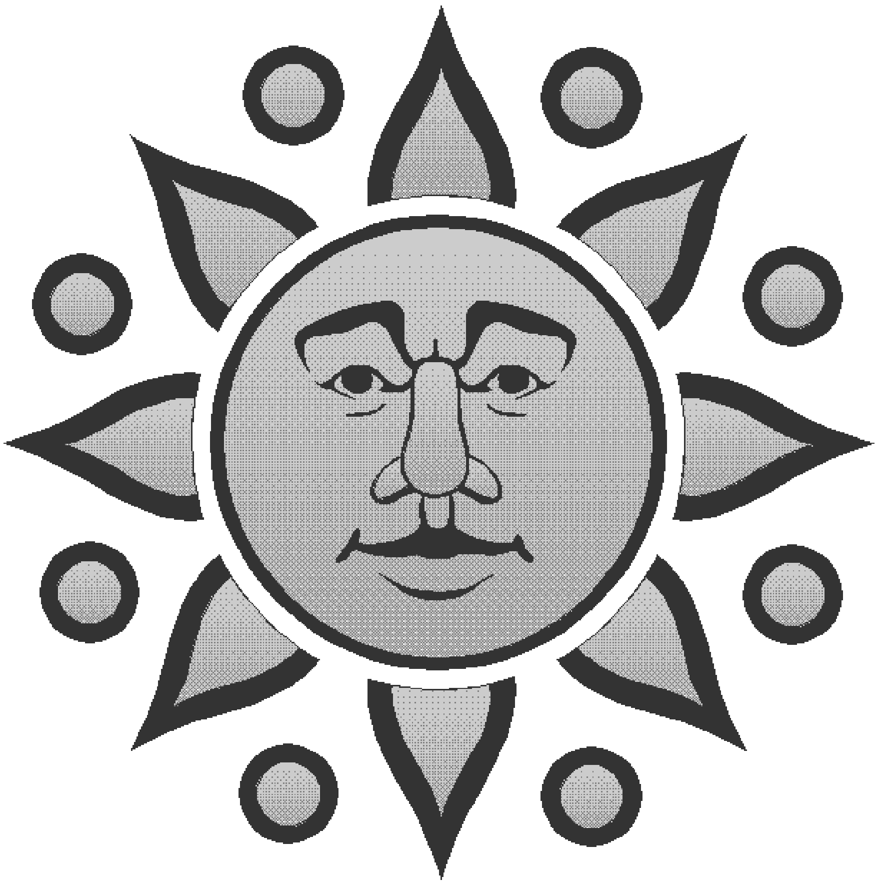
NMSU ASTRONOMY
ASTR 110G:
Laboratory Notebook



(Download from http://astronomy.nmsu.edu/astro/)

Contents

Name:____________________________

Date:_____________________________

1 Introduction to the Astronomy 110 Labs

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 later this semester. When needed, the weekly laboratory exercise you are performing will refer back to the examples in this introduction—so keep the worked 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 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. In the Astronomy 110 labs you will mostly encounter units of length/distance (variations on the meter).

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 hear in this class are listed in Table 1.1.

In the metric system 3,600 meters is equal to 3.6 kilometers; while 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

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)

wavelength of spectral lines in nanometers, and measure the sizes of features on the Sun that are larger than 100,000 kilometers.

1.2.1 Beyond the Metric System

When we talk about the sizes or distances to those 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 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.

When we talk about how far away the stars are in our own Milky Way galaxy, we have to switch to an even larger unit of distance to keep the numbers manageable. One such unit is the "light year". A light year (ly) is the distance light travels in one year. The speed of light is enormous: 300,000 kilometers per second (km/s) or 186,000 miles per second. Since one year contains 31,536,000 seconds, one ly = 9,460,000,000,000 km! The nearest star, Alpha Centauri, is 4.2 ly away. The Milky Way galaxy is more than 150,000 light years across. The nearest galaxy with a size similar to that of the Milky Way, the Andromeda Galaxy (see the sky chart for November online at http://astronomy.nmsu.edu/tharriso/skycharts.html for a picture and description of the Andromeda galaxy), is 2.2 million light years away!

In the Parallax lab we will introduce the somewhat odd unit of "parsecs". For now, we will simply state that one parsec ("pc") = 3.26 ly. Thus, Alpha Centauri is 1.28 pc away. During the semester you will frequently hear the term parsec, kiloparsec (1 thousand pc), Megaparsec (1 million pc), and even the term Gigaparsec (1 billion pc). Astronomers have borrowed the prefixes from the metric system to construct their own shorthand way of describing extremely large distances. The Andromeda Galaxy is at a distance of 700,000 pc = 0.7 Megaparsecs ("Mpc").

1.2.2 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. The concept is fairly straightforward, so let's just work some examples.

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. How many parsecs are there in 1.4 Mpc?

6. How many AU are there in 299,200,000 km?

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. In Figure 1.1 is a map of the state of New Mexico. Down at the bottom left hand corner is a scale in Miles and Kilometers.

Map Exercises (using a ruler determine):

1) How many kilometers is it from Las Cruces to Albuquerque?

2) What is the distance in miles from the border with Arizona to the border with Texas if you were to drive along I40?

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

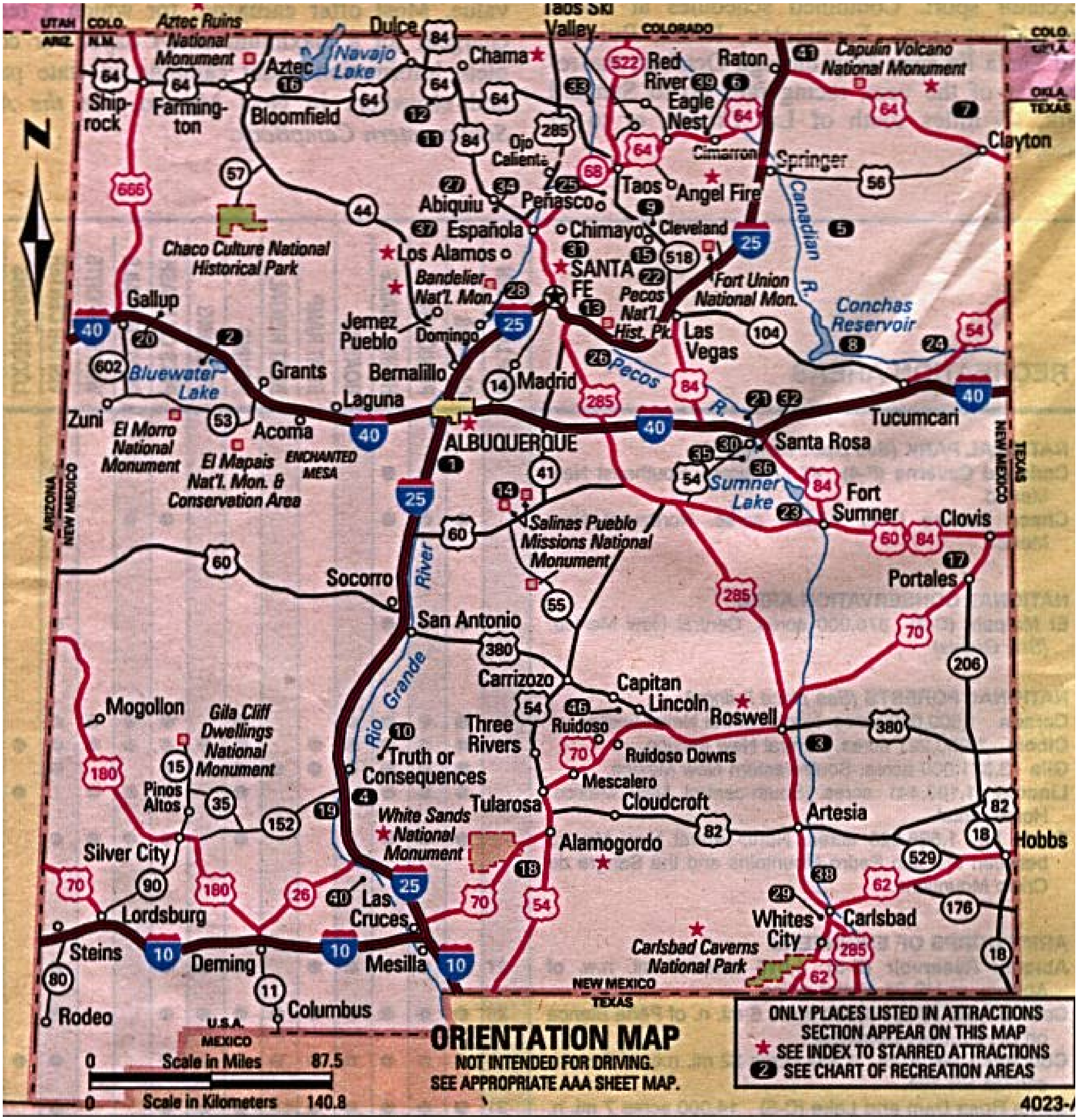


Figure 1.1: A map of New Mexico.

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

1.2.3 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:

1) $7^2 = 7 \times 7 = 49$

2) $7^5 = 7 \times 7 \times 7 \times 7 \times 7 = 16{,}807$

3) The cube of $9 = 9^3 = 9 \times 9 \times 9 = 729$

4) The exponent of 12^{16} is 16

5) $2.56^3 = 2.56 \times 2.56 \times 2.56 = 16.777$

Your turn:

7) $6^3 =$

8) $4^4 =$

9) $3.1^2 =$

The concept of a square root is 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 $2 \times 2 = 4$. The square root of 9 is 3 ($9 = 3 \times 3$). 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 $27^{1/3} = 3$ ($3 \times 3 \times 3 = 27$). The fourth root is written as $16^{1/4}$ ($= 2$), and so on. We will encounter square roots in the algebra section shortly. Here are some examples/problems:

1) $\sqrt{100} = 10$

2) $10.5^3 = 10.5 \times 10.5 \times 10.5 = 1157.625$

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

1.3 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? $6{,}563 = 6563.0 = 6.563 \times 10^3$. To figure out the exponent on the power of ten, we simply count-up the numbers to the left of the decimal point, but do not include the left-most number. Here are some other examples:

$1{,}216 = 1216.0 = 1.216 \times 10^3$

$8{,}735{,}000 = 8735000.0 = 8.735000 \times 10^6$

$1{,}345{,}999{,}123{,}456 = 1345999123456.0 = 1.345999123456 \times 10^{12}$

Your turn! Work the following examples:

$121 = 121.0 =$

$735{,}000 =$

$999{,}563{,}982 =$

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 $0.1 = 1/10$. In scientific notation we would write this as 1×10^{-1}. The negative number in the exponent is the way we write the fraction 1/10. How about 0.001? We can rewrite 0.001 as $1/10 \times 1/10 \times 1/10 = 0.001 = 1 \times 10^{-3}$. 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:

$0.0121 =$

$0.0000735 =$

$0.0000000999 =$

$-0.121 =$

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.

How do we multiply and divide two numbers in Scientific Notation? It is a three step process: 1) multiply (divide) the numbers out front, 2) add (subtract) the exponents, and 3) reconstruct the number in Scientific Notation. It is easier to just show some examples:

$(2 \times 10^4) \times (3 \times 10^5) = (2 \times 3) \times 10^{(4+5)} = 6 \times 10^9$

$(2.00 \times 10^4) \times (3.15 \times 10^7) = (2.00 \times 3.15) \times 10^{(4+7)} = 6.30 \times 10^{11}$

$(2 \times 10^4) \times (6 \times 10^5) = (2 \times 6) \times 10^{(4+5)} = 12 \times 10^9 = 1.2 \times 10^{10}$

$(6 \times 10^4) \div (3 \times 10^8) = (6 \div 3) \times 10^{(4-8)} = 2 \times 10^{-4}$

$(3.0 \times 10^4) \div (6.0 \times 10^8) = (3.0 \div 6.0) \times 10^{(4-8)} = 0.5 \times 10^{-4} = 5.0 \times 10^{-5}$

Your turn:

$(6 \times 10^3) \times (3 \times 10^2) =$

$(8.0 \times 10^{18}) \div (4.0 \times 10^{14}) =$

Note how we rewrite the exponent to handle cases where the number out front is greater than 10, or less than 1.

1.4 Algebra

Because this is a freshman laboratory, we do not use high-level mathematics. But we do sometimes encounter a little basic algebra and we need to briefly review the main concepts. Algebra deals with equations and "unknowns". Unknowns, or "variables", are usually represented as a letter in an equation: $y = 3x + 7$. In this equation both "x" and "y" are variables. You do not know what the value of y is until you assign a value to x. For example, if $x = 2$, then $y = 13$ ($y = 3\times2 + 7 = 13$). Here are some additional examples:

y = 5x + 3, if x=1, what is y? Answer: y = 5×1 + 3 = 5 + 3 = 8

q = 3t + 9, if t=5, what is q? Answer: q = 3×5 + 9 = 15 + 9 = 24

y = $5x^2$ + 3, if x=2, what is y? Answer: y = 5×(2^2) + 3 = 5×4 + 3 = 20 + 3 = 23

What is y if x = 6 in this equation: y = 3x + 13 =

These problems were probably easy for you, but what happens when you have this equation: y = 7x + 14, and you are asked to figure out what x is if y = 21? Let's do this step by step, first we re-write the equation:

y = 7x + 14

We now substitute the value of y (y = 21) into the equation:

$21 = 7x + 14$

Now, if we could get rid of that 14 we could solve this equation! Subtract 14 from both sides of the equation:

$21 - 14 = 7x + 14 - 14$ (this gets rid of that pesky 14!)

$7 = 7x$ (divide both sides by 7)

$x = 1$

Ok, your turn: If you have the equation $y = 4x + 16$, and $y = 8$, what is x?

We frequently encounter more complicated equations, such as $y = 3x^2 + 2x - 345$, or $p^2 = a^3$. There are ways to solve such equations, but that is beyond the scope of our introduction. However, you do need to be able to solve equations like this: $y^2 = 3x + 3$ (if you are told what "x" is!). Let's do this for $x = 11$:

Copy down the equation again:

$y^2 = 3x + 3$

Substitute $x = 11$:

$y^2 = 3\times11 + 3 = 33 + 3 = 36$

Take the square root of both sides:

$(y^2)^{1/2} = (36)^{1/2}$

$y = 6$

Did that make sense? To get rid of the square of a variable you have to take the square root: $(y^2)^{1/2} = y$. So to solve for y^2, we took the square root of both sides of the equation.

1.5 Graphing and/or Plotting

The last subject we want to discuss is graphing data, and the equation of a line. You probably learned in high school about making graphs. 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 the next figure (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

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

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) and y (the value of the Dow Jones index). In the next table is the data for 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 in this table is plotted in Figure 1.3.

Looking at the plot of temperature versus altitude, we see that a straight line can be drawn through the data points. We can figure out the equation of this straight line and then predict the temperature at any altitude. In high school you learned that the equation of a line was y = mx + b, where "m" is the "slope" of the line, and "b" is the "y intercept". The y intercept is simply where the line crosses the y-axis. In the plot, the y intercept is at 59.0, so b = 59. So, we can rewrite the equation for this line as y = mx + 59.0. How can we figure out m? Simple, pick any other data point and solve the equation–let's choose the data at 10,000 feet. The temperature (y) is 23.3 at 10,000 feet (= x): 23.3 = 10000m + 59. Subtracting 59 from both sides shows 23.3 − 59 = 10000x + 59 − 59, or −35.7 = 10000m. To find m we simply divide both sides by 10,000: m = −35.7/10000 = −0.00357. In scientific notation, the equation for the temperature vs. altitude is y = -3.57×10^{-3}x + 59.0. Why is the

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

slope negative? What is happening here? As you go up in altitude, the temperature goes down. Increasing the altitude (x) decreases the temperature (y). Thus, the slope has to be negative.

Using the equation for temperature versus altitude just derived, what is the temperature at 20,000 feet?

Ok, your turn. On the blank sheet of graph paper in Figure 1.4 plot the equation y = 2x + 2 for x = 1, 2, 3, and x = −1, −2, and −3. What is the y intercept of this line? What is its slope?

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 measurements have error. So, even though there might be a perfect relationship between x and y, the noise 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. An example of a plot with real data is shown in Figure 1.5. In this case, the data suggest that there is a general trend between the absolute magnitude (M_V) and the Orbital Period in certain types of binary stars. But some other factor plays a role in determining the final relationship, so some stars do not fit very well, and hence their absolute magnitudes cannot be estimated very well from their orbital periods (the vertical bars associated with each data point are error bars, and represent the measurement error).

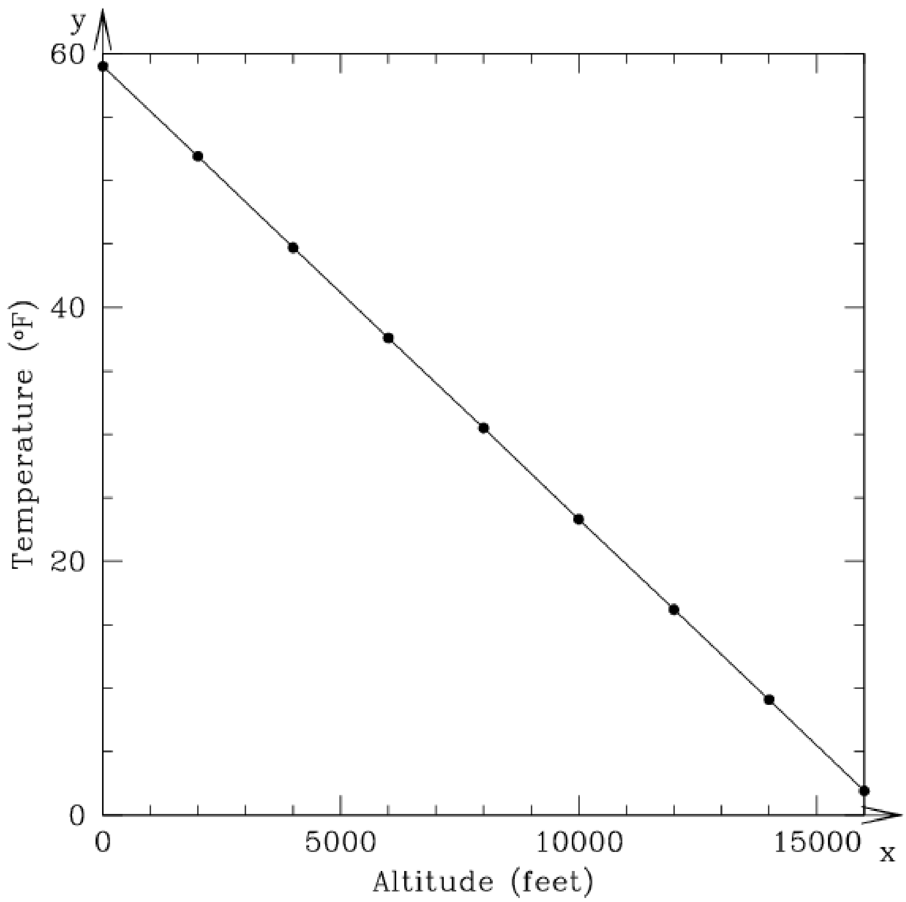


Figure 1.3: The change in temperature as you climb in altitude with the data from the preceding table. At sea level (0 ft altitude) the surface temperature is 59°F. As you go higher in altitude, the temperature goes down.

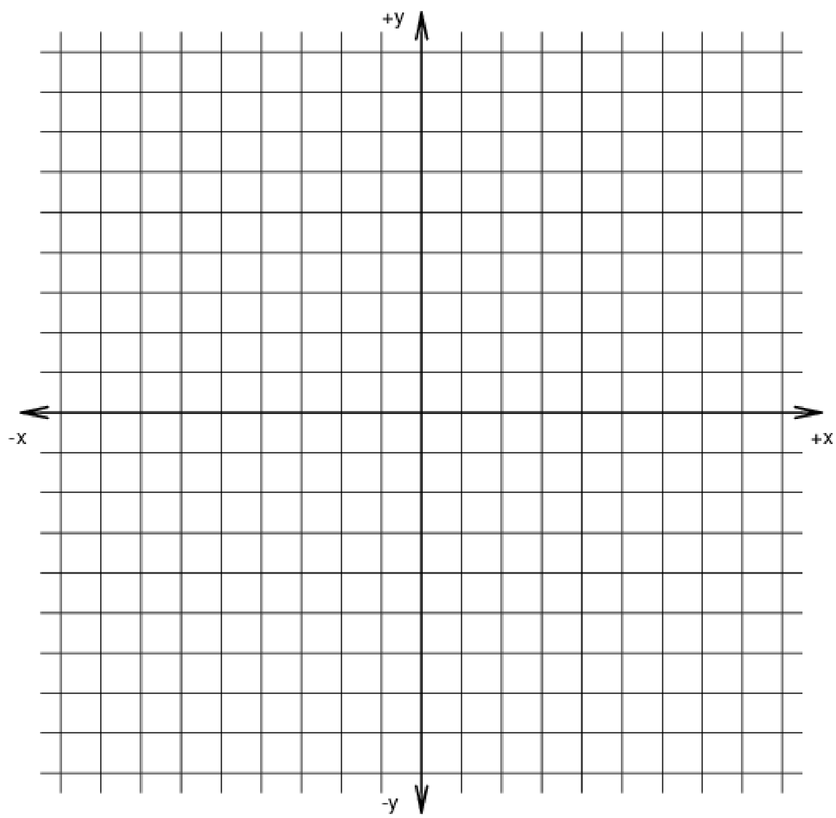


Figure 1.4: Graph paper for plotting the equation y = 2x + 2.

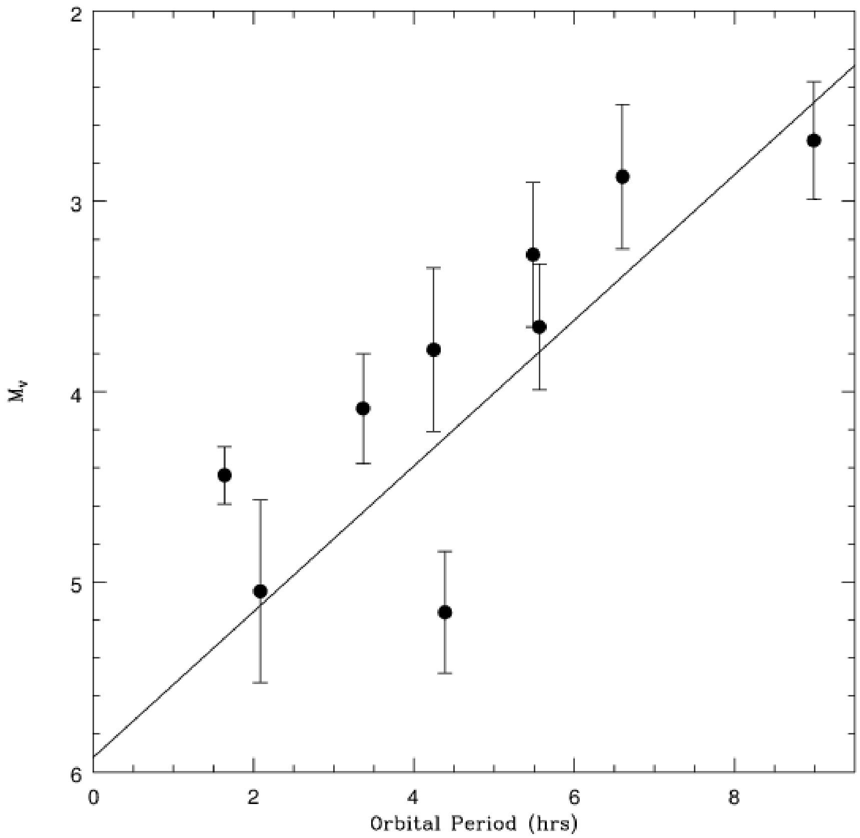


Figure 1.5: The relationship between absolute visual magnitude (M_V) and Orbital Period for cataclysmic variable binary stars.

Name:______________________________

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 is—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 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

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. An "S" following the latitude means that it is in the southern hemisphere, *South* of the Earth's 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.

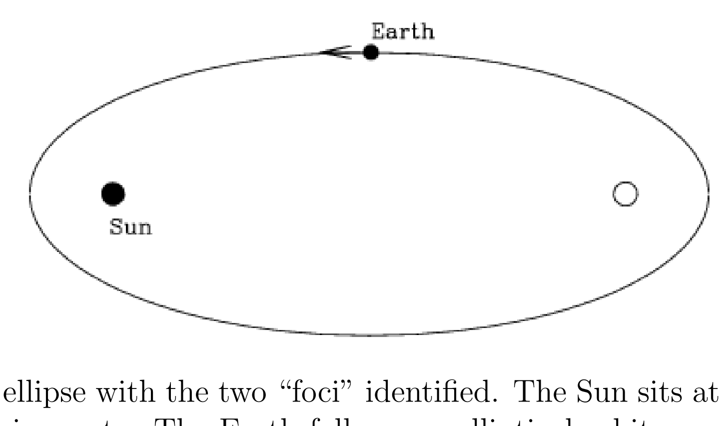


Figure 2.1: An ellipse with the two "foci" identified. The Sun sits at one focus, while the other focus is empty. The Earth follows an elliptical orbit around the Sun, but not nearly as exaggerated as that shown here!

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**)

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 23rd, 1992, and one was taken on the 21st 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, since an object appears bigger when we get closer to it, when 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°. 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 in 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:

11) While the latitudes of Las Cruces and Sydney are similar, Las Cruces is

____________ of the Equator, and Sydney is ____________ of the Equator. (**2 points**)

12) In January, there are more daylight hours in _______________________. (**1 point**)

13) In July, there are more daylight hours in _______________________. (**1 point**)

14) **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**)

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

16) 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 local 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°, 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° 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 subsection 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 (Figs. 2.2, 2.3).

Figure 2.2: Pointing a camera at 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.

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 the smallest circle at the very center.

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 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 globes, a piece of string, a ruler, and the halogen desk lamp. **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 paint can be easily damaged.** 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 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 (*if* there is a dim, and a bright setting–some lights only have one brightness 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.

For the first experiment, arrange the globe so the tilted axis of the "Earth" is pointed perpendicular (or at a "right" angle = 90°) to the direction of the "Sun". Use your best judgement. Now adjust the height of the desk lamp 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.

Experiment #1: 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 (it is probably best to do this more than once). Fill in the following table (**4 points**):

Table 2.2: Position #1: Equinox Data Table

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

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 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 2.3: Position #1: Length of Night and Day

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

18) The caption for Table 2.2 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 2.3 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**):

Table 2.4: Position #2: Solstice Data Table

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

Table 2.5: Position #2: Length of Night and Day

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

19) Compare your results in Table 2.5 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**)

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 2.6: Position #3: Solstice Data Table

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

Table 2.7: Position #3: Length of Night and Day

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

21) As in question #19, compare the results found here for the length of daytime and 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 ($\sim$ Sept. 20^{th}) and Spring ($\sim$ 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.

