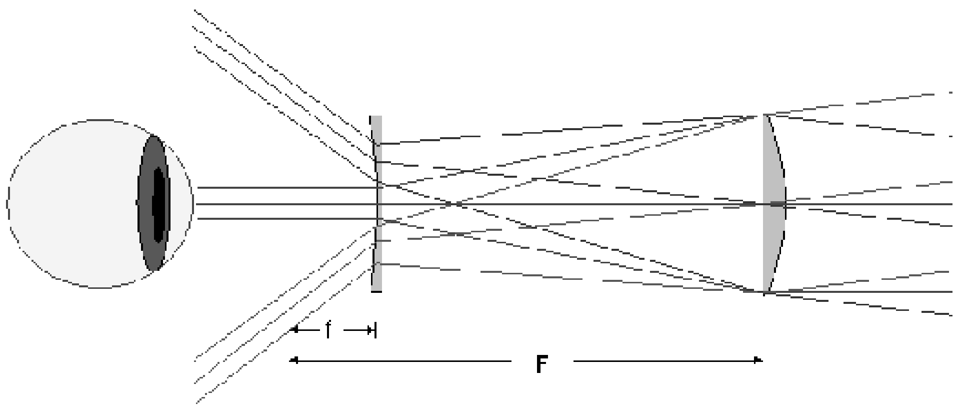


Figure 5.5: The ray diagram for Galileo's telescope.

Figure 5.5, you will see that there is a large "F". This is the focal length of the large, positive lens (the "objective"). In Kepler's telescope, when it is focused, you see that the separation between the two lenses is the sum of the focal lengths of the two lenses. We called this distance "P", above. You should confirm that the "P" you measured above is in fact equal (or fairly close) to the sum of the focal lengths of the two positive lenses: P = f + F (where little "f" is the focal length of the smaller positive lens).

Ok, now look at Figure 5.5. Note that when this telescope is focused, the separation between the two lenses in the Galileo telescope is N = F − f (where F and f have the same definition as before).

23. Find "f" for the Galileo telescope that you built, and determine the magnification of this telescope (**3 pts**):

24. Compare the magnification of your Galileo telescope to that you calculated for the Kepler telescope (**2 pts**):

What do you think of the quality of images that these simple telescopes produce? Note how hard it is to point these telescopes. It was hard work for Galileo, and the observers that followed him, to unravel what they were seeing with these telescopes. You should also know that the lenses you have used in this class, even though they are not very expensive, are far superior to those that could be made in the 17^{th} century. Thus, the simple telescopes you have constructed today are much better than what Galileo used!

5.6 Summary (35 points)

Please summarize the important concepts of this lab.

- Describe the properties of the different types of lenses *and* mirrors discussed in this lab
- What are some of the differences between mirrors and lenses?
- Why is the study of optics important in astronomy?

Use complete sentences, and proofread your lab before handing it in.

5.7 Possible Quiz Questions

1) What is a "normal"?
2) What is a concave mirror?
3) What is a convex lens?
4) Why do astronomers need to use telescopes?

5.8 Extra Credit (ask your TA for permission before attempting, 5 points)

Astronomers constantly are striving for larger and larger optics so that they can collect more light, and see fainter objects. Galileo's first telescope had a simple lens that was 1" in diameter. The largest telescopes on Earth are the Keck 10 m telescopes (10 m = 400 inches!). Just about all telescopes use mirrors. The reason is that lenses have to be supported from their edges, while mirrors can be supported from behind. But, eventually, a single mirror gets too big to construct. For this extra credit exercise look up what kind of mirrors the 8 m Gemini telescopes have (at http://www.gemini.edu) versus the mirror system used by the Keck telescopes (http://keckobservatory.org/about/the_observatory). Try to find out how they were made using links from those sites. Write-up a description of the mirrors used in these two telescopes. Do you think the next generation of 30 or 100 m telescopes will be built, like Gemini, or Keck? Why?