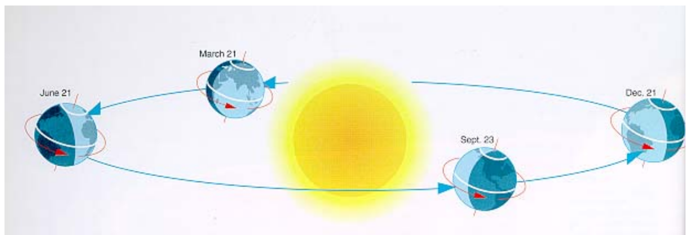


Figure 2.4: The Earth's spin axis always points to one spot in the sky, *and* it is tilted by 23.5° to its orbit. Thus, as the Earth orbits the Sun, the illumination changes with latitude: sometimes the North Pole is bathed in 24 hours of daylight, and sometimes in 24 hours of night. The exact opposite 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 effect 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 21^{st}. On both March 21^{st} and September 20^{th}, the

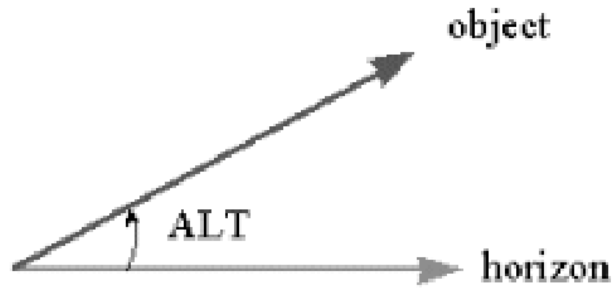


Figure 2.5: Altitude (“Alt”) is simply the angle between the horizon, and an object in the sky. The smallest this angle can be is 0°, and the maximum altitude angle is 90°. Altitude is interchangeably known as elevation.

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).

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 using 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. 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. Take a blank sheet of graph 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.

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?

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. 6.4. The minor axis is the smallest diameter, while the major axis is the longest diameter of an ellipse.

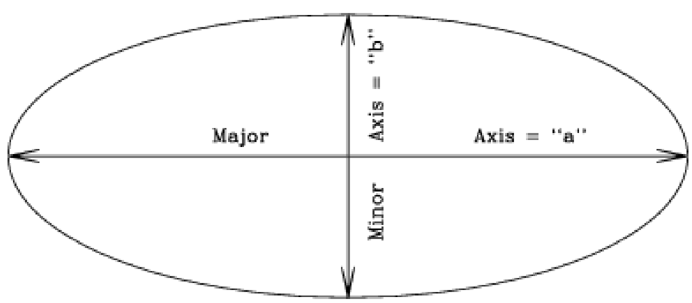


Figure 2.6: An ellipse with the major and minor axes defined.

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

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°.

At 90°, the amount of light per centimeter is 100 divided by the area of circle

= ___________________ units of light per cm^2 (**1 point**).

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**).

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 day 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.

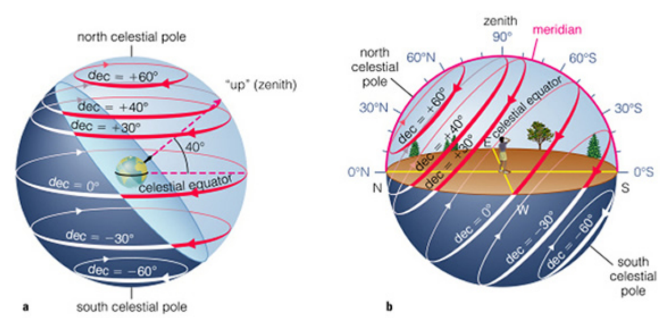


Figure 2.7: The Celestial Equator is the circle in the sky that is straight overhead ("the zenith") of the Earth's equator. In addition, there is a "North Celestial" pole that is the projection of the Earth's North Pole into space (that almost points to Polaris). But the Earth's spin axis is tilted by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

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 that date it retraces its steps until it reaches the Autumnal Equinox (September 20th), after which it is then 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 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".

2.5 Summary (35 points)

Summarize the important points covered in this lab. Questions you should answer include:

- Why does the Earth have seasons?
- What is the origin of the term "Equinox"?
- What is the origin of the term "Solstice"?
- 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?
- 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.
- 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.)
- 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 (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:_________________________

Date:__________________________

3 The Surface of the Moon

3.1 Introduction

One can learn a lot about the Moon by looking at the lunar surface. Even before astronauts landed on the Moon, scientists had enough data to formulate theories about the formation and evolution of the Earth's only natural satellite. However, since the Moon rotates once for every time it orbits around the Earth, we can only see one side of the Moon from the surface of the Earth. Until spacecraft were sent to orbit the Moon, we only knew half the story.

The type of orbit our Moon makes around the Earth is called a synchronous orbit. This phenomenon is shown graphically in Figure 3.1 below. If we imagine that there is one large mountain on the hemisphere facing the Earth (denoted by the small triangle on the Moon), then this mountain is always visible to us no matter where the Moon is in its orbit. As the Moon orbits around the Earth, it turns slightly so we always see the same hemisphere.

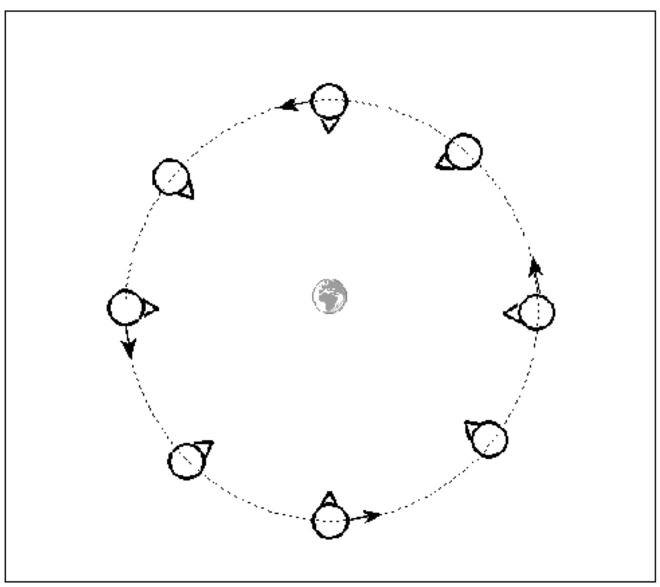


Figure 3.1: The Moon's "synchronous" orbit (not drawn to scale). Note how the Moon spins exactly once during its 27.3 day orbit around the Earth, but keeps the same face pointing towards the Earth.

On the Moon, there are extensive lava flows, rugged highlands, and many impact craters of all different sizes. The overlapping of these features implies relative ages.

Because of the lack of ongoing mountain building processes, or weathering by wind and water, the accumulation of volcanic processes and impact cratering is readily visible. Thus by looking at the images of the Moon, one can trace the history of the lunar surface. Most of the images in this lab were taken by NASA spacecraft or by the Apollo Astronauts.

- *Goals:* to discuss the Moon's terrain, craters, and the theory of relative ages; to use pictures of the Moon to deduce relative ages and formation processes of surface features
- *Materials:* Moon pictures, ruler, calculator
- *Review:* Section 1.2.2 in Lab #1

3.2 Craters and Maria

A crater is formed when a meteor from space strikes the lunar surface. The force of the impact obliterates the meteorite and displaces part of the Moon's surface, pushing the edges of the crater up higher than the surrounding rock. At the same time, more displaced material shoots outward from the crater, creating *rays* of ejecta. These rays of material can be seen as radial streaks centered on some of the craters in some of the pictures you will be using for your lab today. As shown in Figure 3.2, some of the material from the blast "flows" back towards the center of the crater, creating a mountain peak. Some of the craters in the photos you will examine today have these "central peaks". Figure 3.2 also shows that the rock beneath the crater becomes fractured (full of cracks).

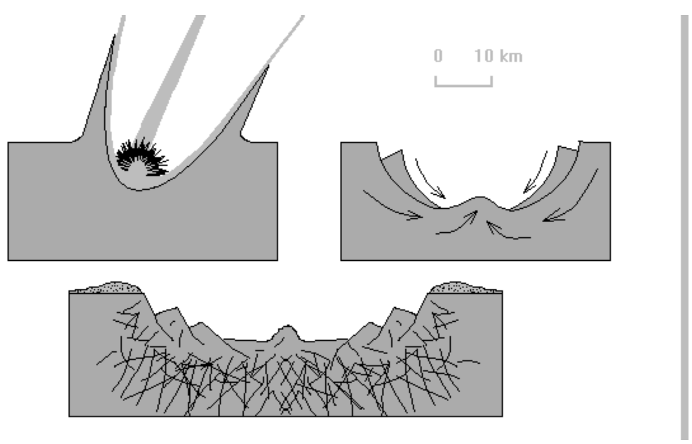


Figure 3.2: Formation of an Impact Crater.

Soon after the Moon formed, its interior was mostly liquid. It was continually being hit by meteors, and the energy (heat) from this period of intense cratering was enough to liquify the Moon's interior. Every so often, a very large meteor would strike the surface, and *crack the Moon's crust*. The over-pressured "lava" from the Moon's molten mantle then flowed up through the cracks made by the impact. The lava filled in the crater, creating a dark, smooth "sea". Such a sea is called a *mare* (plural: *maria*). Sometimes the amount of lava that came out could overfill the crater. In those cases, it spilled out over the crater's edges and could fill in other craters as well as cover the bases of the *highlands*, the rugged, rocky peaks on the surface of the Moon.

3.3 Relative Ages on the Moon

Since the Moon does not have rain or wind erosion, astronomers can determine which features on the Moon are older than others. It all comes down to counting the number of craters a feature has. Since there is nothing on the Moon that can erase the presence of a crater, the more craters something has, the longer it must have been around to get hit. For example, if you have two large craters, and the first crater has 10 smaller craters in it, while the second one has only 2 craters in it, we know that the first crater is older since it has been there long enough to have been hit 10 times. If we look at the highlands, we see that they are covered with lots and lots of craters. This tells us that in general, the highlands are older than the *maria*, which have fewer craters. We also know that if we see a crater on top of a mare, the mare is older. It had to be there in the first place to get hit by the meteor. Crater counting can tell us which features on the Moon are older than other features, but it can not tell us the absolute age of the feature. To determine that, we need to use radioactive dating or some other technique.

3.4 Lab Stations

In this lab you will be using a 3-ring binder that has pictures organized into separate subsections, or "stations". At some stations we present data comparing the Moon to the Earth or Mars. Using your understanding of simple physical processes here on Earth and information from the class lecture and your reading, you will make observations and draw logical conclusions in much the same way that a planetary geologist would.

You should work in groups of two to four, with one notebook for each group. The notebooks contain separate subsections, or "stations", with the photographs and/or images for each specific exercise. Each group must go through all of the stations, and consider and discuss each question and come to a conclusion. **Remember to back up your answers with reasonable explanations, and be sure to answer *all* of the questions.** While you should discuss the questions as a group, be sure to write down one group answer for each question. The take-home questions must be done on your own. **Answers for the take-home questions that are exact duplicates of those of other members of your group will not be acceptable.**

3.5 The Surface of the Moon

Station 1: Our first photograph (#1) is that of the full Moon. It is obvious that the Moon has dark regions, and bright regions. The largest dark regions are the "Maria", while the brighter regions are the "highlands". In image #2, the largest features of the full Moon are labeled. The largest of the maria on the Moon is Mare Imbrium (the "Sea of Showers"), and it is easily located in the upper left quadrant of image #2. Locate Mare Imbrium. Let us take a closer look at Mare Imbrium.

Image #3 is from the Lunar Orbiter IV. Before the Apollo missions landed humans on the Moon, NASA sent several missions to the Moon to map its surface, and to make sure we could safely land there. Lunar Orbiter IV imaged the Moon during May of 1967. The technology of the time was primitive compared to today, and the photographs were built up by making small imaging scans/slices of the surface (the horizontal striping can be seen in the images), then adding them all together to make a larger photograph. Image #3 is one of these images of Mare Imbrium seen from almost overhead.

Question #1: Approximately how many craters can you see inside the dark circular region that defines Mare Imbrium? Compare the number of craters in Mare Imbrium to the brighter regions to the North (above) of Mare Imbrium. (**2 points**)

Images #4 and #5 are close-ups of small subsections of Mare Imbrium. In image #4, the largest crater (in the lower left corner) is "Le Verrier" (named after the French mathematician who predicted the correct position for the planet Neptune). Le Verrier is 20 km in diameter. In image #5, the two largest craters are named Piazzi Smyth (just left of center) and Kirch (below and left of Piazzi Smyth). Piazzi Smyth has a diameter of 13 km, while Kirch has a diameter of 11 km.

Question #2: Using the diameters for the large craters noted above, and a ruler, what is the approximate diameter of the smallest crater you can make out in images #4 and #5? If the NMSU campus is about 1 km in diameter, compare the smallest crater you can see to the size of our campus. (**2 points**)

In image #5 there is an isolated mountain (Mons Piton) located near Piazzi Smyth. It is likely that Mons Piton is related to the range of mountains to its upper right.

Question #3: Roughly how much area (in km^2) does Mons Piton cover? Compare it to the area of the Organ mountains that are located to the east of Las Cruces (estimate a width and a length, and assuming a rectangle, calculate the approximate area of the Organs). How do you think such an isolated mountain came to exist? [Hint: In the introduction to the lab exercises, the process of maria formation was described. Using this idea, how might Mons Piton become so isolated from the mountain range to the northeast?] (**5 points**)

Station #2: Now let's move to the "highlands". In image #6 (which is identical to image #2), the crater Clavius can be seen on the bottom edge—it is the bottom-most labeled feature on this map. In image #7, is a close-up picture of Clavius (just below center) taken from the ground through a small telescope (this is similar to what you would see at the campus observatory). Clavius is one of the largest craters on the Moon, with a diameter of 225 km. In the upper right hand corner is one of the best known craters on the Moon, "Tycho". In image #1 you can identify Tycho by the large number of bright "rays" that emanate from this crater. Tycho is a very young crater, and the ejecta blasted out of the lunar surface spread very far from the impact site.

Question #4: Estimate (in km) the distance from the center of the crater Clavius to the center of Tycho. Compare this to the distance between Las Cruces, and Albuquerque (375 km). (**3 points**)

Images #8 and #9, are two high resolution images of Clavius and nearby regions taken by Lunar Orbiter IV (note the slightly different orientations from the ground-based picture).

Question #5: Compare the region around Clavius to Mare Imbrium. Scientists now know that the lunar highlands are older than the Maria. What evidence do you have (using these photographs) that supports this idea? [Hint: review subsection 2.3 of the introduction.] (**5 points**)

Station #3: Comparing Apollo landing sites. In images #10 and #11 are close-ups of the Apollo 11 landing site in Mare Tranquillitatis (the "Sea of Tranquility"). The actual spot where the "Eagle" landed on July 20, 1969 is marked by the small cross in image 11 (note that three small craters near the landing site have been named for the crew of this mission: Aldrin, Armstrong and Collins). [There are also quite a number of photographic defects in these pictures, especially the white circular blobs near the center of the image to the North of the landing site.] The landing sites of two other NASA spacecraft, Ranger 8 and Surveyor 5, are also labeled in image #11. NASA made sure that this was a safe place to explore!

Images #12 and #13 show the landing site of the last Apollo mission, #17. Apollo 17 landed on the Moon on December 11th, 1972. Compare the two landing sites.

Question #6: Describe the logic that NASA used in choosing the two landing sites– why did they choose the Tranquillitatis site for the first lunar landing? What do you think led them to choose the Apollo 17 site? (**5 points**)

The next two sets of images show photographs taken by the astronauts while on the Moon. The first three photographs (#14, #15, and #16) are scenes from the Apollo 11 site, while the next three (#17, #18, and #19) were taken at the Apollo 17 landing site.

Question #7: Do the photographs from the actual landing sites back-up your answer to why NASA chose these two sites? How? Explain your reasoning. (**5 points**)

Station 4: On the northern-most edge of Mare Imbrium sits the crater Plato (labeled in images #2 and #6). Photo #20 is a close-up of Plato. Do you agree with the theory that the crater floor has been recently flooded? Is the mare that forms the floor of this crater younger, older, or approximately the same age as the nearby region of Mare Imbrium located just to the South (below) of Plato? Explain your reasoning. **(5 points)**

Station 5: Images #21 and #22 are "topographical" maps of the Earth and of the Moon. A topographical map shows the *elevation* of surface features. On the Earth we set "sea level" as the zero point of elevation. Continents, like North America, are above sea level. The ocean floors are below sea level. In the topographical map of the Earth, you can make out the United States. The Eastern part of the US is lower than the Western part. In topographical maps like these, different colors indicate different heights. Blue and dark blue areas are below sea level, while green areas are just above sea level. The highest mountains are colored in red (note that Greenland and Antarctica are both colored in red–they have high elevations due to very thick ice sheets). We can use the same technique to map elevations on the Moon. Obviously, the Moon does not have oceans to define "sea level". Thus, the definition of zero elevation is more arbitrary. For the Moon, sea level is defined by the *average* elevation of the lunar surface.

Image #22 is a topographical map for the Moon, showing the highlands (orange, red, and pink areas), and the lowlands (green, blue, and purple). [Grey and black areas have no data.] The scale is shown at the top. The lowest points on the Moon are 10 km below sea level, while the highest points are about 10 km above sea level. On the left hand edge (the "y axis") is a scale showing the latitude. 0^o latitude is the equator, just like on the Earth. Like the Earth, the North pole of the Moon has a latitude of $+90^o$, and the south pole is at -90^o. On the x-axis is the *longitude* of the Moon. Longitude runs from 0^o to 360^o. The point at 0^o latitude *and* longitude of the Moon is the point on the lunar surface that is closest to the Earth.

It is hard to recognize features on the topographical map of the Moon because of the complex surface (when compared to the Earth's large smooth areas). But let's go ahead and try to find the objects we have been studying. First, see if you can find Plato. The latitude of Plato is $+52^o$ N, and its longitude is 351^o. You can clearly see the outline of Plato if you look closely.

Question #8: Is Plato located in a high region, or a low region? Is Plato lower than Mare Imbrium (centered at 32^oN, 344^o)? [Remember that Plato is on the Northern edge of Mare Imbrium.](**2 points**)

Question #9: Apollo 11 landed at Latitude = 1.0^oN, longitude = 24^o. Did it land in a low area, or a high area? (**2 points**)

As described in the introduction, the Moon keeps the same face pointed towards Earth at all times. We can only see the "far-side" of the Moon from a spacecraft. In image #22, the *hemisphere* of the Moon that we can see runs from a longitude of 270^o, passing through 0^o, and going all the way to 90^o (remember 0, 0 is located at the center of the Moon as seen from Earth). In image #23 is a more conventional topographical map of the Moon, showing the two hemispheres: near side, and far side.

Question #10: Compare the average elevation of the near-side of the Moon to that of the far-side. Are they different? Can you make-out the Maria? Compare the number of Maria on the far side to the number on the near side. (**5 points**)

Station 6: With the surface of the Moon now familiar to you, and your perception of the surface of the Earth in mind, compare the Earth's surface to the surface of the Moon. Does the Earth's surface have more craters or less craters than the surface of the Moon? Discuss two differences between the Earth and the Moon that could explain this. **(5 points)**

3.6 The Chemical Composition of the Moon: Keys to its Origin

Station 7: Now we want to examine the chemical composition of the Moon to reveal its history and origin. The formation of planets (and other large bodies in the solar system like the Moon) is a violent process. Planets grow through the process of "accretion": the gravity of the young planet pulls on nearby material, and this material crashes into the young planet, heating it, and creating large craters. In the earliest days of the solar system, so much material was being accreted by the planets, that they were completely *molten*. That is, they were in the form of liquid rock, like the lava you see flowing from some volcanoes on the Earth. Just like the case with water, heavier objects in molten rock sink to the bottom more quickly than lighter material. This is also true for chemical elements. Iron is one of the heaviest of the common elements, and it sinks toward the center of a planet more quickly than elements like silicon, aluminum, or magnesium. Thus, near the Earth's surface, rocks composed of these lighter elements dominate. In lava, however, we are seeing molten rock from deeper in the Earth coming to the surface, and thus lava and other volcanic (or "igneous") rock, can be rich in iron, nickel, titanium, and other high-density elements.

Images #24 and 25 present two unique views of the Moon obtained by the spacecraft *Clementine*. Using special sensors, *Clementine* could make maps of the surface composition of the Moon. In Image #24 is a map of the amount of iron on the surface of the Moon (redder colors mean more iron than bluer colors). Image #25 is the same type of map, but for titanium.

Question #11: Compare the distribution of iron and titanium to the surface features of the Moon (using images #1, #2 or #6, or the topographical map in image #23). Where are the highest concentrations of iron and titanium found? (**4 points**)

Question #12: If the heavy elements like iron and titanium sank towards the center of the Moon soon after it formed, what does the presence of large amounts of iron and titanium in the maria suggest? [Hint: do you remember how maria are formed?] (**5 points**)

Table 3.1: Composition of the Earth & Moon

Element	Earth	Moon
Iron	34.6%	3.5%
Oxygen	29.5%	60.0%
Silicon	15.2%	16.5%
Magnesium	12.7%	3.5%
Titanium	0.05%	1.0%

The structure of the Earth is shown in the diagram, below. There are three main structures: the crust (where we live), the mantle, and the core. The crust is cool and brittle, the mantle is hotter, and "plastic" (it flows), and the core is very hot and very dense. The density of a material is simply its mass (in grams or kilograms) divided by its volume (in centimeters or meters). Water has a density of 1 gm/cm^3. The density of the Earth's crust is about 3 gm/cm^3, while the mantle has a density of 4.5 gm/cm^3. The core is very dense: 14 gm/cm^3 (this is partly due to its composition, and partly due to the great pressure exerted by the mass located above the core). The core of the Earth is almost pure iron, while the mantle is a mixture of magnesium, silicon, iron and oxygen. The average density of the Earth is 5.5 gm/cm^3.

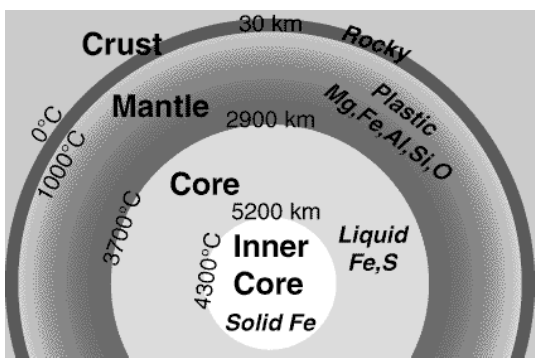


Figure 3.3: The internal structure of the Earth, showing the dimensions of the crust, mantle and core, as well as their composition and temperatures.

Before the astronauts brought back rocks from the Moon, we did not have a good theory about its formation. All we knew was that the Moon had an average density of 3.34 gm/cm^3. If the Moon formed from the same material as the Earth, their compositions would be nearly identical, as would their average densities. In Table 3.1, we present a comparison of the composition of the Moon to that of the Earth. The data for the Moon comes from analysis of the rocks brought back by the Apollo astronauts.

Question #13: Is the Moon composed of the same mixture of elements as the Earth? What are the biggest differences? Does this support a model where the Moon formed out of the same material as the Earth? (**3 points**)

Table 3.2: Chemical Composition of the Earth and Moon

Element	Earth's Crust and Mantle	Moon
Iron	5.0%	3.5%
Oxygen	46.6%	60.0%
Silicon	27.7%	16.5%
Magnesium	2.1%	3.5%
Calcium	3.6%	4.0%

As you will learn in the Astronomy 110 lectures, the inner planets in the solar system (Mercury, Venus, Earth and Mars) have higher densities than the outer planets (Jupiter, Saturn, Uranus and Neptune). One theory for the formation of the Moon is that it formed out near Mars, and "migrated" inwards to be captured by the Earth. This theory arose because the density of Mars, 3.9 gm/cm^3, is similar to that of the Moon. But Mars is rich in iron and magnesium: 17% of Mars is iron, and more than 15% is magnesium.

Question #14: Given this data, do you think it is likely that the Moon formed out near Mars? Why? (**2 points**)

The final theory for the formation of the Moon is called the "Giant Impact" theory. In this model, a large body (about the size of the planet Mars) collided with the Earth, and the resulting explosion sent a large amount of material into space. This material eventually collapsed (coalesced) to form the Moon. Most of the ejected material would have come from the crust and the mantle of the Earth, since it is the material closest to the Earth's surface. In Table 3.6 is a comparison of the composition of the Earth's crust and mantle compared to that of the Moon.

Question #15: Given the data in this table, present an argument for why the giant impact theory is now the favorite theory for the formation of the Moon. Can you think of a reason why the compositions might not be *exactly* the same? (**5 points**)

3.7 Summary

(**35 points**) Please summarize in a few paragraphs what you have learned in this lab. Your summary should include:

- Explain how to determine and assign relative ages of features on the Moon
- Comment on analyzing pictures for information; what sorts of things would you look for? what can you learn from them?
- What is a mare and how is it formed?
- How does the composition of the Moon differ from the Earth, and how does this give us insight into the formation of the Moon?

Use complete sentences and proofread your summary before handing it in.

3.8 Possible Quiz Questions

1. What is an impact crater, and how is it formed?
2. What is a Mare?
3. Which is older the Maria or the Highlands?
4. How are the Maria formed?
5. What is synchronous rotation?
6. How can we determine the relative ages of different lunar surfaces?

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

In the past few years, there have been some new ideas about the formation of the Moon, and why the lunar farside is so different from the nearside (one such idea goes by the name "the big splat"). In addition, we have recently discovered that the interior of the Moon is highly fractured. Write a brief (about one page) review on the new computer simulations and/or observations that are attempting to understand the formation and structure of the Moon.

Name:________________________

Date:________________________

4 Shaping Surfaces in the Solar System: The Impacts of Comets & Asteroids

4.1 Introduction

In the lab exercise on exploring the surface of the Moon, there is a brief discussion on how impact craters form. Note that every large body in the solar system has been bombarded by smaller bodies throughout all of history. In fact, this is one mechanism by which planets grow in size: they collect smaller bodies that come close enough to be captured by the planet's gravity. If a planet or moon has a rocky surface, the surface can still show the scars of these impact events–even if they occurred many billions of years ago! On planets with atmospheres, like our Earth, weather can erode these impact craters away, making them difficult to identify. On planets that are essentially large balls of gas (the "Jovian" planets), there is no solid surface to record impacts. Many of the smaller bodies in the solar system, such as the Moon, the planet Mercury, or the satellites of the Jovian planets, do not have atmospheres, and hence, faithfully record the impact history of the solar system. Astronomers have found that when the solar system was very young, there were large numbers of small bodies floating around the solar system impacting the young planets and their satellites. Over time, the number of small bodies in the solar system has decreased. Today we will investigate how impact craters form, and examine how they appear under different lighting conditions. During this lab we will discuss both asteroids and comets, and you will create your own impact craters as well as construct a "comet".

- *Goals:* to discuss asteroids and comets; create impact craters; build a comet and test its strength and reaction to light
- *Materials:* A variety of items supplied by your TA

4.2 Asteroids and Comets

There are two main types of objects in the solar system that represent left over material from its formation: asteroids and comets. In fact, both objects are quite similar, their differences arise from the fact that comets are formed from material located in the most distant parts of our solar system, where it is very cold, and thus they have large quantities of frozen water and other frozen liquids and gases. Asteroids formed closer-in than comets, and are denser, being made-up of the same types of rocks and minerals as the terrestrial planets (Mercury, Venus, Earth, and Mars). Asteroids are generally just large rocks, as shown in the Figure 4.1.

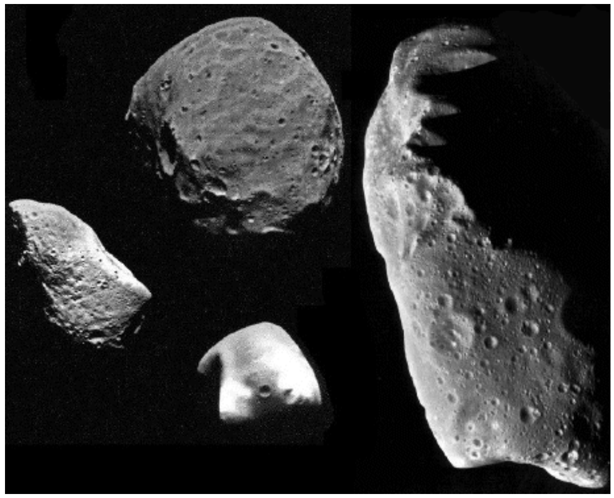


Figure 4.1: Four large asteroids. Note that these asteroids have craters from the impacts of even smaller asteroids!

The first asteroid, Ceres, was discovered in 1801 by the Italian astronomer Piazzi. Ceres is the largest of all asteroids, and has a diameter of 933 km (the Moon has a diameter of 3,476 km). There are now more than 40,000 asteroids that have been discovered, ranging in size from Ceres, all the way down to large rocks that are just a few hundred meters across. It has been estimated that there are at least 1 million asteroids in the solar system with diameters of 1 km or more. Most asteroids are harmless, and spend all of their time in orbits between those of Mars and Jupiter (the so-called "asteroid belt", see Figure 4.2). Some asteroids, however, are in orbits

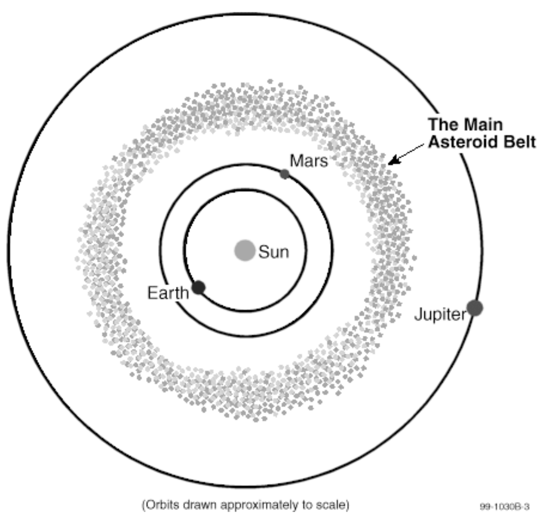


Figure 4.2: The Asteroid Belt.

that take them inside that of the Earth, and could potentially collide with the Earth, causing a great catastrophe for human life. It is now believed that the impact of a large asteroid might have been the cause for the extinction of the dinosaurs when its collision threw up a large cloud of dust that caused the Earth's climate to dramatically cool. Several searches are underway to insure that we can identify future "doomsday" asteroids so that we have a chance to prepare for a collision–as the Earth will someday be hit by another large asteroid.

4.3 Comets

Comets represent some of the earliest material left over from the formation of the solar system, and are therefore of great interest to planetary astronomers. They can also be beautiful objects to observe in the night sky, unlike their darker and less spectacular cousins, asteroids. They therefore often capture the attention of the public.

4.4 Composition and Components of a Comet

Comets are composed of ices (water ice and other kinds of ices), gases (carbon dioxide, carbon monoxide, hydrogen, hydroxyl, oxygen, and so on), and dust particles (carbon and silicon). The dust particles are smaller than the particles in cigarette smoke. In general, the model for a comet's composition is that of a "dirty snowball."

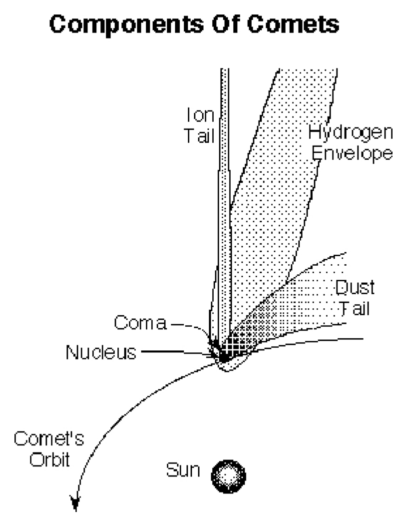


Figure 4.3: The main components of a comet.

Comets have several components that vary greatly in composition, size, and brightness. These components are the following:

- *nucleus*: made of ice and rock, roughly 5-10 km across
- *coma*: the "head" of a comet, a large cloud of gas and dust, roughly 100,000 km in diameter
- *gas tail*: straight and wispy; gas in the coma becomes ionized by sunlight, and gets carried away by the solar wind to form a straight blueish "ion" tail. The

shape of the gas tail is influenced by the magnetic field in the solar wind. Gas tails are pointed in the direction directly opposite the sun, and can extend 10^8 km.

- *dust tail*: dust is pushed outward by the pressure of sunlight and forms a long, curving tail that has a much more uniform appearance than the gas tail. The dust tail is pointed in the direction directly opposite the comet's direction of motion, and can also extend 10^8 km from the nucleus.

These various components of a comet are shown in Figure 4.3.

4.5 Types of Comets

Comets originate from two primary locations in the solar system. One class of comets, called the **long-period comets**, have long orbits around the sun with periods of > 200 years. Their orbits are random in shape and inclination, with long-period comets entering the inner solar system from all different directions. These comets are thought to originate in the **Oort cloud**, a spherical cloud of icy bodies that extends from ~ 20,000 – 150,000 AU from the Sun (see Figure 4.4). Some of these objects might experience only one close approach to the Sun and then leave the solar system (and the Sun's gravitational influence) completely.

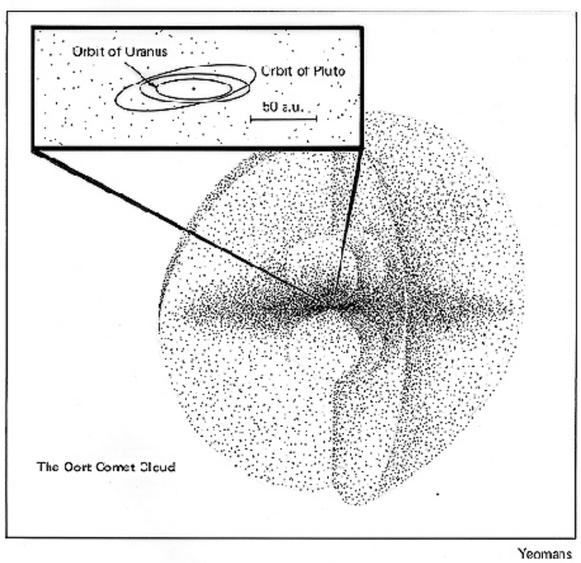


Figure 4.4: The Oort cloud.

In contrast, the **short-period comets** have periods less than 200 years, and their orbits are all roughly in the plane of the solar system. Comet Halley has a 76-year period, and therefore is considered a short-period comet. Comets with orbital periods < 100 years do not get much beyond Pluto's orbit at their farthest distance from the Sun. Short-period comets cannot survive many orbits around the Sun before their ices are all melted away. It is thought that these comets originate in the **Kuiper**

Belt, a belt of small icy bodies beyond the large gas giant planets and in the plane of the solar system (see Fig. 4.5). Quite a few large Kuiper Belt objects have now been discovered, including one (Eris) that is about the same size as Pluto.

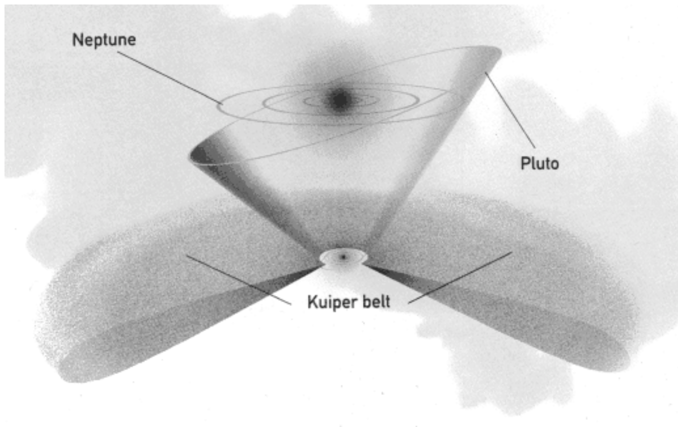


Figure 4.5: The Kuiper Belt.

4.6 The Impacts of Asteroids and Comets

Objects orbiting the Sun in our solar system do so at a variety of speeds that directly depends on how far they are from the Sun. For example, the Earth's orbital velocity is 30 km/s (65,000 mph!). Objects further from the Sun than the Earth move more slowly, objects closer to the Sun than the Earth move more quickly. Note that asteroids and comets near the Earth will have space velocities similar to the Earth, but in (mostly) random directions, thus a collision could occur with a relative speed of impact of nearly 60 km/s! How fast is this? Note that the highest muzzle velocity of any handheld rifle is 1,220 m/s = 1.2 km/s. Thus, the impact of any solar system body with another is a true *high speed collision* that releases a large amount of energy. For example, an asteroid the size of a football field that collides with the Earth with a velocity of 30 km/s releases as much energy as one thousand atomic bombs the size of that dropped on Japan during World War II (the Hiroshima bomb had a "yield" of 13 kilotons of TNT). Since the equation for kinetic energy (the energy of motion) is K.E. = $1/2(\mathrm{mv}^2)$, the energy scales directly as the mass, and mass goes as the cube of the radius (mass = density × Volume = density × R^3). A moving object with ten times the radius of another traveling at the same velocity has 1,000 times the kinetic energy. It is this kinetic energy that is released during a collision.

4.7 Exercise #1: Creating Impact Craters

To create impact craters, we will be dropping steel ball bearings into a container filled with ordinary baking flour. There are two sizes of balls, one that is twice as massive as the other. You will drop both of these balls from three different heights (0.5 meters, 1 meters, and 2 meters), and then measure the size of the impact crater that they produce. Then on graph paper, you will plot the size of the impact crater versus the speed of the impacting ball.

1. Have one member of your lab group take the meter stick, while another takes the smaller ball bearing.
2. Take the plastic tub that is filled with flour, and place it on the floor.
3. Make sure the flour is uniformly level (shake or comb the flour smooth)
4. Carefully hold the meter stick so that it is just touching the top surface of the flour.
5. The person with the ball bearing now holds the ball bearing so that it is located exactly one half meter (50 cm) above the surface of the flour.
6. Drop the ball bearing into the center of the flour-filled tub.
7. Use the magnet to carefully extract the ball bearing from the flour so as to cause the least disturbance.
8. Carefully measure the diameter of the crater caused by this impact, and place it in the data table, below.
9. Repeat the experiment for heights of 1 meter and 2 meters using the smaller ball bearing (note that someone with good balance might have to *carefully* stand on a chair or table to get to a height of two meters!).
10. Now repeat the entire experiment using the larger ball bearing. Record all of the data in the data table.

Height (meters)	Crater diameter (cm) Ball #1	Crater diameter (cm) Ball #2	Impact velocity (m/s)
0.5			
1.0			
2.0			

Now it is time to fill in that last column: Impact velocity (m/s). How can we determine the impact velocity? The reason the ball falls in the first place is because of the pull of the Earth's gravity. This force pulls objects toward the center of the Earth. In the absence of the Earth's atmosphere, an object dropped from a great height above the Earth's surface continues to accelerate to higher, and higher velocities as it falls. We call this the "acceleration" of gravity. Just like the accelerator on your car makes your car go faster the more you push down on it, the force of gravity accelerates bodies downwards (until they collide with the surface!).

We will not derive the equation here, but we can calculate the velocity of a falling body in the Earth's gravitational field from the equation $v = (2ay)^{1/2}$. In this equation, "y" is the height above the Earth's surface (in the case of this lab, it is 0.5, 1, and 2 meters). The constant "a" is the acceleration of gravity, and equals 9.80 m/s^2. The exponent of 1/2 means that you take the square root of the quantity inside the parentheses. For example, if $y = 3$ meters, then $v = (2 \times 9.8 \times 3)^{1/2}$, or $v = (58.8)^{1/2}$ = 7.7 m/s.

1. Now plot the data you have just acquired on the graph paper attached at the end of this lab. Put the impact velocity on the *x axis*, and the crater diameter on the *y* axis. (**10 points**)

4.7.1 Impact crater questions

1. Describe your graph, can the three points for each ball be *approximated* by a single straight line? How do your results for the larger ball compare to that for the smaller ball? (**3 points**)

2. If you could drop both balls from a height of 4 meters, how big would their craters be?**(2 points)**

3. What is happening here? How does the mass/size of the impacting body effect your results. How does the speed of the impacting body effect your results? What have you just proven? **(5 points)**

4.8 Crater Illumination

Now, after your TA has dimmed the room lights, have someone take the flashlight out and turn it on. If you still have a crater in your tub, great, if not create one (any height more than 1 meter is fine). Extract the ball bearing.

1. Now, shine the flashlight on the crater from straight over top of the crater. Describe what you see. **(2 points)**

2. Now, hold the flashlight so that it is just barely above the lip of the tub, so that the light shines at a very oblique angle (like that of the setting Sun!). Now, what do you see?**(2 points)**

3. When is the best time to see fine surface detail on a cratered body, when it is noon (the Sun is almost straight overhead), or when it is near "sunset"? [Confirm this at the observatory sometime this semester!] **(1 point)**

4.9 Exercise #2: Building a Comet

In this portion of the lab, you will actually build a comet out of household materials. These include water, ammonia, potting soil, and dry ice (CO_2 ice). Be sure to distribute the work evenly among all members of your group. Follow these directions: (**12 points**)

1. Put a freezer bag in your bucket.
2. Place about 1/3 cup of water in the bag/bucket.
3. Add 2 spoonfuls of sand, stirring well. (**NOTE:** Do not stir so hard that you rip the freezer bag!)
4. Add a dash of ammonia.
5. Add a dash of organic material (potting soil). Stir until well-mixed.

6. Your TA will place a block or chunk of dry ice inside a towel and crush the block with the mallet and give you some crushed dry ice.

7. Add about 1 cup of crushed dry ice to the bucket, while stirring vigorously. (**NOTE:** Do not stir so hard that you rip the freezer bag!!)

8. Continue stirring until mixture is almost frozen.

9. Lift the comet out of the bucket, keeping it in the freezer bag, and shape it for a few seconds as if you were building a snowball (wear gloves!).

10. If not a solid mass, add small amounts of water and keep working the "snowball" until the mixture is completely frozen.

11. Unwrap the comet once it is frozen enough to hold its shape.

4.9.1 Comets and Light

Observe the comet as it is sitting on a desk. Make note of some of its physical characteristics, for example:

- shape
- color
- smell

Now bring the comet over to a high intensity light source (overhead projector), or heat source (hairdryer) and place it on top. Observe what happens.

4.9.2 Comet Strength

Comets, like all objects in the solar system, are held together by their internal strength. If they pass too close to a large body, such as Jupiter, their internal strength is not large enough to compete with the powerful gravity of the massive body. In such encounters, a comet can be broken apart into smaller pieces. In 1994, we saw evidence of this when Comet Shoemaker-Levy/9 impacted into Jupiter. In 1992, that comet passed very close to Jupiter and was fragmented into pieces. Two years later, more than 21 cometary fragments crashed into Jupiter's atmosphere, creating spectacular (but temporary) "scars" on Jupiter's cloud deck (see Fig. 4.6).

Question: Do you think comets have more or less internal strength than asteroids, which are composed primarily of rock? [Hint: If you are playing outside with your friends in a snow storm, would you rather be hit with a snowball or a rock?]

Exercise: After everyone in your group has carefully examined your comet, it is time to say goodbye. Take a sample rock and your comet, go outside, and drop them

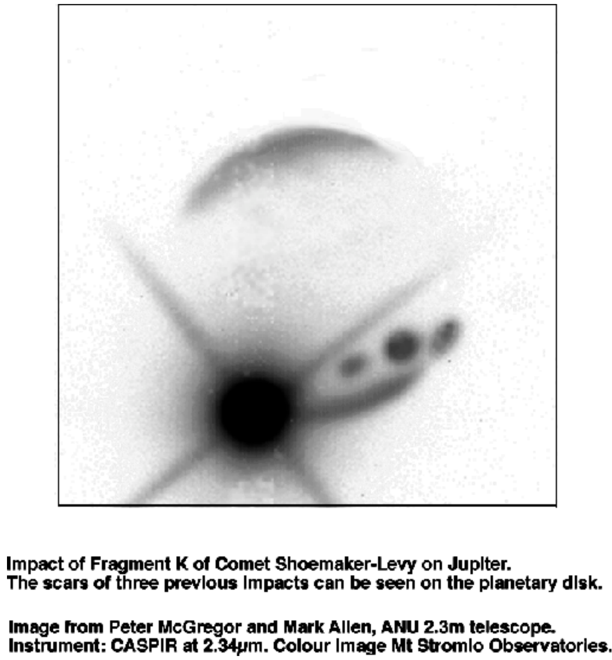


Figure 4.6: The Impact of "Fragment K" of Comet Shoemaker-Levy/9 with Jupiter.

both on the sidewalk. What happened to each object? (**2 points**)

4.9.3 Comet Questions

1. Draw a comet and label all of its components. Be sure to indicate the direction the Sun is in, and the comet's direction of motion. (**8 points**)

2. What are some differences between long-period and short-period comets? Does

it make sense that they are two distinct classes of objects? Why or why not? (**5 points**)

3. List some properties of the comet you built. In particular, describe its shape, color, smell and weight relative to other common objects (e.g. tennis ball, regular snow ball, etc.). (**4 points**)

4. Describe what happened when you put your comet near the light source. Were there localized regions of activity, or did things happen uniformly to the entire comet? (**3 points**)

5. If a comet is far away from the Sun and then it draws nearer as it orbits the Sun, what would you expect to happen? (**3 points**)

6. Which object do you think has more internal strength, an asteroid or a comet, and why? (**3 points**)

4.10 Summary

(**35 points**) Summarize the important ideas covered in this lab. Questions you may want to consider are:

- How does the mass of an impacting asteroid or comet affect the size of an impact crater?
- How does the speed of an impacting asteroid or comet affect the size of an impact crater?
- Why are comets important to planetary astronomers?
- What can they tell us about the solar system?
- What are some components of comets and how are they affected by the Sun?
- How are comets different from asteroids?

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

4.11 Possible Quiz Questions

1. What is the main difference between comets and asteroids, and why are they different?
2. What is the Oort cloud and the Kuiper belt?
3. What happens when a comet or asteroid collides with the Moon?
4. How does weather effect impact features on the Earth?
5. How does the speed of the impacting body effect the energy of the collision?

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

On the 15th of February, 2013, a huge meteorite exploded in the skies over Chelyabinsk, Russia. Write-up a small report about this event, including what might have happened if instead of a grazing, or "shallow", entry into our atmosphere, the meteor had plowed straight down to the surface.

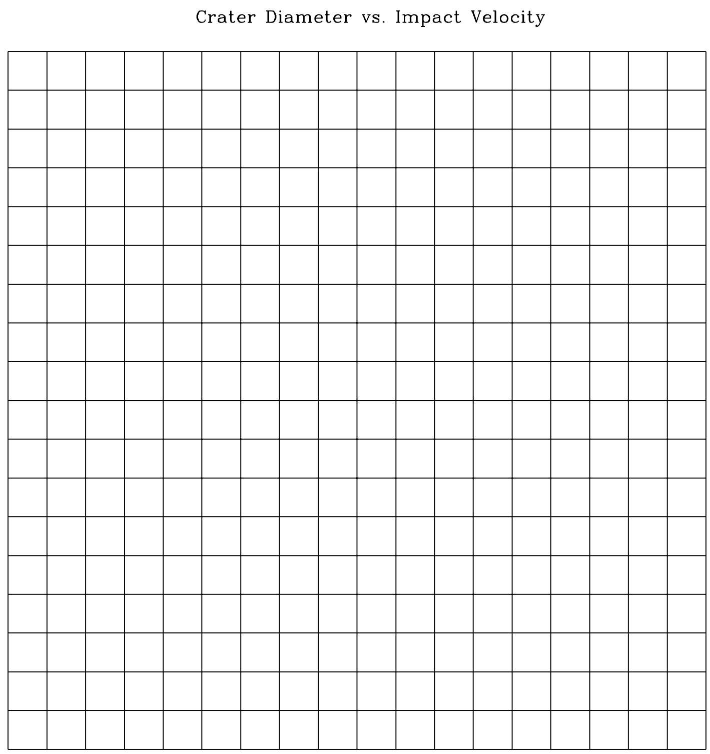


Figure 4.7: Plot your impact crater data here.

Name:______________________________

Date:______________________________

5 Introduction to the Geology of the Terrestrial Planets

5.1 Introduction

There are two main families of planets in our solar system: the Terrestrial planets (Earth, Mercury, Venus, and Mars), and the Jovian Planets (Jupiter, Saturn, Uranus, and Neptune). The terrestrial planets are rocky planets that have properties similar to that of the Earth. In contrast, the Jovian planets are giant balls of gas. Table 5.1 summarizes the main properties of the planets in our solar system (Pluto is an oddball planet that does not fall into either categories, sharing many properties with the "Kuiper belt" objects discussed in the lab # 4).

Table 5.1: The Properties of the Planets

Planet	Mass (Earth Masses)	Radius (Earth Radii)	Density gm/cm^3
Mercury	0.055	0.38	5.5
Venus	0.815	0.95	5.2
Earth	1.000	1.00	5.5
Mars	0.107	0.53	3.9
Jupiter	318	10.8	1.4
Saturn	95	9.0	0.7
Uranus	14.5	3.93	1.3
Neptune	17.2	3.87	1.6
Pluto	0.002	0.178	2.1

It is clear from Table 5.1 that the nine planets in our solar system span a considerable range in sizes and masses. For example, the Earth has 18 times the mass of Mercury, while Jupiter has 318 times the mass of the Earth. But the separation of the planets into Terrestrial and Jovian is not based on their masses or physical sizes, it is based on their densities (the last column in the table). What is density? Density is simply the mass of an object divided by its volume: M/V. In the metric system, the density of water is set to 1.00 gm/cm^3. Densities for some materials you are familiar with can be found in Table 5.2.

If we examine the first table we see that the terrestrial planets all have higher densities than the Jovian planets. Mercury, Venus and Earth have densities above 5

Table 5.2: The Densities of Common Materials

Element or Molecule	Density gm/cm^3	Element	Density gm/cm^3
Water	1.0	Carbon	2.3
Aluminum	2.7	Silicon	2.3
Iron	7.9	Lead	11.3
Gold	19.3	Uranium	19.1

gm/cm^3, while Mars has a slightly lower density ($\sim$ 4 gm/cm^3). The Jovian planets have densities very close to that of water–in fact, the mean density of Saturn is lower than that of water! The density of a planet gives us clues about its composition. If we look at the table of densities for common materials, we see that the mean densities of the terrestrial planets are about halfway between those of silicon and iron. Both of these elements are highly abundant throughout the Earth, and thus we can postulate that the terrestrial planets are mostly composed of iron, silicon, with additional elements like carbon, oxygen, aluminum and magnesium. The Jovian planets, however, must be mostly composed of lighter elements, such as hydrogen and helium. In fact, the Jovian planets have similar densities to that of the Sun: 1.4 gm/cm^3. The Sun is 70% hydrogen, and 28% helium. Except for small, rocky cores, the Jovian planets are almost nothing but hydrogen and helium.

The terrestrial planets share other properties, for example they all rotate much more slowly than the Jovian planets. They also have much thinner atmospheres than the Jovian planets (which are almost *all* atmosphere!). Today we want to investigate the geologies of the terrestrial planets to see if we can find other similarities, or identify interesting differences.

5.2 Topographic Map Projections

In the first part of this lab we will take a look at images and maps of the surfaces of the terrestrial planets for comparison. But before we do so, we must talk about what you will be viewing, and how these maps/images were produced. As you probably know, 75% of the Earth's surface is covered by oceans, thus a picture of the Earth from space does not show very much of the actual rocky surface (the "crust" of the Earth). With modern techniques (sonar, radar, etc.) it is possible to reconstruct the true shape and structure of a planet's rocky surface, whether it is covered in water, or by very thick clouds (as is the case for Venus). Such maps of the "relief" of the surface of a planet are called *topographic* maps. These maps usually color code, or have contours, showing the highs and lows of the surface elevations. Regions of constant elevation above (or below) sea level all will have the same color. This way, large structures such as mountain ranges, or ocean basins, stand out very clearly.

There are several ways to present topographic maps, and you will see two versions today. One type of map is an attempt at a 3D *visualization* that keeps the relative sizes of the continents in correct proportion (see Figure 5.1, below). But such maps only allow you to see a small part of a spherical planet in any one plot. More commonly, the entire surface of the planet is presented as a rectangular map as shown in Figure 5.2. Because the surface of a sphere cannot be properly represented as a rectangle, the regions near the north and south poles of a planet end up being highly distorted in this kind of map. So keep this in mind as you work through the exercises in this lab.

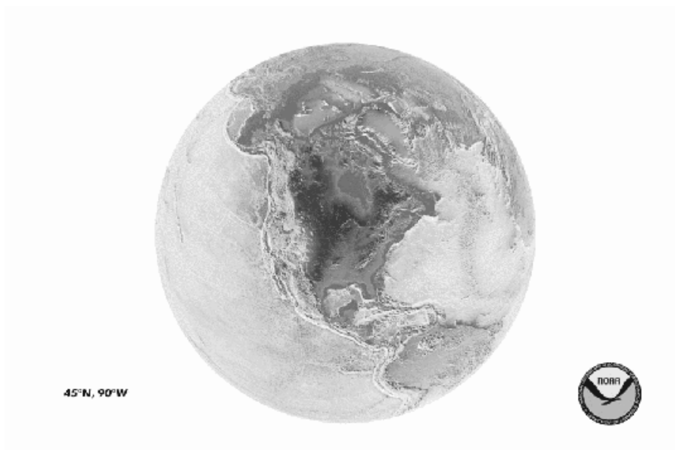


Figure 5.1: A topographic map showing one hemisphere of Earth centered on North America. In this 3D representation the continents are correctly rendered.

5.3 Global Comparisons

In the first part of this lab exercise, you will look at the planets in a *global* sense, by comparing the largest structures on the terrestrial planets.

Exercise #1: At station #1 you will find images of Mercury, Venus, the Earth, the Moon, and Mars. The images for Mercury, Venus and the Earth and Moon are in "false colors" to help emphasize different features, including different types of rocks or large-scale structures. The image of Mars, however, is in "true color".

Impact craters can come in a variety of sizes, from tiny little holes, all the way up to the large "maria" seen on the Moon. Impact craters are usually round.

1. On which of the five objects are large meteorite impact craters obvious? **(1 point)**

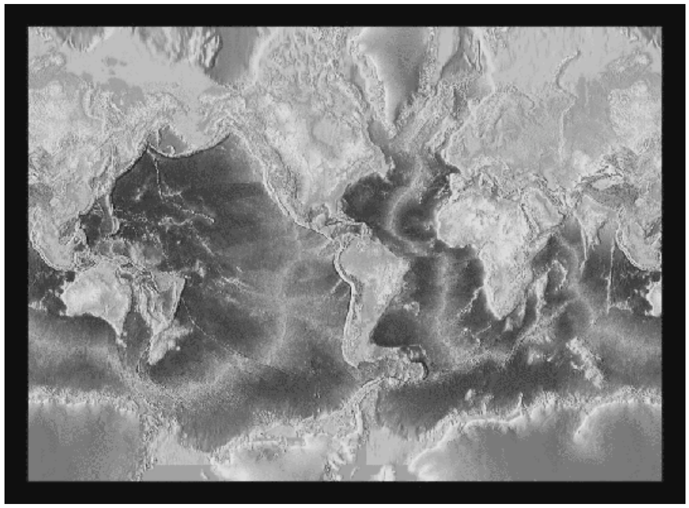


Figure 5.2: A topographic map showing the entire surface of the Earth. In this 2D representation, the continents are incorrectly rendered. Note that Antarctica (the land mass that spans the bottom border of this map) is 50% smaller than North America, but here appears massive. You might also be able to compare the size of Greenland on this map, to that of the previous map.

2. Does Venus or the Earth show any signs of large, round maria (like those seen on Mercury or the Moon)? **(1 point)**

3. Which planet seems to have the most impact craters? **(1 point)**

4. Compare the surface of Mercury to the Moon. Are they similar? **(3 points)**

Mercury is the planet closest to the Sun, so it is the terrestrial planet that gets hit by comets, asteroids and meteoroids more often than the other planets because the Sun's gravity tends to collect small bodies like comets and asteroids. The closer you are to the Sun, the more of these objects there are in the neighborhood. Over time, most of the largest asteroids on orbits that intersect those of the other planets have either collided with a planet, or have been broken into smaller pieces by the gravity of a close approach to a large planet. Thus, only smaller debris is left over to cause impact craters.

5. Using the above information, make an educated guess on why Mercury does not have as many large maria as the Moon, even though both objects have been around for the same amount of time. [Hint: Maria are caused by the impacts of *large* bodies.] **(3 points)**

Mercury and the Moon do not have atmospheres, while Mars has a thin atmosphere. Venus has the densest atmosphere of the terrestrial planets.

6. Does the presence of an atmosphere appear to reduce the number of impact craters? Justify your answer. **(3 points)**

Exercise #2: Topography of Mercury, Venus, Earth, and Mars. At station #2 you will find topographic maps of Mercury, Venus, the Earth, and Mars. The data for Mercury has not been fully published, so we only have topographic maps for about 25% of its surface. These maps are color-coded to help you determine the highest and lowest parts of each planet. You can determine the elevation of a color-coded feature on these maps by using the scale found on each map. [Note that for the Earth and Mars, the scales of these maps are in meters, for Mercury it is in km (= 1,000 meters), while for Venus it is in planetary radius! But the scale for Venus is the same as for Mars, so you can use the scale on the Mars map to examine Venus.]

7. Which planet seems to have the least amount of relief (relief = high and low spots/features)? **(2 points)**

8. Which planet seems to have the deepest/lowest regions? **(2 points)**

9. Which planet seems to have the highest mountains? **(2 points)**

On both the Venus and Mars topographic maps, the polar regions are plotted as separate circular maps so as to reduce distortion.

10. Looking at these polar plots, Mars appears to be a very strange planet. Compare the elevations of the northern and southern hemispheres of Mars. If Mars had an abundance of surface water (oceans), what would the planet look like? **(3 points)**

5.4 Detailed Comparison of the Surfaces of the Terrestrial Planets

In this subsection we will compare some of the smaller surface features of the terrestrial planets using a variety of close-up images. In the following, the images of features on Venus have been made using radar (because the atmosphere of Venus is so cloudy, we cannot see its surface). While these images look similar to the pictures for the other planets, they differ in one major way: in radar, smooth objects reflect the radio waves differently than rough objects. In the radar images of Venus, the rough areas are "brighter" (whiter) than smooth areas.

In the Moon lab (lab # 3), we discussed how impact craters form. For large impacts, the center of the crater may "rebound" and produce a central mountain (or several small peaks). Sometimes an impact is large enough to crack the surface of the planet, and lava flows into the crater filling it up, and making the floor of the crater smooth. On the Earth, water can also collect in a crater, while on Mars it might collect large quantities of dust.

Exercise #3: Impact craters on the terrestrial planets. At station #3 you will find close-up pictures of the surfaces of the terrestrial planets showing impact craters.

11. Compare the impact craters seen on Mercury, Venus, Earth, and Mars. How are they alike, how are they different? Are central mountain peaks common to craters on all planets? Of the sets of craters shown, does one planet seem to have more lava-filled craters than the others? **(4 points)**

12. Which planet has the sharpest, roughest, most detailed and complex craters? [Hint: details include ripples in the nearby surface caused by the crater formation, as well as numerous small craters caused by large boulders thrown out of the bigger crater. Also commonly seen are “ejecta blankets” caused by material thrown out of the crater that settles near its outer edges.] **(2 points)**

13. Which planet has the smoothest, and least detailed craters? **(2 points)**

14. What is the main difference between the planet you identified in question #12 and that in question #13? [Hint: what processes help erode craters?] **(2 points)**

You have just examined four different craters found on the Earth: Berringer, Wolfe Creek, Mistastin Lake, and Manicouagan. Because we can visit these craters we can accurately determine when they were formed. Berringer is the youngest crater with an age of 49,000 years. Wolf Creek is the second youngest at 300,000 years. Mistastin Lake formed 38 million years ago, while Manicouagan is the oldest, easily identified crater on the surface of the Earth at 200 million years old.

15. Describe the differences between young and old craters on the Earth. What

happens to these craters over time? **(4 points)**

5.5 Erosion Processes and Evidence for Water

Geological erosion is the process of the breaking down, or the wearing-away of surface features due to a variety of processes. Here we will be concerned with the two main erosion processes due to the presence of an atmosphere: wind erosion, and water erosion. With daytime temperatures above 700°F, both Mercury and Venus are too hot to have liquid water on their surfaces. In addition, Mercury has no atmosphere to sustain *water or a wind*. Interestingly, Venus has a very dense atmosphere, but as far as we can tell, very little wind erosion occurs at the surface. This is probably due to the incredible pressure at the surface of Venus due to its dense atmosphere: the atmospheric pressure at the surface of Venus is 90 times that at the surface of the Earth–it is like being 1 km below the surface of an Earth ocean! Thus, it is probably hard for strong winds to blow near the surface, and there are probably only gentle winds found there, and these do not seriously erode surface features. This is not true for the Earth or Mars.

On the surface of the Earth it is easy to see the effects of erosion by wind. For residents of New Mexico, we often have dust storms in the spring. During these events, dust is carried by the wind, and it can erode ("sandblast") any surface it encounters, including rocks, boulders and mountains. Dust can also collect in cracks, arroyos, valleys, craters, or other low, protected regions. In some places, such as at the White Sands National Monument, large fields of sand dunes are created by wind-blown dust and sand. On the Earth, most large dunefields are located in arid regions.

Exercise #4: Evidence for wind blown sand and dust on Earth and Mars. At station #4 you will find some pictures of the Earth and Mars highlighting dune fields.

16. Do the sand dunes of Earth and Mars appear to be very different? Do you think you could tell them apart in black and white photos? Given that the atmosphere of Mars is only 1% of the Earth's, what does the presence of sand dunes tell you about the winds on Mars? **(3 points)**

Exercise #5: Looking for evidence of water on Mars. In this exercise, we will closely examine geological features on Earth caused by the erosion action of water. We will then compare these to similar features found on Mars. The photos are found at Station #5.

As you know, water tries to flow "down hill", constantly seeking the lowest elevation. On Earth most rivers eventually flow into one of the oceans. In arid regions, however, sometimes the river dries up before reaching the ocean, or it ends in a shallow lake that has no outlet to the sea. In the process of flowing down hill, water carves channels that have fairly unique shapes. A large river usually has an extensive, and complex drainage pattern.

17. The drainage pattern for streams and rivers on Earth has been termed "dendritic", which means "tree-like". In the first photo at this station (#23) is a dendritic drainage pattern for a region in Yemen. Why was the term dendritic used to describe such drainage patterns? Describe how this pattern is formed. **(3 points)**

18. The next photo (#24) is a picture of a sediment-rich river (note the brown water) entering a rather broad and flat region where it becomes shallow and spreads out. Describe the shapes of the "islands" formed by this river. **(3 points)**

In the next photo (#25) is a picture of the northern part of the Nile river as it passes through Egypt. The Nile is 4,184 miles from its source to its mouth on the Mediterranean sea. It is formed in the highlands of Uganda and flows North, down hill to the Mediterranean. Most of Egypt is a very dry country, and there are no major rivers that flow into the Nile, thus there is no dendritic-like pattern to the Nile in Egypt. [Note that in this image of the Nile, there are several obvious dams that have created lakes and reservoirs.]

19. Describe what you see in this image from Mars (Photo #26). **(2 points)**

20. What is going on in this photo (#27)? How were these features formed? Why do the small craters not show the same sort of "teardrop" shapes? **(2 points)**

21. Here are some additional images of features on Mars. The second one (Photo #29) is a close-up of the region delineated by the white box seen in Photo #28. Compare these to the Nile. **(2 points)**

22. While Mars is dry now, what do you conclude about its past? Justify your answer. What technique can we use to determine when water might have flowed in Mars' past? [Hint: see your answer for #20.] **(4 points)**

5.6 Volcanoes and Tectonic Activity

While water and wind-driven erosion is important in shaping the surface of a planet, there are other important events that can act to change the appearance of a planet's surface: volcanoes, earthquakes, and plate tectonics. The majority of the volcanic and earthquake activity on Earth occurs near the boundaries of large slabs of rock called "plates". As shown in Figure 5.3, the center of the Earth is very hot, and this heat flows from hot to cold, or from the center of the Earth to its surface (and into space). This heat transfer sets up a boiling motion in the semi-molten mantle of the Earth.

As shown in the next figure (Fig. 5.4), in places where the heat rises, we get an up-welling of material that creates a ridge that forces the plates apart. We also get volcanoes at these boundaries. In other places, the crust of the Earth is pulled down into the mantle in what is called a subduction zone. Volcanoes and earthquakes are also common along subduction zone boundaries. There are other sources of earthquakes and volcanoes which are not directly associated with plate tectonic activity. For example, the Hawaiian islands are all volcanoes that have erupted in the middle of the Pacific plate. The crust of the Pacific plate is thin enough, and there is sufficiently hot material below, to have caused the volcanic activity which created the chain of islands called Hawaii. In the next exercise we will examine the other terrestrial planets for evidence of volcanic and plate tectonic activity.

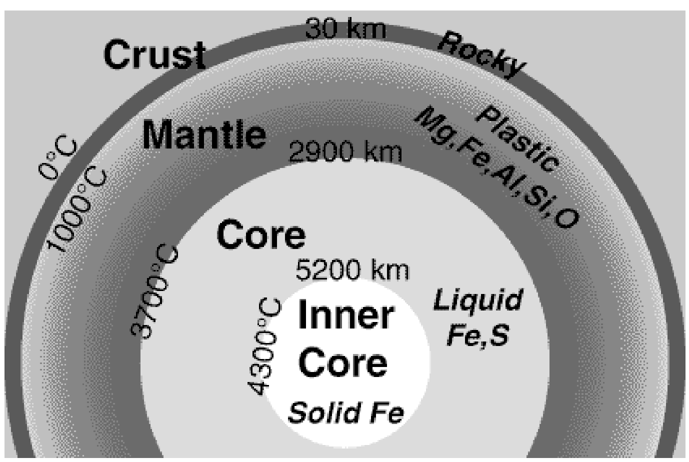


Figure 5.3: A cut-away diagram of the structure of the Earth showing the hot core, the mantle, and the crust. The core of the Earth is very hot, and is composed of both liquid and solid iron. The mantle is a zone where the rocks are partially melted ("plastic-like"). The crust is the cold, outer skin of the Earth, and is very thin.

Exercise #6: Using the topographical maps from station #2, we will see if you can identify evidence for plate tectonics on the Earth. Note that plates have fairly dis-

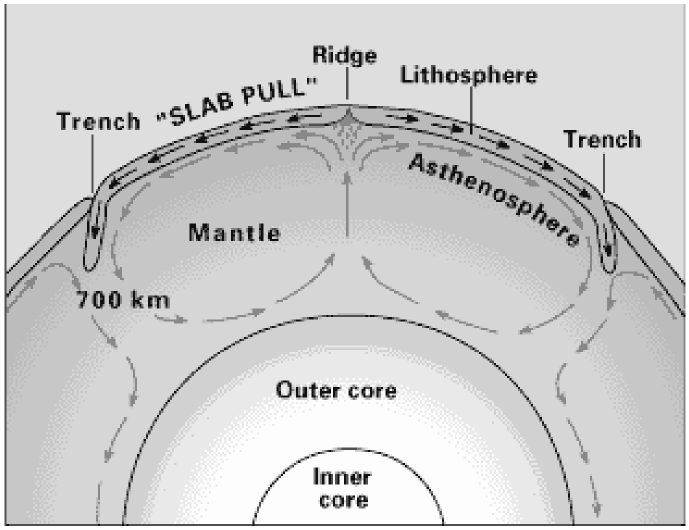


Figure 5.4: The escape of the heat from the Earth's core sets-up a boiling motion in the mantle. Where material rises to the surface it pushes apart the plates and volcanoes, and mountain chains are common. Where the material is cooling, it flows downwards (subsides) back into the mantle pulling down on the plates ("slab-pull'). This is how the large crustal plates move around on the Earth's surface.

tinct boundaries, usually long chains of mountains are present where two plates either are separating (forming long chains of volcanoes), or where two plates run into each other creating mountain ranges. Sometimes plates fracture, creating fairly straight lines (sometimes several parallel features are created). The remaining photos can be found at Station #6.

23. Identify and describe several apparent tectonic features on the topographic map of the Earth. [Hint: North and South America are moving away from Europe and Africa]. **(2 points)**

24. Now, examine the topographic maps for Mars and Venus (ignoring the grey areas that are due to a lack of spacecraft data). Do you see any evidence for large

scale tectonic activity on either Mars or Venus?**(3 points)**

The fact that there is little large-scale tectonic activity present on the surfaces of either Mars or Venus today does not mean that they never had any geological activity. Let us examine the volcanoes found on Venus, Earth and Mars. The first set of images contain views of a number of volcanoes on Earth. Several of these were produced using space-based radar systems carried aboard the Space Shuttle. In this way, they better match the data for Venus. There are a variety of types of volcanoes on Earth, but there are two main classes of large volcanoes: "shield" and "composite". Shield volcanoes are large, and have very gentle slopes. They are caused by low-viscosity lava that flows easily. They usually are rather flat on top, and often have a large "caldera" (summit crater). Composite volcanoes are more explosive, smaller, and have steeper sides (and "pointier" tops). Mount St. Helens is one example of a composite volcano, and is the first picture (Photo #31) at this station (note that the apparent crater at the top of St. Helens is due to the 1980 eruption that caused the North side of the volcano to collapse, and the field of devastation that emanates from there). The next two pictures are also of composite volcanoes while the last three are of the shield volcanoes Hawaii, Isabela and Miakijima (the last two in 3D).

25. Here are some images of Martian volcanoes (Photos #37 to #41). What one type of volcano does Mars have? How did you arrive at this answer? **(3 points)**

26. In the next set (Photos #42 to #44) are some false-color images of Venusian volcanoes. Among these are both overhead shots, and 3D images. Because Venus was mapped using radar, we can reconstruct the data to create images as if we were located on, or near, the surface of Venus. *Note, however, that the vertical elevation*

detail has been exaggerated by a factor of ten! It might be hard to tell, but Venus is also dominated by one main type of Volcano, what is it? **(3 points)**

5.7 Summary (35 points)

As we have seen, many of the geological features common to the Earth can be found on the other terrestrial planets. Each planet, however, has its own peculiar geology. For example, Venus has the greatest number of volcanoes of any of the terrestrial planets, while Mars has the biggest volcanoes. Only the Earth seems to have active plate tectonics. Mercury appears to have had the least amount of geological activity in the solar system and, in this way, is quite similar to the Moon. Mars and the Earth share something that none of the other planets in our solar system do: erosion features due to liquid water. This, of course, is why there continues to be interest in searching for life (either alive or extinct) on Mars.

- Describe the surfaces of each of the terrestrial planets, and the most important geological forces that have shaped their surfaces.
- Of the four terrestrial planets, which one seems to be the least interesting? Can you think of one or more reasons why this planet is so inactive?
- If you were in charge of searching for life on Mars, where would you want to begin your search?

5.8 Possible Quiz Questions

1. What are the main differences between Terrestrial and Jovian planets?
2. What is density?
3. How are impact craters formed?
4. What is a topographic map?

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

Since Mars currently has no large bodies of water, what is probably the most important erosion process there? How can we tell? What is the best way to observe or monitor this type of erosion? Researching the images from the several small landers and some of the orbiting missions, is there strong evidence for this type of erosion? What is that evidence?

Name: ____________________

Date: ____________________

6 Kepler's Laws and Gravitation

6.1 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, even foretelling the future using astrology, 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 each 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! It was left to the Egyptian astronomer Ptolemy ($85 - 165$ AD) to develop a model for the motion of the planets (you can read more about the details of the Ptolemaic model in your textbook). Ptolemy developed a complicated system to explain the motion of the planets, including "epicycles" and "equants", that in the end worked so well, that 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 and the law of gravity.

6.2 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. 6.1. 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.

Today you will be using a computer program called "Planets and Satellites" by Eugene Butikov to explore Kepler's laws, and how planets, double stars, and planets in double star systems move. This program uses the law of gravity to simulate how celestial objects move.

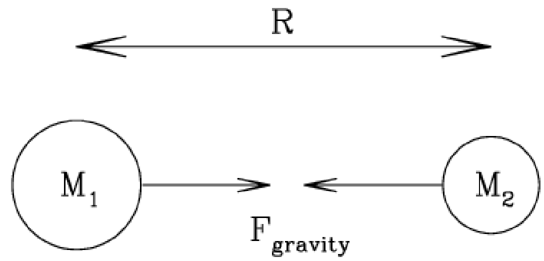


Figure 6.1: The force of gravity depends on the masses of the two objects (M_1, M_2), and the distance between them (R).

- *Goals:* to understand Kepler's three laws and use them in conjunction with the computer program "Planets and Satellites" to explain the orbits of objects in our solar system and beyond

- *Materials: Planets and Satellites* program, a ruler, and a calculator

6.3 Kepler's Laws

Before you begin the lab, it is important to recall 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: $P^2 \propto a^3$"

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. 6.2.

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 $2\pi R$. The radius, R, is the distance between the center of the circle and any point on the circle itself. In mathematical terms, the center of the circle is called the "focus". An ellipse, as shown in Fig. 6.3, 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

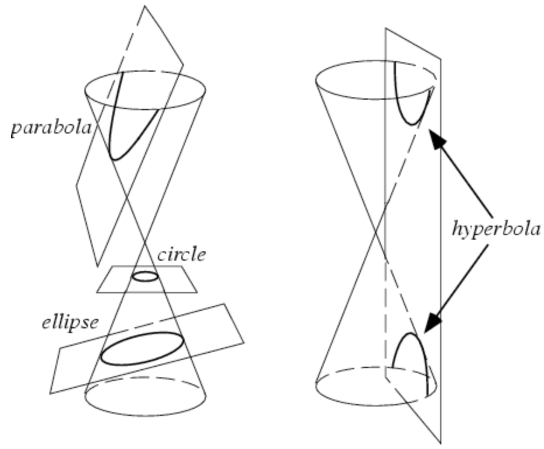


Figure 6.2: Four types of curves can be generated by slicing a cone with a plane: a circle, an ellipse, a parabola, and a hyperbola. Strangely, these four curves are also the allowed shapes of the orbits of planets, asteroids, comets and satellites!

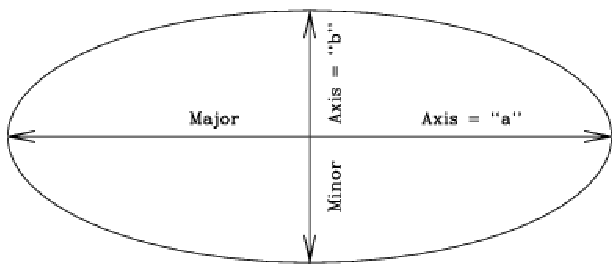


Figure 6.3: An ellipse with the major and minor axes identified.

"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. 6.4 is an ellipse with the two foci identified, "F_1" and "F_2".

Exercise #1: On the ellipse in Fig. 6.4 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. (**2 points**)

Exercise #2: In the ellipse shown in Fig. 6.5, 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. (**2 points**)

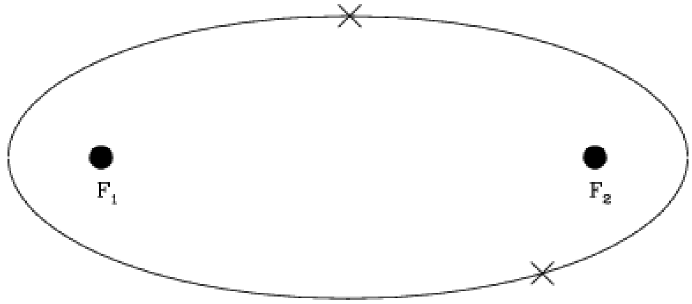


Figure 6.4: An ellipse with the two foci identified.

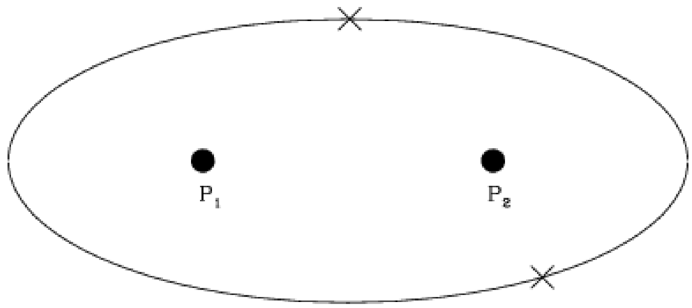


Figure 6.5: An ellipse with two non-foci points identified.

Now we will use the Planets and Satellites program to examine Kepler's laws. It is possible that the program will already be running when you get to your computer. If not, however, you will have to start it up. If your TA gave you a CDROM, then you need to insert the CDROM into the CDROM drive on your computer, and open that device. On that CDROM will be an icon with the program name. It is also possible that Planets and Satellites has been installed on the computer you are using. Look on the desktop for an icon, or use the start menu. Start-up the program, and you should see a title page window, with four boxes/buttons ("Getting Started", "Tutorial", "Simulations", and "Exit"). Click on the "Simulations" button. We will be returning to this level of the program to change simulations. Note that there are help screens and other sources of information about each of the simulations we will be running–do not hesitate to explore those options.

Exercise #3: Kepler's first law. Click on the "Kepler's Law button" and then the "First Law" button inside the Kepler's Law box. A window with two panels opens up. The panel on the left will trace the motion of the planet around the Sun, while the panel on the right sums the distances of the planet from the foci. Remember, Kepler's first law states "the orbit of a planet is an ellipse with the Sun at one focus". The Sun in this simulation sits at one focus, while the other focus is empty (but whose location will be obvious once the simulation is run!).

At the top of the panel is the program control bar. For now, simply hit the "Go" button. You can clear and restart the simulation by hitting "Restart" (do this as often as you wish). After hitting Go, note that the planet executes an orbit along the ellipse. The program draws the "vectors" from each focus to 25 different positions of the planet in its orbit. It draws a blue vector from the Sun to the planet, and a yellow vector from the other focus to the planet. The right hand panel sums the blue and yellow vectors. [Note: if your computer runs the simulation too quickly, or too slowly, simply adjust the "Slow down/Speed Up" slider for a better speed.]

Describe the results that are displayed in the right hand panel for this first simulation. **(2 points)**.

Now we want to explore another ellipse. In the extreme left hand side of the control bar is a slider to control the "Initial Velocity". At start-up it is set to "1.2". Slide it up to the maximum value of 1.35 and hit Go.

Describe what the ellipse looks like at 1.35 vs. that at 1.2. Does the sum of the vectors (right hand panel) still add up to a constant? **(3 points)**

Now let's put the Initial Velocity down to a value of 1.0. Run the simulation. What is happening here? The orbit is now a circle. Where are the two foci located? In this case, what is the distance between the focus and the orbit equivalent to? **(4 points)**

The point in the orbit where the planet is closest to the Sun is called "perihelion", and that point where the planet is furthest from the Sun is called "aphelion". For a circular orbit, the aphelion is the same as the perihelion, and can be defined to be anywhere! Exit this simulation (click on "File" and "Exit").

Exercise #4: Kepler's Second Law: "A line from a planet to the Sun sweeps out equal areas in equal intervals of time." From the simulation window, click on the "Second Law" after entering the Kepler's Law window. Move the Initial Velocity slide bar to a value of 1.2. Hit Go.

Describe what is happening here. Does this confirm Kepler's second law? How? When the planet is at perihelion, is it moving slowly or quickly? Why do you think this happens? **(4 points)**

Look back to the equation for the force of gravity. You know from personal experience that the harder you hit a ball, the faster it moves. The act of hitting a ball is the act of applying a force to the ball. The larger the force, the faster the ball moves (and, generally, the farther it travels). In the equation for the force of gravity, the amount of force generated depends on the masses of the two objects, and the distance between them. But note that it depends on one over the square of the distance: $1/R^2$. Let's explore this "inverse square law" with some calculations.

- If $R = 1$, what does $1/R^2 =$ ________________________?

- If $R = 2$, what does $1/R^2 =$ ________________________?

- If R = 4, what does $1/R^2$ = ______________________?

What is happening here? As R gets bigger, what happens to $1/R^2$? Does $1/R^2$ decrease/increase quickly or slowly? **(2 points)**

The equation for the force of gravity has a $1/R^2$ in it, so as R increases (that is, the two objects get further apart), does the force of gravity *felt* by the body get larger, or smaller? Is the force of gravity stronger at perihelion, or aphelion? Newton showed that the speed of a planet in its orbit depends on the force of gravity through this equation:

$$V = \sqrt{(G(M_{\mathrm{sun}} + M_{\mathrm{planet}})(2/r - 1/a))} \tag{2}$$

where "r" is the radial distance of the planet from the Sun, and "a" is the mean orbital radius (the semi-major axis). Do you think the planet will move faster, or slower when it is closest to the Sun? Test this by assuming that r = 0.5a at perihelion, and r = 1.5a at aphelion, and that a=1! [Hint, simply set $G(M_{\mathrm{sun}} + M_{\mathrm{planet}}) = 1$ to make this comparison very easy!]

Does this explain Kepler's second law? **(4 points)**

What do you think the motion of a planet in a circular orbit looks like? Is there a definable perihelion and aphelion? Make a prediction for what the motion is going to look like–how are the triangular areas seen for elliptical orbits going to change as the planet orbits the Sun in a circular orbit? Why? **(3 points)**

Now let's run a simulation for a circular orbit by setting the Initial Velocity to 1.0. What happened? Were your predictions correct? **(3 points)**

Exit out of the Second Law, and start-up the Third Law simulation.

Exercise 4: Kepler's Third Law: "A planet's orbital period squared is proportional to its average distance from the Sun cubed: $P^2 \propto a^3$". As we have just learned, the law of gravity states that the further away an object is, the weaker the force. We have already found that at aphelion, when the planet is far from the Sun, it moves more slowly than at perihelion. Kepler's third law is merely a reflection of this fact–the further a planet is from the Sun ("a"), the more slowly it will move. The more slowly it moves, the longer it takes to go around the Sun ("P"). The relation is $P^2 \propto a^3$, where P is the orbital period in years, while a is the average distance of the planet from the Sun, and the mathematical symbol for proportional is represented by "$\propto$". To turn the proportion sign into an equal sign requires the multiplication of the a^3 side of the equation by a constant: $P^2 = C \times a^3$. But we can get rid of this constant, "C", by making a ratio. We will do this below.

In the next simulation, there will be two planets: one in a smaller orbit, which will represent the Earth (and has $a = 1$), and a planet in a larger orbit (where a is adjustable). Start-up the Third Law simulation and hit Go. You will see that the inner planet moves around more quickly, while the planet in the larger ellipse moves more slowly. Let's set-up the math to better understand Kepler's Third Law. We begin by constructing the ratio of of the Third Law equation ($\mathrm{P}^2 = C \times a^3$) for an arbitrary planet divided by the Third Law equation for the Earth:

$$\frac{P_P^2}{P_E^2} = \frac{C \times a_P^3}{C \times a_E^3} \tag{3}$$

In this equation, the planet's orbital period and average distance are denoted by P_P and a_P, while the orbital period of the Earth and its average distance from the Sun are P_E and a_E. As you know from from your high school math, any quantity that appears on both the top and bottom of a fraction can be canceled out. So, we can get rid of the pesky constant "C", and Kepler's Third Law equation becomes:

$$\frac{P_P^2}{P_E^2} = \frac{a_P^3}{a_E^3} \tag{4}$$

But we can make this equation even simpler by noting that if we use years for the orbital period ($P_E = 1$), and Astronomical Units for the average distance of the Earth to the Sun ($a_E = 1$), we get:

$$\frac{P_P^2}{1} = \frac{a_P^3}{1} \quad or \quad P_P^2 = a_P^3 \tag{5}$$

(Remember that the cube of 1, and the square of 1 are both 1!)

Let's use equation (5) 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:

$$P_J^2 = a_J^3 = 5^3 = 5 \times 5 \times 5 = 125 \tag{6}$$

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:

$$\sqrt{P^2} = P = \sqrt{125} = 11.2 \;\; years \tag{7}$$

The orbital period of Jupiter is approximately 11.2 years. Your turn:

If an asteroid has an average distance from the Sun of 4 AU, what is its orbital period? Show your work. **(2 points)**

In the Third Law simulation, there is a slide bar to set the average distance from the Sun for any hypothetical solar system body. At start-up, it is set to 4 AU. Run the simulation, and confirm the answer you just calculated. Note that for each orbit of the inner planet, a small red circle is drawn on the outer planet's orbit. Count up these red circles to figure out how many times the Earth revolved around the Sun during a single orbit of the asteroid. Did your calculation agree with the simulation? Describe your results. **(2 points)**

If you were observant, you noticed that the program calculated the number of orbits that the Earth executed for you (in the "Time" window), and you do not actually have to count up the little red circles. Let's now explore the orbits of the nine planets in our solar system. In the following table are the semi-major axes of the nine planets. Note that the "average distance to the Sun" (a) that we have been using above is actually a quantity astronomers call the "semi-major axis" of a planet. a is simply one half the major axis of the orbit ellipse. Fill in the missing orbital periods of the planets by running the Third Law simulator for each of them. **(3 points)**

Table 6.1: The Orbital Periods of the Planets

Planet	a (AU)	P (yr)
Mercury	0.387	0.24
Venus	0.72	
Earth	1.000	1.000
Mars	1.52	
Jupiter	5.20	
Saturn	9.54	29.5
Uranus	19.22	84.3
Neptune	30.06	164.8
Pluto	39.5	248.3

Notice that the further the planet is from the Sun, the slower it moves, and the longer it takes to complete one orbit around the Sun (its "year"). Neptune was discovered in 1846, and Pluto was discovered in 1930 (by Clyde Tombaugh, a former professor at NMSU). How many orbits (or what fraction of an orbit) have Neptune and Pluto completed since their discovery? **(3 points)**

6.4 Going Beyond the Solar System

One of the basic tenets of physics is that all natural laws, such as gravity, are the same everywhere in the Universe. Thus, when Newton used Kepler's laws to figure out how gravity worked in the solar system, we suddenly had the tools to understand how stars interact, and how galaxies, which are large groups of billions of stars, behave: the law of gravity works the same way for a planet orbiting a star that is billions of light years from Earth, as it does for the planets in our solar system. Therefore, we can use the law of gravity to construct simulations for all types of situations—even how the Universe itself evolves with time! For the remainder of the lab we will investigate binary stars, and planets in binary star systems.

First, what is a binary star? Astronomers believe that about one half of all stars that form, end up in binary star systems. That is, instead of a single star like the Sun, being orbited by planets, a pair of stars are formed that orbit around each other. Binary stars come in a great variety of sizes and shapes. Some stars orbit around each other very slowly, with periods exceeding a million years, while there is one binary system containing two white dwarfs (a white dwarf is the end product of the life of a star like the Sun) that has an orbital period of 5 minutes!

To get to the simulations for this part of the lab, exit the Third Law simulation (if you haven't already done so), and click on button "7", the "Two-Body and Many-Body" simulations. We will start with the "Double Star" simulation. Click Go.

In this simulation there are two stars in orbit around each other, a massive one (the blue one) and a less massive one (the red one). Note how the two stars move. Notice that the line connecting them at each point in the orbit passes through one spot–this is the location of something called the "center of mass". In Fig. 6.6 is a diagram explaining the center of mass. If you think of a teeter-totter, or a simple balance, the center of mass is the point where the balance between both sides occurs. If both objects have the same mass, this point is halfway between them. If one is more massive than the other, the center of mass/balance point is closer to the more massive object.

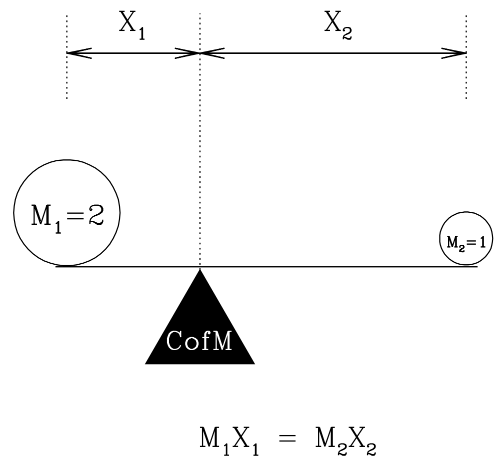


Figure 6.6: A diagram of the definition of the center of mass. Here, object one (M_1) is twice as massive as object two (M_2). Therefore, M_1 is closer to the center of mass than is M_2. In the case shown here, $X_2 = 2X_1$.

Most binary star systems have stars with similar masses ($M_1 \approx M_2$), but this is not always the case. In the first (default) binary star simulation, $M_1 = 2M_2$. The "mass ratio" ("q") in this case is 0.5, where mass ratio is defined to be $q = M_2/M_1$. Here, $M_2 = 1$, and $M_1 = 2$, so $q = M_2/M_1 = 1/2 = 0.5$. This is the number that appears in the "Mass Ratio" window of the simulation.

Exercise 5: Binary Star systems. We now want to set-up some special binary star orbits to help you visualize how gravity works. This requires us to access the "Input" window on the control bar of the simulation window to enter in data for each simulation. Clicking on Input brings up a menu with the following parameters: Mass Ratio, "Transverse Velocity", "Velocity (magnitude)", and "Direction". Use the slide bars (or type in the numbers) to set Transverse Velocity = 1.0, Velocity (magnitude) = 0.0, and Direction = 0.0. For now, we simply want to play with the mass ratio.

Use the slide bar so that Mass Ratio = 1.0. Click "Ok". This now sets up your new simulation. Click Run. Describe the simulation. What are the shapes of the two orbits? Where is the center of mass located relative to the orbits? What does q = 1.0 mean? Describe what is going on here. **(4 points)**

Ok, now we want to run a simulation where only the mass ratio is going to be changed. Go back to Input and enter in the correct mass ratio for a binary star system with $M_1 = 4.0$, and $M_2 = 1.0$. Run the simulation. Describe what is happening in this simulation. How are the stars located with respect to the center of mass? Why? [Hint: see Fig. 6.6.] **(4 points)**

Finally, we want to move away from circular orbits, and make the orbit as elliptical as possible. You may have noticed from the Kepler's law simulations that the Transverse Velocity affected whether the orbit was round or elliptical. When the Transverse Velocity = 1.0, the orbit is a circle. Transverse Velocity is simply how fast the planet in an elliptical orbit is moving *at perihelion* relative to a planet in a circular orbit of the same orbital period. The maximum this number can be is about 1.3. If it goes much faster, the ellipse then extends to infinity and the orbit becomes a parabola. Go back to Input and now set the Transverse Velocity = 1.3. Run the simulation. Describe what is happening. When do the stars move the fastest? The slowest? Does this make sense? Why/why not? **(4 points)**

The final exercise explores what it would be like to live on a planet in a binary star system–not so fun! In the "Two-Body and Many-Body" simulations window, click on the "Dbl. Star and a Planet" button. Here we simulate the motion of a planet going around the less massive star in a binary system. Click Go. Describe the simulation—what happened to the planet? Why do you think this happened? **(4 points)**

In this simulation, two more windows opened up to the right of the main one. These are what the simulation looks like if you were to sit on the surface of the two stars in the binary. For a while the planet orbits one star, and then goes away to orbit the other one, and then returns. So, sitting on these stars gives you a different viewpoint than sitting high above the orbit. Let's see if you can keep the planet from wandering away from its parent star. Click on the "Settings" window. As you can tell, now that we have three bodies in the system, there are lots of parameters to play with. But let's confine ourselves to two of them: "Ratio of Stars Masses" and "Planet–Star Distance". The first of these is simply the q we encountered above, while the second changes the size of the planet's orbit. The default values of both at the start-up are $q = 0.5$, and Planet–Star Distance = 0.24. Run simulations with $q = 0.4$ and 0.6. Compare them to the simulations with $q = 0.5$. What happens as q gets larger, and larger? What is increasing? How does this increase affect the force of gravity between the star and its planet? **(4 points)**

See if you can find the value of q at which larger values cause the planet to "stay home", while smaller values cause it to (eventually) crash into one of the stars (stepping up/down by 0.01 should be adequate). **(2 points)**

Ok, reset $q = 0.5$, and now let's adjust the Planet–Star Distance. In the Settings window, set the Planet–Star Distance = 0.1 and run a simulation. Note the outcome of this simulation. Now set Planet–Star Distance = 0.3. Run a simulation. What happened? Did the planet wander away from its parent star? Are you surprised? **(4 points)**

Astronomers call orbits where the planet stays home, "stable orbits". Obviously, when the Planet–Star Distance = 0.24, the orbit is unstable. The orbital parameters are just right that the gravity of the parent star is not able to hold on to the planet. But some orbits, even though the parent's hold on the planet is weaker, are stable–the force of gravity exerted by the two stars is balanced just right, and the planet can happily orbit around its parent and never leave. Over time, objects in unstable orbits are swept up by one of the two stars in the binary. This can even happen in the solar system. If you have done the comet lab, then you saw some images where a comet ran into Jupiter. The orbits of comets are very long ellipses, and when they come close to the Sun, their orbits can get changed by passing close to a major planet. The gravitational pull of the planet changes the shape of the comet's orbit, it speeds up, or slows down the comet. This can cause the comet to crash into the Sun, or into a planet, or cause it to be ejected completely out of the solar system. (You can see an example of the latter process by changing the Planet–Star Distance = 0.4 in the current simulation.)

6.5 Summary (35 points)

Please summarize the important concepts of this lab. Your summary 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.

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

6.6 Possible Quiz Questions

1) Briefly describe the contributions of the following people to understanding planetary motion: Tycho Brahe, Johannes Kepler, Isaac Newton.
2) What is an ellipse?
3) What is a "focus"?
4) What is a binary star?
5) Describe what is meant by an "inverse square law".
6) What is the definition of "semi-major axis"?

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

Derive Kepler's third law ($P^2 = C \times a^3$) for a circular orbit. First, what is the circumference of a circle of radius a? If a planet moves at a constant speed "v" in its orbit, how long does it take to go once around the circumference of a circular orbit of radius a? [This is simply the orbital period "P".] Write down the relationship that exists between the orbital period "P", and "a" and "v". Now, if we only knew what the velocity (v) for an orbiting planet was, we would have Kepler's third law. In fact, deriving the velocity of a planet in an orbit is quite simple with just a tiny bit of physics (go to this page to see how it is done: http://www.go.ednet.ns.ca/~larry/orbits/kepler.html). Here we will simply tell you that the speed of a planet in its orbit is $v = (\mathrm{GM}/a)^{1/2}$, where "G" is the gravitational constant mentioned earlier, "M" is the mass of the Sun, and a is the radius of the orbit. Rewrite your orbital period equation, substituting for v. Now, one side of this equation has a square root in it–get rid of this by squaring both sides of the equation and then simplifying the result. Did you get $P^2 = C \times a^3$? What does the constant "C" have to equal to get Kepler's third law?

Name:______________________________

Date:______________________________

7 The Orbit of Mercury

7.1 Introduction

Of the five planets known since ancient times (Mercury, Venus, Mars, Jupiter, and Saturn), Mercury is the most difficult to see. In fact, of the 7 billion people on the planet Earth it is likely that fewer than 1,000,000 (0.0002%) have *knowingly* seen the planet Mercury. The reason for this is that Mercury orbits very close to the Sun, about one third of the Earth's average distance. Therefore it is always located very near the Sun, and can only be seen for short intervals soon after sunset, or just before sunrise. It is a testament to how carefully the ancient peoples watched the sky that Mercury was known at least as far back as 3,000 BC. In Roman mythology Mercury was a son of Jupiter, and was the god of trade and commerce. He was also the messenger of the gods, being "fleet of foot", and commonly depicted as having winged sandals. Why this god was associated with the planet Mercury is obvious: Mercury moves very quickly in its orbit around the Sun, and is only visible for a very short time during each orbit. In fact, Mercury has the shortest orbital period ("year") of any of the planets. You will determine Mercury's orbital period in this lab. [Note: it is very helpful for this lab exercise to review Lab #1, subsection 1.3.]

- *Goals:* to learn about planetary orbits
- *Materials:* a protractor, a straight edge, a pencil and calculator

Mercury and Venus are called "inferior" planets because their orbits are interior to that of the Earth. While the planets Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto are called "superior" planets, as their orbits lie outside that of the Earth. Because the orbits of Mercury and Venus are smaller than the Earth's, these planets can never be located very far from the Sun as seen from the Earth. As discovered by Galileo in 1610 (see Fig. 7.1), the planet Venus shows phases that look just like those of the Moon. Mercury also shows these same phases. As can be envisioned from Figure 7.1, when Mercury or Venus are on the far side of the Sun from Earth (a configuration called "superior" conjunction), these two planets are seen as "full". Note, however, that it is almost impossible to see a "full" Mercury or Venus because at this time the planet is very close to, or behind the Sun. When Mercury or Venus are closest to the Earth, a time when they pass between the Earth and the Sun (a configuration termed "inferior" conjunction), we would see a "new" phase. During their new phases, it is also very difficult to see Mercury or Venus because their illuminated hemispheres are pointed away from us, and they are again located *very* close to the Sun in the sky.

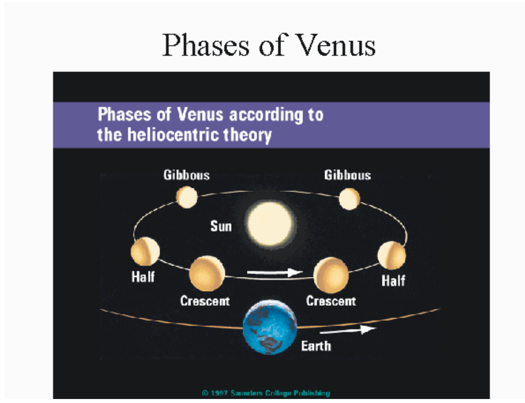


Figure 7.1: A diagram of the phases of Venus as it orbits around the Sun. The planet Mercury exhibits the same set of phases as it too is an "inferior" planet like Venus.

The best time to see Mercury is near the time of "greatest elongation". At the time of greatest elongation, the planet Mercury has its largest *angular* separation from the Sun as seen from the Earth. There are six or seven greatest elongations of Mercury each year. At the time of greatest elongation, Mercury can be located up to 28° from the Sun, and sets (or rises) about two hours after (or before) the Sun. In Figure 7.2, we show a diagram for the greatest elongation of Mercury that occurred on August 14, 2003. In this diagram, we plot the positions of Mercury and the Sun at the time of sunset (actually just a few minutes before sunset!). As this diagram shows, if we started our observations on July 24th, Mercury would be located close to the Sun at sunset. But as the weeks passed, the angle between Mercury and the Sun would increase until it reached its maximum value on August 14th. After this date, the separation between the Sun and Mercury quickly decreases as it heads towards inferior conjunction on September 11th.

You can see from Figure 7.2 that Mercury is following an orbit around the Sun: it was "behind" the Sun (superior conjunction) on July 5th, and quickly races around its orbit until the time of greatest elongation, and then passes between the Earth and the Sun on September 11th. If we used a telescope and made careful drawings of Mercury throughout this time, we would see the phases shown in Figure 7.3. On the first date in Figure 7.2 (July 24th), Mercury was still on the far side of the Sun from the Earth, and almost had a full phase (which it only truly has at the time of superior conjunction). The disk of Mercury on July 24th is very small because the planet is far away from the Earth. As time passes, however, the apparent size of the disk of Mercury grows in size, while the illuminated portion of the disk decreases. On August 14th, Mercury reaches greatest elongation, and the disk is half-illuminated. At this time it looks just like the first quarter Moon! As it continues to catch up with the Earth, the distance between the two planets shrinks, so the apparent size of Mercury continues to grow. As the angular separation between Mercury and the Sun shrinks, so does the amount of the illuminated hemisphere that we can see. Eventually Mercury becomes a crescent, and at inferior conjunction it becomes a "new" Mercury.

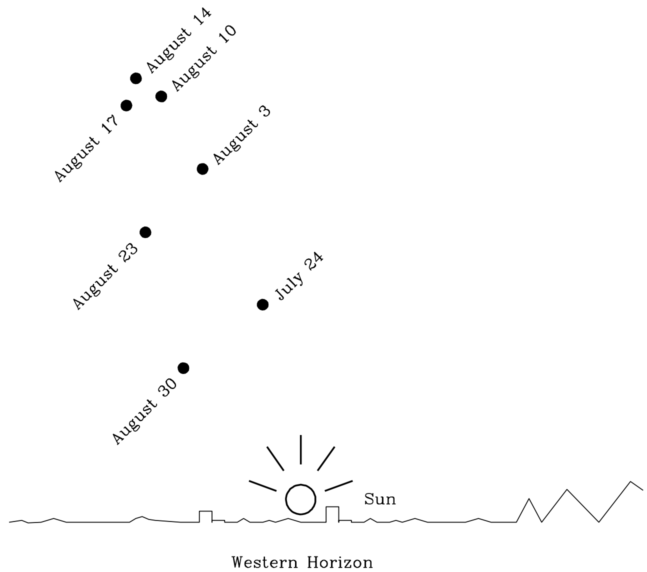


Figure 7.2: The eastern elongation of August, 2003. Mercury was at superior conjunction on July 5th, and quickly moved around its orbit increasing the angular separation between it and the Sun. By July 24th, Mercury could be seen just above the Sun shortly after sunset. As time passed, the angular separation between the Sun and Mercury increased, reaching its maximum value on August 14th, the time of greatest Eastern elongation. As Mercury continued in its orbit it comes closer to the Earth, but the angular separation between it and the Sun shrinks. Eventually, on September 11th, the time of inferior conjunction, Mercury passed directly between the Earth and the Sun.

7.1.1 Eastern and Western Elongations

The greatest elongation that occurred on August 14, 2003 was a "greatest Eastern elongation". Why? As you know, the Sun sets in the West each evening. When Mercury is visible *after* sunset it is located to the East of the Sun. It then sets in the West *after* the Sun has set. As you can imagine, however, the same type of geometry can occur in the morning sky. As Mercury passed through inferior conjunction on September 11th, it moved into the morning sky. Its angular separation from the Sun increased until it reached "greatest Western elongation" on September 27th, 2003. During this time, the phase of Mercury changed from "new" to "last quarter" (half). After September 27th the angular separation between the Sun and Mercury shrinks, as does the apparent size of the disk of Mercury, as it reverses the sequence shown in Figure 7.3. A diagram showing the geometry of eastern and western elongations is shown in Figure 7.4. [Another way of thinking about what each of these means, and

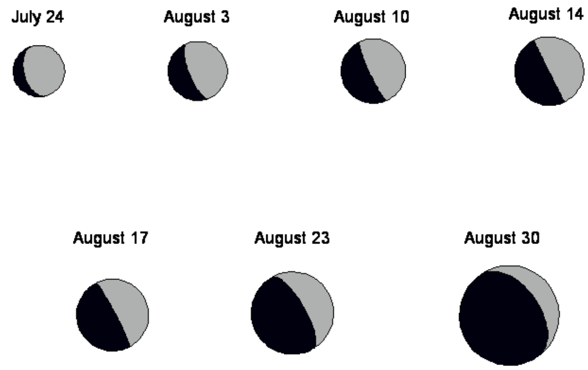


Figure 7.3: A diagram showing the actual appearance of Mercury during the August 2003 apparition. As Mercury comes around its orbit from superior conjunction (where it was "full"), it is far away from the Earth, so it appears small (as on July 24^{th}). As it approaches greatest elongation (August 14^{th}) it gets closer to the Earth, so its apparent size grows, but its phase declines to half (like a first quarter moon). Mercury continues to close its distance with the Earth so it continues to grow in size–but note that the illuminated portion of its disk shrinks, becoming a thin crescent on August 30^{th}. As Mercury passes between the Earth and Sun it is in its "new" phase, and is invisible.

an analogy that might come in useful when you begin plotting the orbit of Mercury, is to think about where Mercury is relative to the Sun at Noon. At Noon, the Sun is due south, and when facing the Sun, East is to the left, and West is to the right. Thus, during an Eastern elongation Mercury is to the left of the Sun, and during a Western elongation Mercury is to the right of the Sun (as seen in the Northern Hemisphere).]

7.1.2 Why Greatest Elongations are Special

We have just spent a lot of time describing the greatest elongations of Mercury. We did this because the time of greatest elongation is very special: it is the only time when we know where an inferior planet is in its orbit (except in the rare cases where the planet "transits" across the face of the Sun!). We show why this is true in the next figure. In this figure, we have represented the orbits of Mercury and the Earth as two circles (only about one fourth of the orbits are plotted). We have also plotted the positions of the Earth, the Sun, and Mercury. At the time of greatest elongation, the angle between the Earth, Mercury and the Sun is a right angle. If you were to plot Mercury at some other position in its orbit, the angle between the Earth, Mercury and the Sun would not be a right angle. Therefore, the times of greatest elongation are special, because at this time we know the exact angle between the Earth, Mercury, and the Sun. [You can also figure out from this diagram why Mercury has only

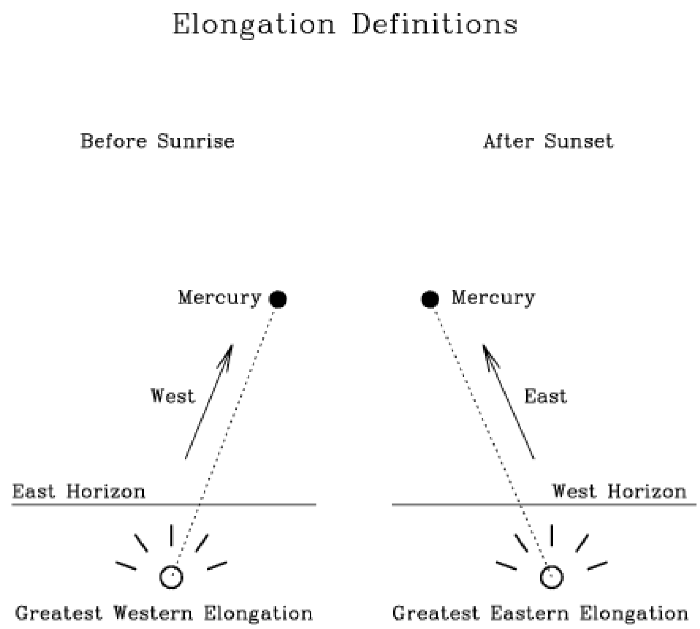


Figure 7.4: A diagram showing the geometry of greatest Western elongations (left side), and greatest Eastern elongations (right side). If you see Mercury–or any other star or planet–above the Western horizon after sunset, that object is located to the East of the Sun. The maximum angular separation between Mercury and the Sun at this time is called the greatest Eastern elongation. A greatest Western elongation occurs when Mercury is seen in the East *before* sunrise.

one-half of its disk illuminated (a phase of "first quarter").]

Of course, plotting only one elongation is not sufficient to figure out the orbit of Mercury–you need to plot many elongations. In today's lab exercise, you will plot thirteen greatest elongations of Mercury, and trace-out its orbit. There are a lot of angles in this lab, so you need to get comfortable with using a protractor. Your TA will help you figure this out. But the most critical aspect is to not confuse eastern and western elongations. Look at Figure 7.5 again. What kind of elongation is this? Well, as seen from the Earth, Mercury is to the left of the Sun. As described earlier (in the square brackets at the end of subsection 7.1.1), if Mercury is to the left of the Sun, it is an *eastern elongation*.

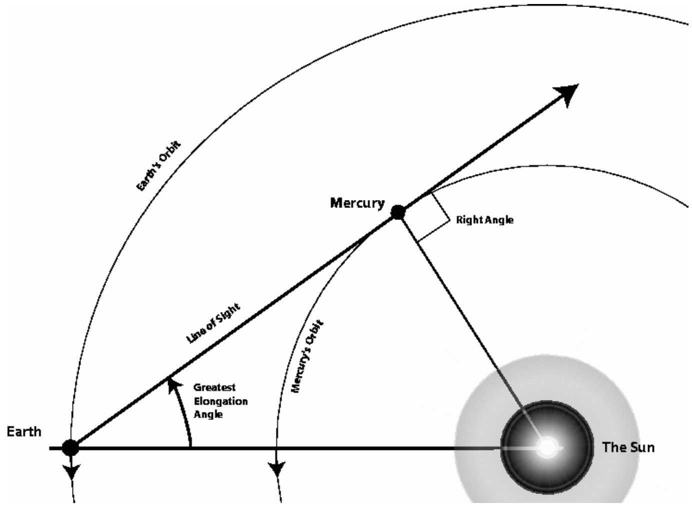


Figure 7.5: A diagram showing the orbital geometry of the Earth and Mercury during a greatest Eastern elongation. The orbits of the Earth and Mercury are the two large circles. The line of sight to Mercury at the time of greatest elongation is indicated. Note that at this time the angle between the Earth, Mercury, and the Sun is a *right* angle. The direction of motion of the two planets is shown by the arrows on the orbits.

7.2 The Orbits of Earth and Mercury

As shown in the previous diagram, both the Earth and Mercury are orbiting the Sun. That means that every single day they are at a different position in their orbits. Before we can begin this lab, we must talk about how we can account for this motion! A year on Earth, the time it takes the Earth to complete one orbit around the Sun, is 365 days. If we assume that the Earth's orbit is a perfect circle, then the Earth moves on that circle by about 1 degree per day. Remember that a circle contains 360 degrees (360°). If it takes 365 days to go 360°, the Earth moves 360°/365 = 0.986 degrees per day (°/day). For this lab, we will assume that the Earth moves exactly one degree per day which, you can see, is very close to the truth. How far does the Earth move in 90 days? 90 degrees! How about 165 days?

7.2.1 The Data

In Table 7.1, we have listed the thirteen dates of the greatest elongations of Mercury, as well as the angle of each greatest elongation. **Note that the elongations are either East or West!** In the third column, we have listed something called the Julian date. Over long time intervals, our common calendar is very hard to use to figure out how much time has elapsed. For example, how many days are there between March 13^{th}, 2001 and December 17^{th} 2004? Remember that 2004 is a leap year! This is difficult to do in your head. To avoid such calculations, astronomers have used a calendar that simply counts the days that have passed since some distant day #1. The system used by astronomers sets Julian date 1 to January 1st, 4713 BC (an arbitrary date chosen in the sixteenth century). Using this calendar, March 13th, 2001 has a Julian date of 2451981. While December 17th 2004 has a Julian date of 2453356. Taking the difference of these two numbers (2453356 − 2451981) we find that there are 1,375 days between March 13th, 2001 and December 17th 2004.

Exercise #1: Fill-in the Data Table
The fourth and fifth columns of the table are blank, and must be filled-in by you. The fourth column is the number of days that have elapsed between elongations in this table (that is, simply subtract the Julian date of the previous elongation from the *following* elongation). We have worked the first one of these for you as an example. The last column lists how far the Earth has moved in degrees. This is simply the number of days times the number 1.0! As the Earth moves one degree per day. (If you wish, instead of using 1.0, you could multiply this number by 0.986 to be more accurate. You will get better results doing it that way.) So, if there are 42 days between elongations, the Earth moves 42 degrees in its orbit (or 41.4 degrees using the correct value of 0.986 °/day). (**10 points**)

Table 7.1: Elongation Data For Mercury

#	Date	Elongation Angle	Julian Date	Days	Degrees
#1	Sep. 1, 2002	27.2 degrees east	2452518	–	–
#2	Oct. 13, 2002	18.1 degrees west	2452560	42	42
#3	Dec. 26, 2002	19.9 degrees east	2452634		
#4	Feb. 4, 2003	25.4 degrees west	2452674		
#5	Apr. 16, 2003	19.8 degrees east	2452745		
#6	Jun. 3, 2003	24.4 degrees west	2452793		
#7	Aug. 14, 2003	27.4 degrees east	2452865		
#8	Sep. 27, 2003	17.9 degrees west	2452909		
#9	Dec. 09, 2003	20.9 degrees east	2452982		
#10	Jan. 17, 2004	23.9 degrees west	2453021		
#11	Mar. 29, 2004	18.8 degrees east	2453093		
#12	May 14, 2004	26.0 degrees west	2453139		
#13	Jul. 27, 2004	27.1 degrees east	2453213		

Exercise #2: Plotting your data.
Before we describe the plotting process, go back and review Figure 7.5. Unlike that diagram, you do not know what the orbit of Mercury looks like–this is what you are going to figure out during this lab! But we do know two things: the first is that the Earth's orbit is nearly a perfect circle, and two, that the Sun sits at the exact center of this circle. On the next page is a figure containing a large circle with a dot drawn at the center to represent the Sun. At one position on the large circle we have put a

little "X" as a reference point. The large circle here is meant to represent the Earth's orbit, and the "X" is simply a good starting point.

To plot the first elongation of Mercury from our data table, using a pencil, draw a line connecting the X, and the Sun using a straight edge (ruler or protractor). The first elongation in the table (September 1, 2002) is 27.2 degrees East. Using your protractor, put the "X" that marks the Earth's location at the center hole/dot on your protractor. Looking back to Figure 7.5, that elongation was also an *eastern* elongation. So, using that diagram as a guide, measure an angle of 27.2 degrees on your protractor and put a small mark on the worksheet. Now, draw a line from the Earth's location through this mark just like the "line of sight" arrow in Figure 7.5. Now, rotate your protractor so that the 90 degree mark is on this line and towards the position of the Earth, while the reference hole/dot is on the same line. Slide the protractor along the line until the 0° (or 180°) reference line intersects the center of the Sun. Mark this spot with a dark circle. This is the position of Mercury!

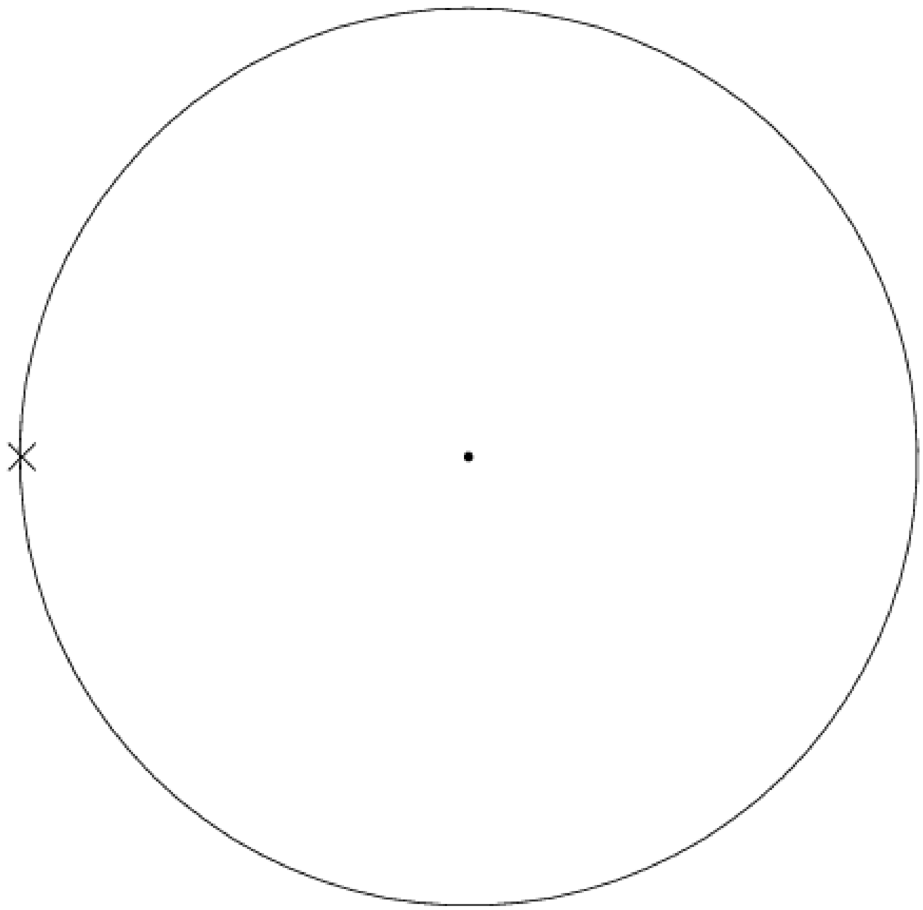
This is the procedure that you will use for all of the elongations, so if this is confusing to you, have your TA come over and clarify the technique for you so that you don't get lost and waste time doing this incorrectly.

Ok, now things become slightly more difficult—the Earth moves! Looking back to Figure 7.5, note the arrows on the orbits of Earth and Mercury. This is the direction that both planets are moving in their orbits. For the second elongation, the Earth has moved 42 degrees. We have to locate where the Earth is in its orbit before we can plot the next elongation. So, now put the center hole/dot of your protractor on the Sun. Line up the 0/180 degree mark with the first line that connected the Earth and Sun. Measure an angle of 42 degrees (in the correct direction) and put a small mark. Draw a line through this mark that intersects the position of the Sun, the mark, and the orbit of the Earth. Put an X where this line intersects the Earth's orbit. This is the spot from where you will plot the next elongation of Mercury.

Now, repeat the process for plotting this next elongation angle. Note, however, that this elongation is a western elongation, so that the line of sight arrow this time will be to the right of the Sun. It is extremely important to remember that on eastern elongations the line of sight arrow to Mercury goes to the left of the Sun, while during western elongations it goes to the right of the Sun.

[Hints: It is helpful to label each one of the X's you place on the Earth's orbit with the elongation number from Table 7.1. This will allow you to go back and fix any problems you might find. Note that you will have a large number of lines drawn in this plot by the time you get finished. Use a sharp pencil so that you can erase some/all/pieces of these lines to help clean-up the plot and reduce congestion. You might also find it helpful to simply put a "left" or a "right" each time you encounter East and West in Table 7.1 to insure you plot your data correctly.]

Now, plot all of the data (28 points)!



Exercise #3: Connecting the dots.
Note that planets move on smooth, almost circular paths around the Sun. So try to connect the various positions of Mercury with a smooth arc. Do all of your points fit on this closed curve? If not, identify the bad points and go back and see what you did wrong. Correct any bad elongations.

1) Is Mercury's orbit circular? Describe its shape. (**5 points**)

Exercise #4: Finding the *semi-major axis* of Mercury's orbit.
Using a ruler, find the position on Mercury's orbit that is closest to the Sun ("perihelion") and mark this spot with an "X". Now find the point on the orbit of Mercury that is furthest from the Sun ("aphelion") and mark it with an "X". Draw a line that goes through the Sun that comes closest to connecting these two positions–note that it is likely that these two points will not lie on a line that intercepts the Sun. *Just attempt to draw the best possible line connecting these two points that passes through the Sun.*

2) Measure the length of this line. Astronomers call this line the major axis of the planet's orbit. Divide the length you have just measured by two, to get the "semi-major" axis of Mercury's orbit: ______________ (mm). Measure the diameter of the Earth's orbit and divide that number by two to get the Earth's semi-major axis: ______________ (mm).

Divide the semi-major axis of Mercury by that of the Earth: ____________ AU. Since the semi-major axis of the Earth's orbit is defined to be "one astronomical unit", this ratio tells us the size of Mercury's semi-major axis in astronomical units (AU). (**5 points**)

3) As you have probably heard in class, the fact that the orbits of the planet's are ellipses, and not circles, was discovered by Kepler in about 1614. Mercury and Pluto have the most unusual orbits in the solar system in that they are the most non-circular. Going back to the line you drew that went through the Sun and that connected the points of perihelion and aphelion, measure the lengths of the two line segments:

Perihelion (p) = ________________ mm. Aphelion (q) = ________________ mm.

Astronomers use the term *eccentricity* ("e") to measure how out-of-round a planet's orbit is, and the eccentricity is defined by the equation:

e = (q − p)/(p + q) = ________________

Plug your values into this equation and calculate the eccentricity of Mercury's orbit. (**5 points**)

4) The eccentricity for the Earth's orbit is e = 0.017. How does your value of the eccentricity for Mercury compare to that of the Earth? Does the fact that we used a circle for the Earth's orbit now seem justifiable? (**5 points**)

Exercise #5: The orbital period of Mercury. Looking at the positions of Mercury at elongation #1, and its position at elongation #2, approximately how far around the orbit did Mercury move in these 42 days? Estimate how long you think it would take Mercury to complete one orbit around the Sun: ________________ days. **(2 points)**

Using Kepler's laws, we can estimate the orbital period of a planet (for a review of Kepler's laws, see lab #5). Kepler's third law says that the orbital period squared (P^2) is proportional to the cube of the semi-major axis (a^3): $P^2 \propto a^3$. This is a type of equation you might not remember how to solve (if you have not done so already, review Lab #1, subsection 1.3). But let's take it in pieces:

$a^3 = a \times a \times a =$ ________________

Plug-in your value of a for Mercury and find its cube.

To find the period of Mercury's orbit, we now need to take the square root of the number you just calculated (see your TA if you do not know whether your calculator can perform this operation). (**3 points**)

$$P = \sqrt{a^3} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_. \tag{8}$$

Now, the number you just calculated probably means nothing to you. But what you have done is calculate Mercury's orbital period as a fraction of the Earth's orbital period (that is because we have been working in AU, a unit that is defined by the Earth-Sun distance). Since the Earth's orbital period is exactly 365.25 days, find Mercury's orbital period by multiplying the number you just calculated for Mercury by 365.25:

P_{orb}(Mercury) = ________________ days.

5) How does the orbital period you just calculated using Kepler's laws compare to the one you estimated from your plot at the beginning of this exercise? (**2 points**)

7.3 Summary (35 points)

Before you leave lab, your TA will give you the real orbital period of Mercury, as well as its true semi-major axis (in AU) and its orbital eccentricity.

- Compare the precisely known values for Mercury's orbit with the ones you derived. How well did you do?
- What would be required to enable you to do a better job?
- Describe how you might go about making the observations on your own so that you could create a data table like the one in this lab. Do you think this could be done with just the naked eye and some sort of instrument that measured angular separation? What else might be necessary?

7.4 Possible Quiz Questions

- What does the term "inferior planet" mean?
- What is meant by elongation angle?
- Why do Mercury and Venus show phases like the Moon?

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

In this lab you have measured three of the five quantities that completely define a planet's orbit. The other two quantities are the orbital inclination, and the longitude of perihelion. Determining the orbital inclination, the tilt of the plane of Mercury's orbit with respect to the Earth's orbit, is not possible using the data in this lab. But it is possible to determine the longitude of perihelion. Astronomers define the zero point of solar system longitude as the point in the Earth's orbit at the time of the Vernal Equinox (the beginning of Spring in the northern hemisphere). In 2004, the Vernal Equinox occurred on March 20. If you notice, one of the elongations in the table (#11) occurs close to this date. Thus, you can figure out the true location of the Vernal Equinox by moving back from position #11 by the right number of degrees. The longitude of Mercury's perihelion is just the angle measured counterclockwise from the Earth's vernal equinox. You should find that your angle is larger than 180 degrees. Subtract off 180 degrees. How does your value compare with the precise value of 77°?

Name:______________________________

Date:______________________________

8 Measuring Distances Using Parallax

8.1 Introduction

How do astronomers know how far away a star or galaxy is? Determining the distances to the objects they study is one of the the most difficult tasks facing astronomers. Since astronomers cannot simply take out a ruler and measure the distance to any object, they have to use other methods. Inside the solar system, astronomers can simply bounce a radar signal off of a planet, asteroid or comet to directly measure the distance to that object (since radar is an electromagnetic wave, it travels at the speed of light, so you know how fast the signal travels–you just have to count how long it takes to return and you can measure the object's distance). But, as you will find out in your lecture sessions, some stars are hundreds, thousands or even tens of thousands of "light years" away. A light year is how far light travels in a single year (about 9.5 trillion kilometers). To bounce a radar signal of a star that is 100 light years away would require you to wait 200 years to get a signal back (remember the signal has to go out, bounce off the target, and come back). Obviously, radar is not a feasible method for determining how far away stars are.

In fact, there is one, and only one direct method to measure the distance to a star: "parallax". Parallax is the angle that something appears to move when the observer looking at that object changes their position. By observing the size of this angle and knowing how far the observer has moved, one can determine the distance to the object. Today you will experiment with parallax, and appreciate the small angles that astronomers must measure to determine the distances to stars.

To introduce you to parallax, perform the following simple experiment:

Hold your thumb out in front of you at arm's length and look at it with your left eye closed. Now look at it with your right eye closed. As you look at your thumb, alternate which eye you close several times. You should see your thumb move relative to things in the background. Your thumb is not moving but your point of view is moving, so your thumb *appears* to move.

- *Goals:* to discuss the theory and practice of using parallax to find the distances to nearby stars, and use it to measure the distance to objects in the classroom
- *Materials:* classroom "ruler", worksheets, ruler, protractor, calculator, small object

8.2 Parallax in the classroom

The "classroom parallax ruler" will be installed/projected on one side of the classroom. For the first part of this lab you will be measuring motions against this ruler.

Now work in groups: have one person stand at one wall and have the others stand somewhere in between along the line that goes straight to the other wall, and hold up a skewer or a pencil at the right height so the observer (person against the wall) can see it against the background ruler. The observer should blink his/her eyes and measure the number of lines on the background ruler against which the object appears to move. **Note that you can estimate the motion measurement to a fraction of tick mark, e.g., your measurement might be 2 1/2 tick marks).** Do this for three different distances, with the closest being within a few feet of the observer, and the furthest being at most half the classroom away. Leave the object (or a mark) where the object was located each of the three times, so you can go back later and measure the distances. Switch places and do it again. Each person should estimate the motion for each of the three distances.

How many tick marks did the object move at the closest distance? **(2 points)**:

How many tick marks did the object move at the middle distance? **(2 points)**:

How many tick marks did the object move at the farthest distance? **(2 points)**:

What is your estimate of the *uncertainty* in your measurement of the apparent motion? For example, do you think your recorded measurements could be off by half a tick mark? a quarter of a tick mark? You might wish to make the measurement several times to get some estimate of the reliability of your measurements. **(2 points)**

The apparent motion of the person against the background ruler is what we are calling parallax. It is caused by looking at an object from two different vantage points, in this case, the difference in the location of your two eyes. Qualitatively, what do you see? As the object gets farther away, is the apparent motion smaller or larger?

What if the vantage points are further apart? For example, imagine you had a huge head and your eyes were a foot apart rather than several inches apart. What would you predict for the apparent motion? Try the experiment again, this time using the object at one of the distances used above, but now measuring the apparent motion by using just one eye, but moving your whole head a few feet from side to side to get more widely separated vantage points.

How many tick marks did the person move from the more widely separated vantage points? ________________________

For an object at a fixed distance, how does the apparent motion change as you observe from more widely separated vantage points?

8.3 Measuring distances using parallax

We have seen that the apparent motion depends on both the distance to an object and also on the separation of the two vantage points. We can then turn this around: if we can measure the apparent motion and also the separation of the two vantage points, we should be able to infer the distance to an object. This is very handy: it provides a way of measuring a distance without actually having to go to an object. Since we can't travel to them, this provides the only direct measurement of the distances to stars.

We will now see how parallax can be used to **determine the distances to the objects you looked at** just based on your measurements of their apparent motions and a measurement of the separation of your two vantage points (your two eyes).

8.3.1 Angular motion of an object

How can we measure the apparent motion of an object? As with our background ruler, we can measure the motion as it appears against a background object. But what are the appropriate units to use for such a measurement? Although we can measure how far apart the lines are on our background ruler, the apparent motion is not really properly measured in a unit of length; if we had put our parallax ruler further away, the apparent motion would have been the same, but the number of tick marks it moved would have been larger.

The apparent motion is really an *angular* motion. As such, it can be measured in *degrees*, with 360 degrees in a circle.

Figure out the angular separation of the tick marks on the ruler as seen from the opposite side of the classroom. Do this by putting one eye at the origin of one of the tripod-mounted protractors and measuring the angle from one end of the background ruler to the other end of the ruler. You might lay a pencil from your eye at the origin of the protractor toward each end and use this to measure the the total angle. Divide this angle by the total number of tick marks to figure out the angle for each tick mark.

Number of degrees for the entire background ruler: ________________________

Number of tick marks in the whole ruler: ________________________

Number of degrees in each tick mark: ________________________

Convert your measurements of apparent motion in tick marks above to angular measurements by multiplying the number of tick marks by the number of degrees per tick mark:

How many degrees did the object appear to move at the closest distance? **(2 points)**:

How many degrees did the object appear to move at the middle distance? **(2 points)**:

How many degrees did the object appear to move at the farthest distance? **(2 points)**:

Based on your estimate of the uncertainty in the number of tick marks each object moved, what is your estimate of the uncertainty in the number of degrees that each object moved? **(2 points)**

8.3.2 Distance between the vantage points

Now you need to measure the distance between the two different vantage points, in this case, the distance between your two eyes. Have your partner measure this with a ruler. Since you see out of the pupil part of your eyes, you want to measure the distance between the centers of your two pupils.

What is the distance between your eyes? **(2 points)**________________________

8.3.3 Using parallax measurements to determine the distance to an object

To determine the distance to an object for which you have a parallax measurement, you can construct an imaginary triangle between the two different vantage points and the object, as shown in Figure 8.1.

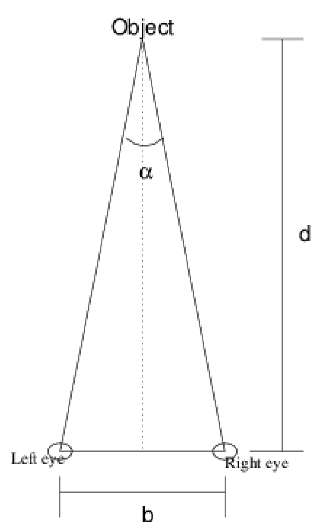


Figure 8.1: Parallax triangle

The angles you have measured correspond to the angle α on the diagram, and the distance between the vantage points (your pupils) corresponds to the distance b on the diagram. The distance to the object, which is what you want to figure out, is d.

The three quantities b, d, and α are related by a trigonometric function called the *tangent*. Now, you may have never heard of a *tangent*, if so don't worry–we will show you how to do this using another easy (but less accurate) way! But for those of you who are familiar with a little basic trigonometry, here is how you find the distance to an object using parallax: If you split your triangle in half (dotted line), then the tangent of $(\alpha/2)$ is equal to the quantity $(b/2)/d$:

$$\tan\left(\frac{\alpha}{2}\right) = \frac{(b/2)}{d}$$

Rearranging the equation gives:

$$d = \frac{(b/2)}{\tan(\alpha/2)}$$

You can determine the tangent of an angle using your calculator by entering the angle and then hitting the button marked *tan*. There are several other units for measuring angles besides degrees (for example, radians), so you have to **make sure that your calculator is set up to use degrees** for angles before you use the tangent function.

The "Non-Tangent" way to figure out distances from angles

Because the angles in astronomical parallax measurement are very small, astronomers do not have to use the *tangent* function to determine distances from angles–they use something called the "small angle approximation formula":

$$\frac{\theta}{57.3} = \frac{(b/2)}{d}$$

In this equation, we have defined $\theta = \alpha/2$, where α is the same angle as in the earlier equations (and in Fig. 8.1). Rearranging the equation gives:

$$d = \frac{57.3 \times (b/2)}{\theta}$$

To use this equation your parallax angle "θ" has to be in degrees. (If you are interested in where this equation comes from, talk to your TA, or look up the definition of "radian" and "small angle formula" on the web.) Now you can proceed to the next step!

Combine your measurements of angular distances and the distance between the vantage points to determine the three different distances to your partner. The units of the distances which you determine will be the same as the units you used to measure the distance between your eyes; if you measured that in inches, then the derived distances will be in inches.

Distance when object was at closest distance: **(2 points)**________________________

Distance when object was at middle distance: **(2 points)**________________________

Distance when object was at farthest distance: **(2 points)**________________________

Based on your estimate of the uncertainty in the angular measurements and also on the uncertainty of your measurement of the separation of your eyes, estimate the uncertainty in your measurements of the distances to the objects. To do so, you might wish to redo the calculation allowing each of your measurements to change by your estimated errors. **(2 points)**

Now go and measure the actual distances to the locations of the objects using a yardstick, meterstick, or tape measure. How well did the parallax distances work? Are the differences between the actual measurements and your parallax measurements within your estimated errors? If not, can you think of any reasons why your measurements might have some additional error in them? **(5 points)**

8.4 Using Parallax to measure distances on Earth, and within the Solar System

We just demonstrated how parallax works in the classroom, now lets move to a larger scale then the classroom. *Using the small angle formula*, and your eyes, what would be the parallax angle (in degrees) for Organ Summit, the highest peak in the Organ mountains, if the Organ Summit is located 12 miles (or 20 km) from this classroom?

[Hint: there are 5280 feet in a mile, and 12 inches in a foot. There are 1,000 meters in a km.]: **(2 points)**

You should have gotten a tiny angle! The smallest angle that the best human eyes can resolve is about 0.02 degrees. Obviously, our eyes provide an inadequate baseline for measuring this large of a distance. How can we get a bigger baseline? Well surveyors use a "transit" to carefully measure angles to a distant object. A transit is basically a small telescope mounted on a (fancy!) protractor. By locating the transit at two different spots separated by 100 yards (and carefully measuring this baseline!), they can get a much larger parallax angle, and thus it is fairly easy to measure the distances to faraway trees, mountains, buildings or other large objects.

How about an object in the Solar System? We will use Mars, the planet that comes closest to Earth. At favorable oppositions, Mars gets to within about 0.4 AU of the Earth. Remember, 1 AU is the average distance between the Earth and Sun: 149,600,000 km. Calculate the parallax angle for Mars (using the small angle approximation) using a baseline of 1000 km. **(2 points)**

Ouch! Also a very small angle.

8.5 Distances to stars using parallax, and the "Parsec"

Because stars are very far away, the parallax motion will be very small. For example, the nearest star is about 1.9×10^{13} miles or 1.2×10^{18} inches away! At such a tremendous distance, the apparent angular motion is very small. Considering the two vantage points of your two eyes, the angular motion of the nearest star corresponds to the apparent diameter of a human hair seen at the distance of the Sun! This is a truly tiny angle and totally unmeasurable by your eye.

Like a surveyor, we can improve our situation by using two more widely separated vantage points. The two points farthest apart we can use from Earth is to use two opposite points in the Earth's orbit about the Sun. In other words, we need to observe a star at two different times separated by six months. The distance between our two vantage points, b, will then be twice the distance between the Earth and the Sun: "2 AU". Figure 8.2 shows the idea.

Using 299.2 million km as the distance b, we find that the apparent angular motion

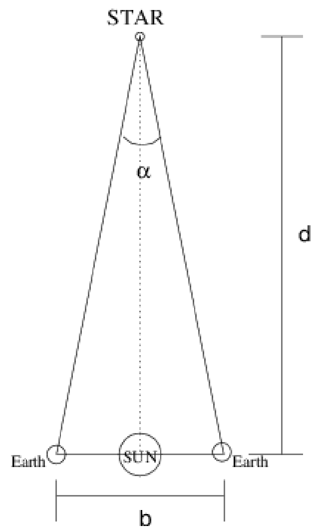


Figure 8.2: Parallax Method for Distance to a Star

(α) of even the nearest star is only about 0.0004 degrees. This is also unobservable using your naked eye, which is why we cannot directly observe parallax by looking at stars with our naked eye. However, this angle is relatively easy to measure using modern telescopes and instruments.

Time to talk about a new distance unit, the "Parsec". Before we do so, we have to review the idea of smaller angles than degrees. Your TA or professor might already have mentioned that a degree can be broken into 60 arcminutes. Thus, instead of saying the parallax angle is 0.02 degrees, we can say it is 1.2 arcminutes. But note that the nearest star only has a parallax angle of 0.024 arcminutes. We need to switch to a smaller unit to keep from having to use scientific notation: the arcsecond. There are 60 arcseconds in an arcminute, thus the parallax angle (α) for the nearest star is 1.44 arcseconds. To denote arcseconds astronomers append a single quotation mark (") at the end of the parallax angle, thus α = 1.44" for the nearest star. But remember, in converting an angle into a distance (using the tangent or small angle approximation) we used the angle $\alpha/2$. So when astronomers talk about the parallax of a star they use this angle, $\alpha/2$, which we called "θ" in the small angle approximation equation.

How far away is a star that has a parallax angle of θ = 1"? The answer is 3.26 light years, and this distance is defined to be "1 Parsec". The word Parsec comes from **Par**allax **Sec**ond. An object at 1 Parsec has a parallax of 1". An object at 10 Parsecs has a parallax angle of 0.1". Remember, the further away an object is, the smaller the parallax angle. The nearest star (Alpha Centauri) has a parallax of θ = 0.78", and is thus at a distance of $1/\theta = 1/0.78 = 1.3$ Parsecs. Depending on your professor, you might hear the words Parsec, kiloparsec, Megaparsec and even Gigaparsec in your lecture classes. These are just shorthand methods of talking about distances in astronomy. A kiloparsec is 1,000 Parsecs, or 3,260 light years. A Megaparsec is one million parsecs, and a Gigaparsec is one billion parsecs. To convert to light years, you simply have to multiply by 3.26. The Parsec is a strange unit, but you have already encountered other strange units this semester!

Let's work some examples:

- If a star has a parallax angle of $\theta = 0.25$", what is its distance in Parsecs? **(1 point)**

- If a star is at a distance of 5 Parsecs, what is its parallax angle? **(1 point)**

- If a star is at a distance of 5 Parsecs, how many light years away is it? **(1 point)**

8.6 Questions

1. How does the parallax angle change as an object is moved further away? Given that you can usually only measure an angular motion to some accuracy, would it be easier to measure the distance to a nearby star or a more distant star? Why? **(4 points)**

2. Relate the experiment you did in lab to the way parallax is used to measure the distances to nearby stars in astronomy. Describe the process an astronomer has to go through in order to determine the distance to a star using the parallax

method. What do your two eyes represent in that experiment? **(5 points)**

3. Imagine that you observe a star field twice one year, separated by six months and observe the configurations of stars shown in Figure 8.3:

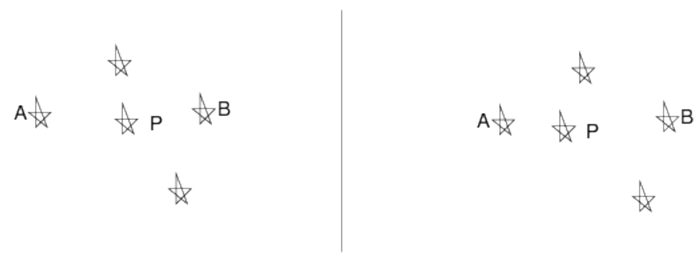


Figure 8.3: Star field seen at two times of year six months apart.

The star marked P appears to move between your two observations because of parallax. So you can consider the two pictures to be like our lab experiment where the left picture is what is seen by one eye and the right picture what is seen by the other eye. All the stars except star P do not appear to change position; they correspond to the background ruler in our lab experiment. If the angular distance between stars A and B is 0.5 arcminutes (remember, 60 arcminutes = 1 degree), then how far away would you estimate that star P is? Proceed by estimating the amount that star P moves between the two pictures relative to the distance between stars A and B. This gives you the apparent angular motion. You also know the distance between the two vantage points (which is the Earth at two opposite sides of its orbit) from the number given above). You can then use the parallax equation to estimate the distance to star P. **(11 points)**

4. Imagine that you did the classroom experiment by putting your partner all the way against the far wall. How big would the apparent motion be relative to the tick marks? What would you infer about the distance to your partner? Why do you think this estimate is incorrect? What can you infer about where the background objects in a parallax experiment need to be located? **(7 points)**

8.7 Summary (35 points)

Please summarize the important concepts discussed in this lab. Your summary should include:

- A brief description on the basic principles of parallax and how astronomers can use parallax to determine the distance to nearby stars

Also think about and answer the following questions:

- Does the parallax method work for all stars we can see in our Galaxy and why?
- Why do you think it is important for astronomers to determine the distances to the stars which they study?

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

8.8 Possible Quiz Questions

1) How do astronomers measure distances to stars?
2) How can astronomers measure distances inside the Solar System?
3) What is an Astronomical Unit?
4) What is an arcminute?
5) What is a Parsec?

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

Use the web to find out about the planned GAIA Mission. What are the goals of GAIA? How accurately can it measure a parallax? Discuss the units of milliarcseconds ("mas") and microarcseconds. How much better is GAIA than the best ground-based parallax measurement programs?

Name:____________________________

Date:____________________________

9 Optics

9.1 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

9.2 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 9.1 since they relate to the reflective (mirrors) and refractive (lenses) optics which will be discussed in this lab.

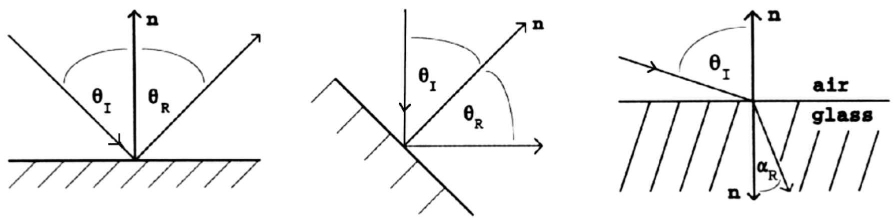


Fig 1a.   Fig 1b.   Fig 1c.

Figure 9.1: 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

9.3 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 9.1: Data Table

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

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 90^o corresponds to the "normal" defined above (see Fig. 9.1a). Fill in Table 9.1 with the data for angle of incidence vs. angle of reflection. (**3 pts**)

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**:

$$\text{angle of incidence} = \text{angle of reflection}$$

$$\theta_I = \theta_R$$

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! 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.

1) 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 9.4). (**5 pts**)

2) 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**)

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**):

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!

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

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**):

9.4 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 or transformer using the alligator clips (be careful not to let the alligator clips touch each other or else the transformer will be damaged). 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!). 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**)

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":

$$\frac{1}{F} = \frac{1}{a} + \frac{1}{b} \tag{9}$$

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

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**)

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 9.5. Note some similarities and differences between what you have drawn in Fig. 9.4, and what you drew in Fig. 9.5 and write them in the space below. (**5 pts**)

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. 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**)

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

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

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:

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

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**):

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**):

9.5.1 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:

$$M = \frac{F}{f} \tag{10}$$

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*:

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:

$$M = \frac{F}{f} \tag{11}$$

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 9.2 and Figure 9.3, 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).

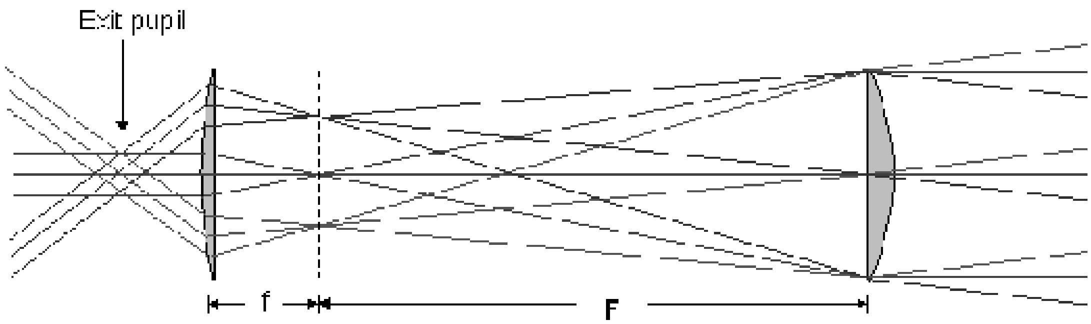


Figure 9.2: The ray diagram for Kepler's telescope.

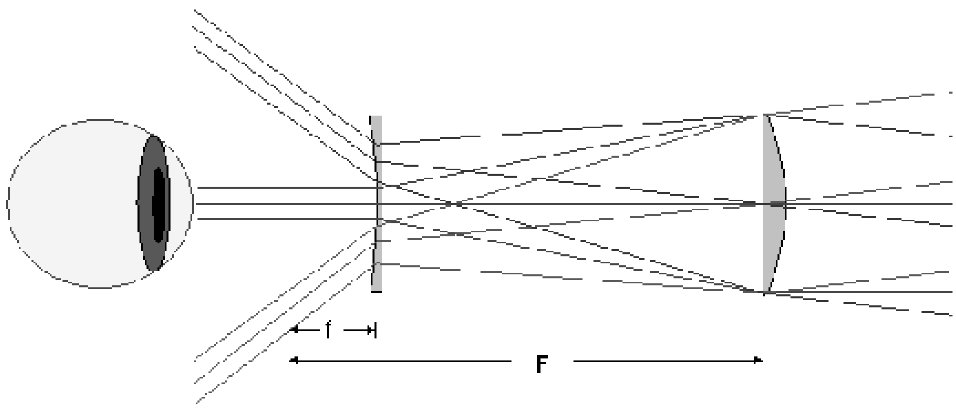


Figure 9.3: The ray diagram for Galileo's telescope.

Ok, now look at Figure 9.3. 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).

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

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$^{\mathrm{th}}$ century. Thus, the simple telescopes you have constructed today are much better than what Galileo used!

9.6 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.

9.7 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?

9.8 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?

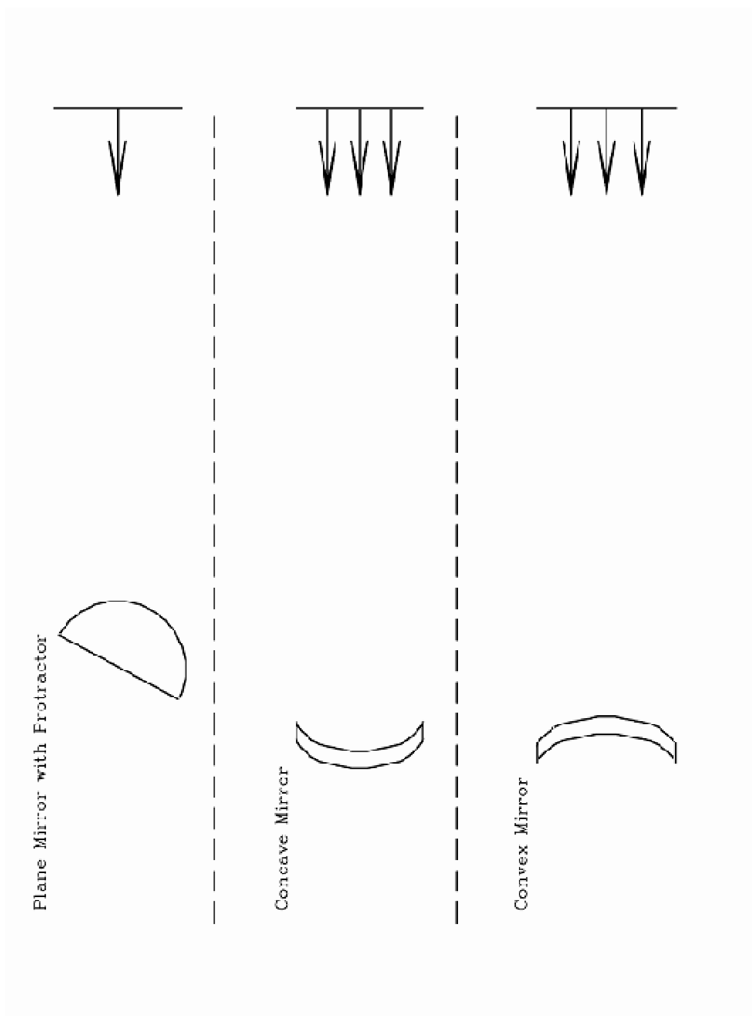


Figure 9.4: The worksheet needed in subsection 2

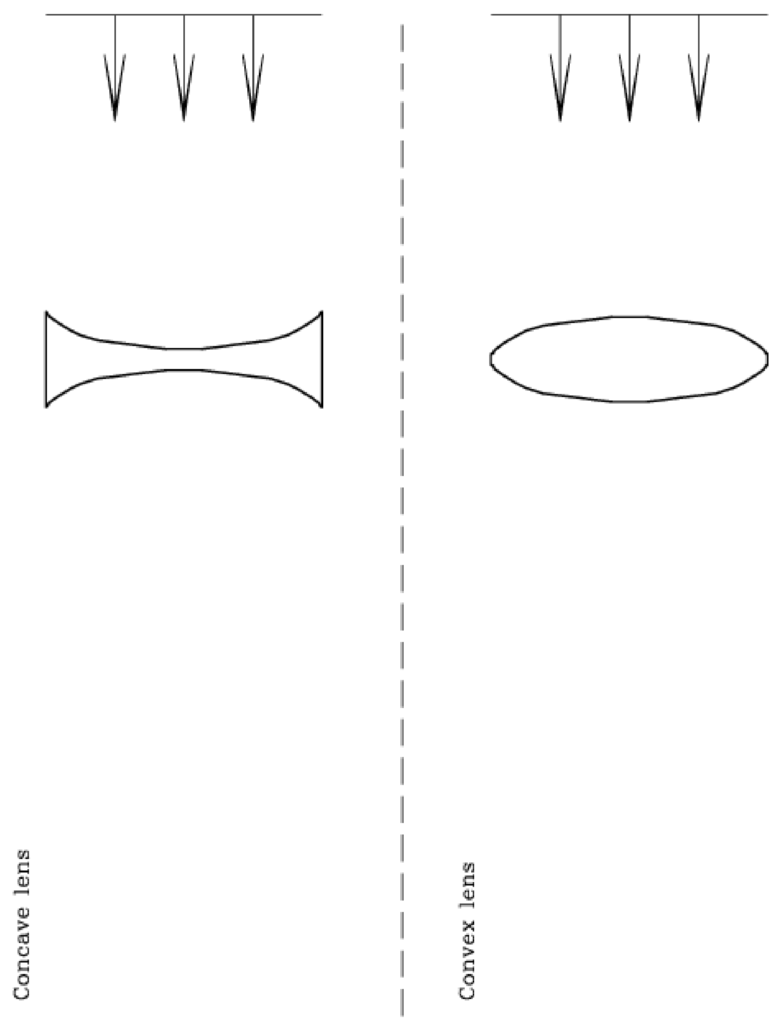


Figure 9.5: The worksheet needed in subsection 3. The positive lenses used in this lab are "double convex" lenses, while the negative lens is a "double concave" lens.

Name:__________________________

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10 The Power of Light: Understanding Spectroscopy

10.1 Introduction

For most celestial objects, light is the astronomer's only subject for study. Light from celestial objects is packed with amazingly large amounts of information. Studying the distribution of brightness for each wavelength (color) which makes up the light provides the temperature of a source. A simple example of this comes from flame color comparison. Think of the color of a flame from a candle (yellow) and a flame from a chemistry class Bunson burner (blue). Which is hotter? The flame from the Bunson burner is hotter. By observing which color is dominant in the flame, we can determine which flame is hotter or cooler. The same is true for stars; by observing the color of stars, we can determine which stars are hot and which stars are cool. If we know the temperature of a star, and how far away it is (see the "Measuring Distances Using Parallax" lab), we can determine how big a star is.

We can also use a device, called a spectroscope, to break-up the light from an object into smaller segments and explore the chemical composition of the source of light. For example, if you light a match, you know that the predominant color of the light from the match is yellow. This is partly due to the temperature of the match flame, but it is also due to very strong *emission lines* from sodium. When the sodium atoms are excited (heated in the flame) they emit yellow light.

In this lab, you will learn how astronomers can use the light from celestial objects to discover their nature. You will see just how much information can be packed into light! The close-up study of light is called *spectroscopy*.

This lab is split into three main parts:

- Experimentation with actual blackbody light sources to learn about the qualitative behavior of blackbody radiation.
- Computer simulations of the quantitative behavior of blackbody radiation.
- Experimentation with emission line sources to show you how the spectra of each element is unique, just like the fingerprints of human beings.

Thus there are three main components to this lab, and they can be performed in any order. So one third of the groups can work on the computers, while the other groups work with the spectrographs and various light sources.

- *Goals:* to discuss the properties of blackbody radiation, filters, and see the relationship between temperature and color by observing light bulbs and the spectra of elements by looking at emission line sources through a spectrograph. Using a computer to simulate blackbody. radiation

- *Materials:* spectrograph, adjustable light source, gas tubes and power source, computers, calculators

10.2 Blackbody Radiation

Blackbody radiation (light) is produced by any hot, dense object. By "hot" we mean any object with a temperature above absolute zero. All things in the Universe emit radiation, since all things in the Universe have temperatures above absolute zero. Astronomers *idealize* a perfect absorber and perfect emitter of radiation and call it a "blackbody". This does not mean it is black in color, simply that it absorbs and emits light at all wavelengths, so no light is reflected. A blackbody is an object which is a perfect absorber (absorbs at all wavelengths) and a perfect emitter (emits at all wavelengths) and does not reflect any light from its surface. Astronomical objects are not perfect blackbodies, but some, in particular, stars, are fairly well approximated by blackbodies.

The light emitted by a blackbody object is called blackbody radiation. This radiation is characterized simply by the *temperature* of the blackbody object. Thus, if we can study the blackbody radiation from an object, we can determine the temperature of the object.

To study light, astronomers often split the light up into a spectrum. A spectrum shows the distribution of brightness at many different wavelengths. Thus, a spectrum can be shown using a graph of brightness vs. wavelength. A simple example of this is if you were to look at a rainbow and record how bright each of the separate colors were. Figure 10.1 shows what the brightness of the colors in a hot flame or hot star might look like. At each separate color, a brightness is measured. By fitting a curve to the data points, and finding the peak in the curve, we can determine the temperature of the blackbody source.

10.3 Absorption and Emission Lines

One question which you may have considered is: how do astronomers know what elements and molecules make up astronomical objects? How do they know that the Universe is made up mostly of hydrogen with a little bit of helium and a tiny bit of all the other elements we have discovered on Earth? How do astronomers know the chemical make up of the planets in our Solar System? They do this by examining the absorption or emission lines in the spectra of astronomical sources. [Note that the plural of *spectrum* is *spectra*.]

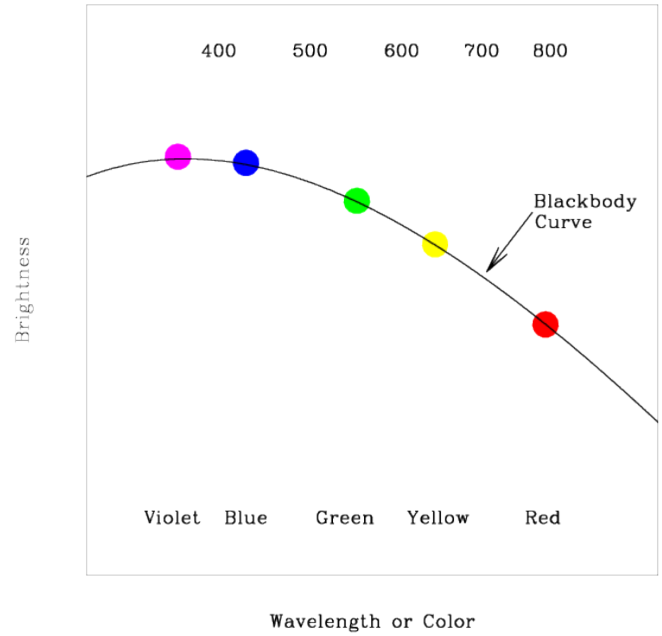


Figure 10.1: Astronomers measure the amount of light at a number of different wavelengths (or colors) to determine the temperature of a blackbody source. Every blackbody has the same shape, but the peak moves to the violet/blue for hot sources, and to the red for cool sources. Thus we can determine the temperature of a blackbody source by figuring out where the most light is emitted.

10.3.1 The Bohr Model of the Atom

In the early part of the last century, a group of physicists developed the *Quantum Theory of the Atom*. Among these scientists was a Danish physicist named Niels Bohr. His model of the atom, shown in the figure below, is the easiest to understand. In the Bohr model, we have a nucleus at the center of the atom, which is really much, much smaller relative to the electron orbits than is illustrated in our figure. Almost all of the atom's mass is located in the nucleus. For Hydrogen, the simplest element known, the nucleus consists of just one proton. A proton has an atomic mass unit of 1 and a positive electric charge. In Helium, the nucleus has two protons and two other particles called neutrons which do not have any charge but do have mass. An electron cloud surrounds the nucleus. For Hydrogen there is only one electron. For Helium there are two electrons and in a larger atom like Oxygen, there are 8. The electron has about $\frac{1}{2000}$ the mass of the proton but an equal and opposite electric charge. So protons have positive charge and electrons have negative charge. Because of this, the electron is attracted to the nucleus and will thus stay as close to the nucleus as possible.

In the Bohr model, Figure 10.2, the electron is allowed to exist only at *certain* distances from the nucleus. This also means the electron is allowed to have *only certain* *orbital energies*. Often the terms *orbits*, *levels*, and *energies* are used interchangeably so try not to get confused. They all mean the same thing and all refer to the electrons in the Bohr model of the atom.

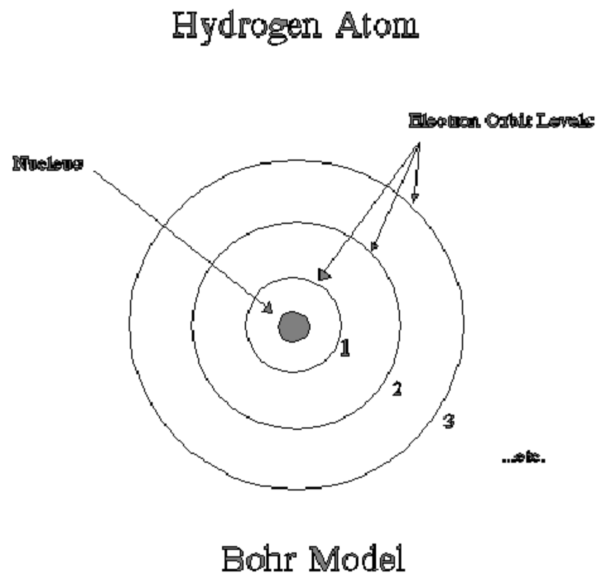


Figure 10.2: In the Bohr model, the negatively charged electrons can only orbit the positively charged nucleus in specific, "quantized", orbits.

Now that our model is set up let's look at some situations of interest. When scientists studied simple atoms in their normal, or average state, they found that the electron was found in the lowest level. They named this level the ground level. When an atom is exposed to conditions other than average, say for example, putting it in a very strong electric field, or by increasing its temperature, the electron will jump from inner levels toward outer levels. Once the abnormal conditions are taken away, the electron jumps downward towards the ground level and emits some light as it does so. The interesting thing about this light is that it comes out at only *particular* wavelengths. It does not come out in a continuous spectrum, but at solitary wavelengths. What has happened here?

After much study, the physicists found out that the atom had taken-in energy from the collision or from the surrounding environment and that as it jumps downward in levels, it re-emits the energy as light. The light is a particular color because the electron really is allowed only to be in certain discrete levels or orbits. It cannot be halfway in between two energy levels. This is not the same situation for large scale objects like ourselves. Picture a person in an elevator moving up and down between floors in a building. The person can use the emergency stop button to stop in between any floor if they want to. An electron cannot. It can only exist in certain energy levels around a nucleus.

Now, since each element has a different number of protons and neutrons in its nucleus and a different number of electrons, you may think that studying "electron gymnastics" would get very complicated. Actually, nature has been kind to us because at any one time, only a single electron in a given atom jumps around. This means that each element, when it is excited, gives off certain colors or wavelengths. This allows scientists to develop a color *fingerprint* for each element. This even works for molecules. These fingerprints are sometimes referred to as spectral lines. The light coming from these atoms does not take the shape of lines. Rather, each atom produces its own set of distinct colors. Scientists then use lenses and slits to produce an image in the shape of a line so that they can measure the exact wavelength accurately. This is why spectral lines get their name, because they are generally studied in a linear shape, but they are actually just different wavelengths of light.

10.3.2 Kirchoff's Laws

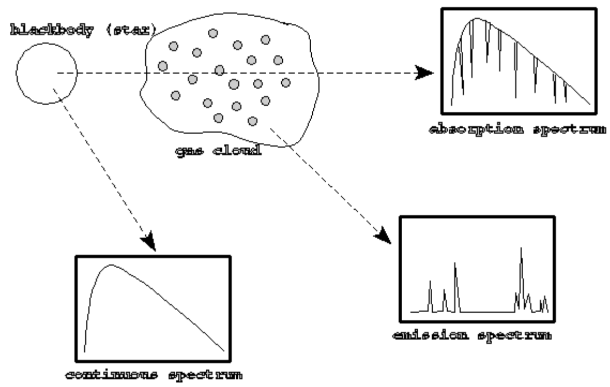
Continuous spectra are the same as blackbody spectra, and now you know about spectral lines. But there are two types of spectral lines: *absorption* lines and *emission* lines. Emission lines occur when the electron is moving down to a lower level, and emits some light in the process. An electron can also move up to a higher level by absorbing the right wavelength of light. If the atom is exposed to a continuous spectrum, it will absorb only the right wavelength of light to move the electron up. Think about how that would affect the continuous spectrum. One wavelength of light would be absorbed, but nothing would happen to the other colors. If you looked at the source of the continuous spectrum (light bulb, core of a star) through a spectrograph, it would have the familiar Blackbody spectrum, with a dark line where the light had been absorbed. This is an absorption line.

The absorption process is basically the reverse of the emission process. The electron must acquire energy (by absorbing some light) to move to a higher level, and it must get rid of energy (by emitting some light) to move to a lower level. If you're having a hard time keeping all this straight, don't worry. Gustav Kirchoff made it simple in 1860, when he came up with three laws describing the processes behind the three types of spectra. The laws are usually stated as follows:

- **I.** A dense object will produce a continuous spectrum when heated.

- **II.** A low-density, gas that is excited (meaning that the atoms have electrons in higher levels than normal) will produce an emission-line spectrum.

- **III.** If a source emitting a continuous spectrum is observed through a cooler, low-density gas, an absorption-line spectrum will result.



Kirchoff's Laws

A blackbody produces a continuous spectrum. This is in agreement with Kirchoff's first law. When the light from this blackbody passes through a cloud of cooler gas, certain wavelengths are absorbed by the atoms in that gas. This produces an absorption spectrum according to Kirchoff's third law. However, if you observe the cloud of gas from a different angle, so you cannot see the blackbody, you will see the light emitted from the atoms when the excited electrons move to lower levels. This is the emission spectrum described by Kirchoff's second law.

Kirchoff's laws describe the conditions that produce each type of spectrum, and they are a helpful way to remember them, but a real understanding of what is happening comes from the Bohr model.

In the second half of this lab you will be observing the spectral lines produced by several different elements when their gaseous forms are heated. The goal of this subsection of the lab is to observe these emission lines and to understand their formation process.

10.4 Creating a Spectrum

Light which has been split up to create a spectrum is called dispersed light. By dispersing light, one can see how pure white light is really made up of all possible colors. If we disperse light from astronomical sources, we can learn a lot about that object. To split up the light so you can see the spectrum, one has to have some kind of tool which disperses the light. In the case of the rainbow mentioned above, the dispersing element is actually the raindrops which are in the sky. Another common dispersing element is a prism.

We will be using an optical element called a *diffraction grating* to split a source of white light into its component colors. A diffraction grating is a bunch of really, really, small rectangular openings called slits packed close together on a single sheet of material (usually plastic or glass). They are usually made by first etching a piece of glass with a diamond and a computer driven etching machine and then taking either casts of the original or a picture of the original.

The diffraction grating we will be using is located at the optical entrance of an instrument called a *spectroscope*. The image screen inside the spectroscope is where the dispersed light ends up. Instead of having all the colors land on the same spot, they are dispersed across the screen when the light is split up into its component wavelengths. The resultant dispersed light image is called a spectrum.

10.5 Observing Blackbody Sources with the Spectrograph

In part one of this lab, we will study a common blackbody in everyday use: a simple white light bulb. Your Lab TA will show you a regular light bulb at two different brightnesses (which correspond to two different temperatures). The light bulb emits at all wavelengths, even ones that we can't see with our human eyes. You will also use a spectroscope to observe emission line sources.

1. First, get a spectroscope from your lab instructor. Study Figure 10.3 figure out which way the entrance slit should line up with the light source. **DO NOT TOUCH THE ENTRANCE SLIT OR DIFFRACTION GRATING!** Touching the plastic ends degrades the effectiveness and quality of the spectroscope.

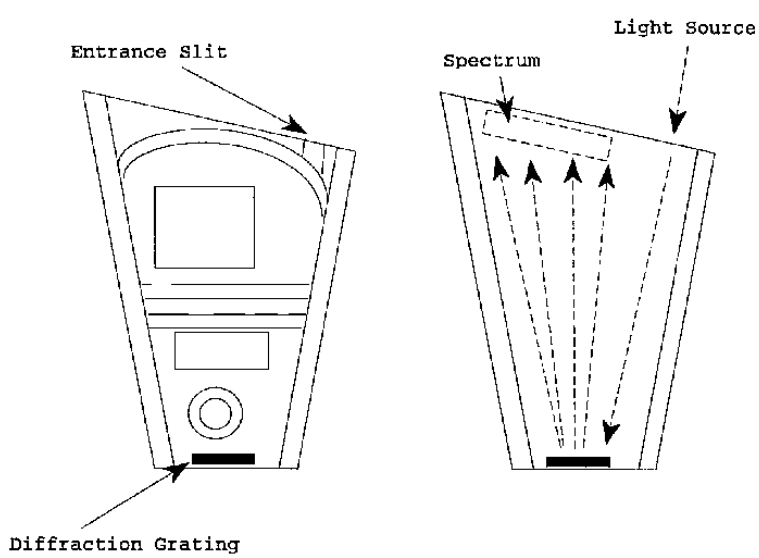


Figure 10.3:

2. Observe the light source at the brighter (hotter) setting.

3. Do you see light at all different wavelengths/colors or only a few discrete wavelengths? (**2 points**)

4. Of all of the colors which you see in the spectrographs, which color appears the brightest?(**3 points**)

5. Now let us observe the light source at a cooler setting. Do you see light at all different wavelengths/colors or only a few discrete wavelengths? Of all of the colors which you see in the spectrographs, which color appears the brightest? (**3 points**)

6. Describe the changes between the two light bulb observations. What happened to the spectrum as the brightness and temperature of the light bulb increased? Specifically, what happened to the relative amount of light at different wavelengths?(**5 points**)

7. Betelgeuse is a Red Giant Star found in the constellation Orion. Sirius, the brightest star in the sky, is much hotter and brighter than Betelgeuse. Describe

how you might expect the colors of these two stars to differ. (**4 points**)

10.6 Quantitative Behavior of Blackbody Radiation

This subsection, which your TA may make optional (or done as one big group), should be done outside of class on a computer with network access, we will investigate how changing the temperature of a source changes the characteristics of the radiation which is emitted by the source. We will see how the measurement of the *color* of an object can be used to determine the object's temperature. We will also see how changing the temperature of a source also affects the source's *brightness*.

To do this, we will use an online computer program which simulates the spectrum for objects at a given temperature. This program is located here:

`http://www.mhhe.com/physsci/astronomy/applets/Blackbody/`
`applet_files/BlackBody.html`

The program just produces a graph of wavelength on the x-axis vs. brightness on the y-axis; you are looking at the relative brightness of this source at different wavelengths.

The program is simple to use. There is a sliding bar on the bottom of the "applet" that allows you to set the temperature of the star. Play around with it a bit to get the idea. Be aware that the y-axis scale of the plot will change to make sure that none of the spectrum goes off the top of the plot; thus if you are looking at objects of different temperature, the y-scale can be different.

Note that the temperature of the objects are measured in units called degrees Kelvin (K). These are very similar to degrees Centigrade/Celsius (C); the only difference is that: $K = C + 273$. So if the outdoor temperature is about 20 C (68 Fahrenheit), then it is 293 K. Temperatures of stars are measured in *thousands* of degrees Kelvin; they are much hotter than it is on Earth!

1. Set the object to a temperature of around 6000 degrees, which is the temperature of the Sun. Note the wavelength, and the color of the spectrum at the peak of the blackbody curve.

2. Now set the temperature to 3000 K, much cooler than the Sun. How do the spectra differ? Consider both the *relative* amount of light at different wavelengths as well as the overall *brightness*. Now set the temperature to 12,000 K, hotter than Sun. How do the spectra differ? (**5 points**)

3. You can see that each blackbody spectrum has a wavelength where the emission is the brightest (the "top" of the curve). Note that this wavelength changes as the temperature is changed. Fill in the following small table of the wavelength (in "nanometers") of the peak of the curve for objects of several different temperatures. You should read the wavelengths at the peak of the curve by looking at the x-axis value of the peak. (**5 points**)

Temperature	Peak Wavelength
3000	
6000	
12000	
24000	

4. Can you see a pattern from your table? For example, consider how the peak wavelength changes as the temperature increases by a factor of 2, a factor of 3, a factor of 4, etc. Can you come up with a mathematical expression which relates the peak wavelength to the temperature? (**3 points**)

5. Where do you think the peak wavelength would be for objects on Earth, at a temperature of about 300 degrees K? **(2 points)**

10.7 Spectral Lines Experiment

10.7.1 Spark Tubes

In space, atoms in a gas can get excited when light from a continuous source heats the gas. We cannot do this easily because it requires extreme temperatures, but we do have special equipment which allows us to excite the atoms in a gas in another way. When two atoms collide they can exchange kinetic energy (energy of motion) and one of the atoms can become excited. This same process can occur if an atom collides with a high speed electron. We can generate high speed electrons simply - it's called electricity! Thus we can excite the atoms in a gas by running electricity through the gas.

The instrument we will be using is called a spark tube. It is very similar to the equipment used to make neon signs. Each tube is filled with gas of a particular element. The tube is placed in a circuit and electricity is run through the circuit. When the electrons pass through the gas they collide with the atoms causing them to become excited. So the electrons in the atoms jump to higher levels. When these excited electrons cascade back down to the lower levels, they emit light which we can record as a spectrum.

10.7.2 Emission-line Spectra Experiment

For the third, and final subsection of this lab you will be using the spectrographs to look at the spark tubes that are emission line sources.

- The TA will first show you the emission from hot Hydrogen gas. Notice how simple this spectrum is. On the attached graphs, make a drawing of the lines you see in the spectrum of hydrogen. Be sure to label the graph so you remember which element the spectrum corresponds to. **(4 points)**
- Next the TA will show you Helium. Notice that this spectrum is more complicated. Draw its spectrum on the attached sheet.**(4 points)**
- Depending on which tubes are available, the TA will show you at least 3 more elements. Draw and label these spectra on your sheet as well.**(4 points)**

10.7.3 The Unknown Element

Now your TA will show you one of the elements again, but won't tell you which one. This time you will be using a higher quality spectroscope (the large gray instrument) to try to identify which element it is by comparing the wavelengths of the spectral lines with those in a data table. The gray, table-mounted spectrograph is identical in nature to the handheld spectrographs, except it is heavier, and has a more stable wavelength calibration. When you look through the gray spectroscope you will see that there is a number scale at the bottom of the spectrum. These are the wavelengths of the light in "nanometers" (1 nm = 10^{-9} meter). Look through this spectrograph at the unknown element and write down the wavelengths of the spectral lines that you can see in the table below, and note their color.

Table 10.1: Unknown Emission Line Source

Observed Wavelength (nm)	Color of Line

Now, compare the wavelengths of the lines in your data table to each of the three elements listed below. In this next table we list the wavelengths (in nanometers) of the brightest emission lines for hydrogen, helium and argon. Note that most humans cannot see light with a wavelength shorter than 400 nm or with a wavelength longer than 700 nm.

Table 10.2: Emission Line Wavelengths

Hydrogen	Helium	Argon
656.3	728.1	714.7
486.1	667.8	687.1
434.0	587.5	675.2
410.2	501.5	560.6
397.0	492.1	557.2
388.9	471.3	549.5

Which element is the unknown element? ____________________ **(5 points)**

10.8 Questions

1. Describe in detail why the emission or absorption from a particular electron would produce lines only at specific wavelengths rather than at all wavelengths like a blackbody. (Use the Bohr model to help you answer this question.) **(5**

points)

2. What causes a spectrum to have more lines than another spectrum (for example, Helium has more lines than Hydrogen)? **(4 points)**

3. Referring to Fig. 10.4, does the electron transition in the atom labeled "A" cause the emission of light, or require the absorption of light? **(2 points)**

4. Referring to Fig. 10.4, does the electron transition in the atom labeled "B" cause the emission of light, or require the absorption of light? **(2 points)**

5. Comparing the atom labeled “C” to the atom labeled “D”, which transition (that occurring in C, or D) releases the largest amount of energy? **(3 points)**

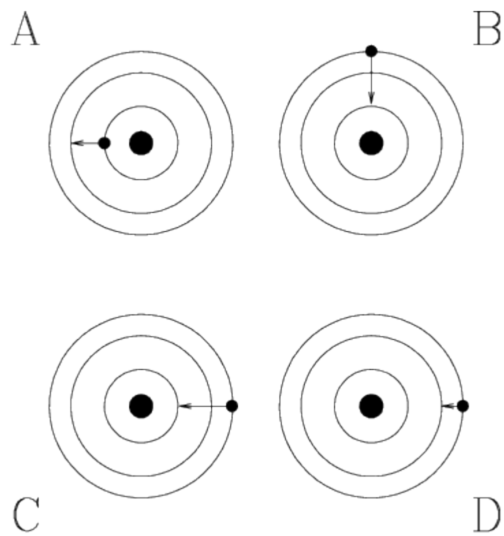


Figure 10.4: Electron transitions in an atom (the electrons are the small dots, the nucleus the large black dots, and the circles are possible orbits.

10.9 Summary (35 points)

Summarize the important ideas covered in this lab. Some questions to answer are:

- What information you can learn about a celestial object just by measuring the peak of its blackbody spectrum?
- What does a blackbody spectrum look like?
- How does the peak wavelength change as the temperature of a blackbody changes?
- How can you *quantitatively* measure the color of an object?
- Do the color of items you see around you on Earth (e.g. a red and blue shirt) tell you something about the temperature of the object? Why or why not?
- What information can you learn about an astronomical object from its spectrum?
- Explain how you would get this information from a spectrum.

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

10.10 Possible Quiz Questions

1. What is meant by the term "blackbody"?
2. What type of sources emit a blackbody spectrum?
3. How is an emission line spectrum produced?
4. How is an absorption line spectrum produced?
5. What type of instrument is used to produce a spectrum?

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

Research how astronomers use the spectra of binary stars to determine their masses. Write a one page paper describing this technique, including a figure detailing what is happening.

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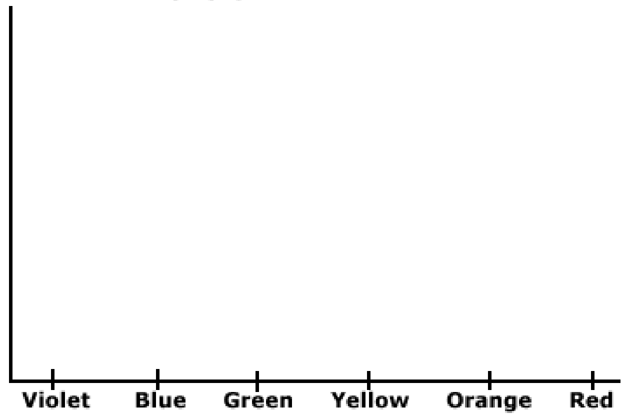

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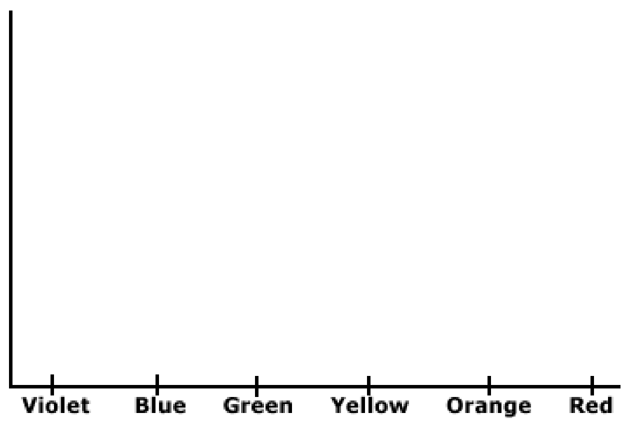

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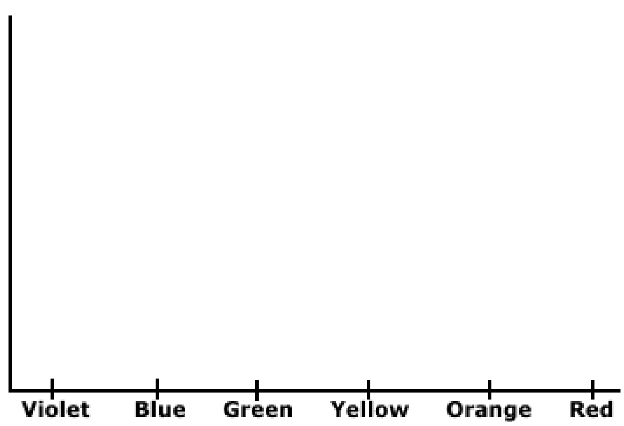

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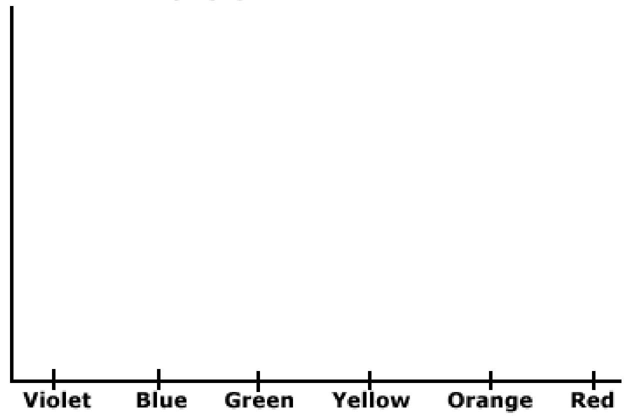

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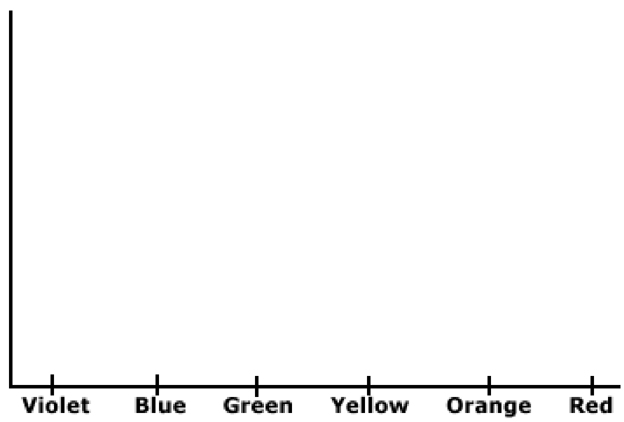

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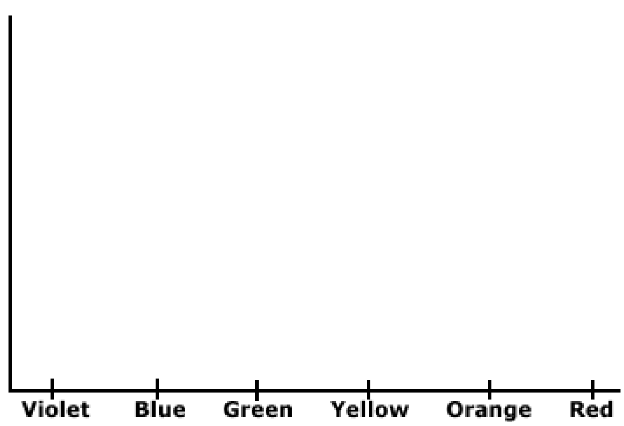


Name:______________________________

Date:______________________________

11 Our Sun

11.1 Introduction

The Sun is a very important object for all life on Earth. The nuclear reactions which occur in its core produce the energy which plants and animals need to survive. We schedule our lives around the rising and setting of the Sun in the sky. During the summer, the Sun is higher in the sky and thus warms us more than during the winter, when the Sun stays low in the sky. But the Sun's effect on Earth is even more complicated than these simple examples.

The Sun is the nearest star to us, which is both an advantage and a disadvantage for astronomers who study stars. Since the Sun is very close, and very bright, we know much more about the Sun than we know about other distant stars. This complicates the picture quite a bit since we need to better understand the physics going in the Sun in order to comprehend all our detailed observations. This difference makes the job of solar astronomers in some ways more difficult than the job of stellar astronomers, and in some ways easier! It's a case of having lots of incredibly detailed data. But all of the phenomena associated with the Sun are occurring on other stars, so understanding the Sun's behavior provides insights to how other stars might behave.

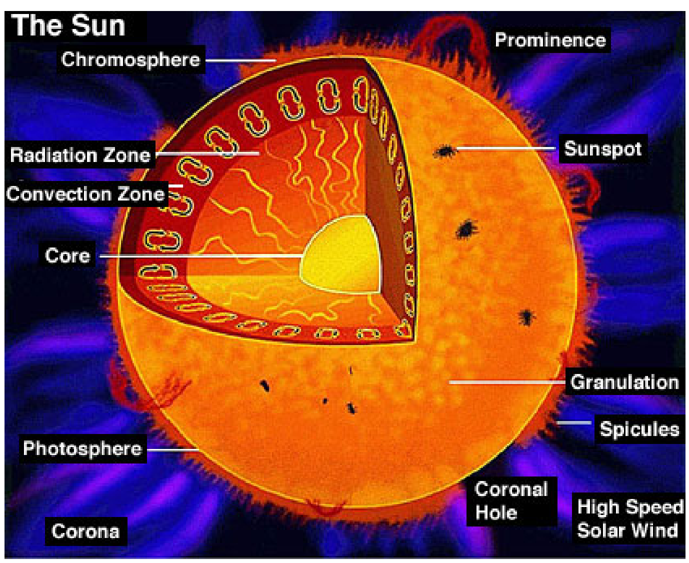


Figure 11.1: A diagram of the various layers/components of the Sun, as well as the appearance and location of other prominent solar features.

- *Goals:* to discuss the layers of the Sun and solar phenomena; to use these concepts in conjunction with pictures to deduce characteristics of solar flares, prominences, sunspots, and solar rotation
- *Materials:* You will be given a Sun image notebook, a bar magnet with iron filings and a plastic tray. You will need paper to write on, a ruler, and a calculator

11.2 Layers of the Sun

One of the things we know best about the Sun is its overall structure. Figure 11.1 is a schematic of the layers of the Sun's interior and atmosphere. The interior of the Sun is made up of three distinct regions: the core, the radiative zone, and the convective zone. The *core* of the Sun is very hot and dense. This is the only place in the Sun where the temperature and pressure are high enough to support nuclear reactions. The *radiative zone* is the region of the sun where the energy is transported through the process of radiation. Basically, the photons generated by the core are absorbed and emitted by the atoms found in the radiative zone like cars in stop and go traffic. This is a very slow process. The *convective zone* is the region of the Sun where energy is transported by rising "bubbles" of material. This is the same phenomenon that takes place when you boil a pot of water. The hot bubbles rise to the top, cool, and fall back down. This gives the the surface of the Sun a granular look. Granules are bright regions surrounded by darker narrow regions. These granules cover the entire surface of the Sun.

The atmosphere of the Sun is also comprised of three layers: the photosphere, the chromosphere, and the corona. The *photosphere* is a thin layer that forms the visible surface of the Sun. This layer acts as a kind of insulation, and helps the Sun retain some of its heat and slow its consumption of fuel in the core. The *chromosphere* is the Sun's lower atmosphere. This layer can only be seen during a solar eclipse since the photosphere is so bright. The *corona* is the outer atmosphere of the Sun. It is very hot, but has a very low density, so this layer can only be seen during a solar eclipse (or using specialized telescopes). More information on the layers of the Sun can be found in your textbook.

11.3 Sunspots

Sunspots appear as dark spots on the photosphere (surface) of the Sun (see Figure 11.2). They last from a few days to over a month. Their average size is about the size of the Earth, although some can grow to many times the size of the Earth! Sunspots are commonly found in pairs. How do these spots form?

The formation of sunspots is attributed to the Sun's *differential rotation*. The Sun is a ball of gas, and therefore does not rotate like the Earth, or any other solid

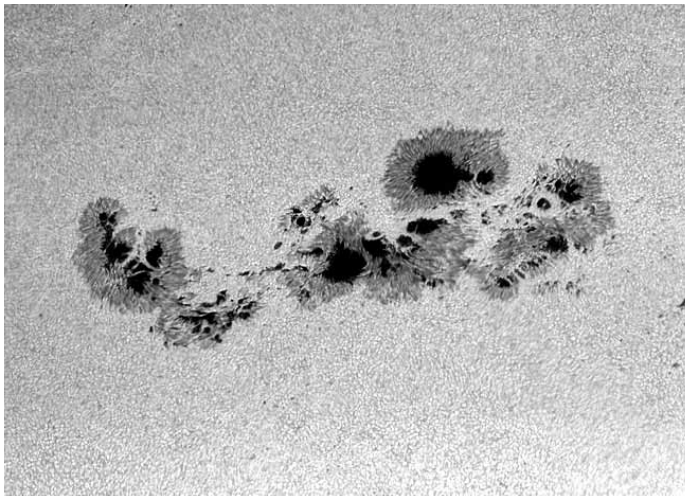


Figure 11.2: A large group of Sunspots. The “umbra” is the darker core of a sunspot, while the “penumbra” is its lighter, frilly edges.

object. The Sun’s equator rotates faster than its poles. It takes roughly 25 days for material to travel once around the equator, but about 35 days for it to travel once around near the north or south poles. This differential rotation acts to twist up the magnetic field lines inside the Sun. At times, the lines can get so twisted that they pop out of the photosphere. Figure 11.3 illustrates this concept. When a magnetic field loop pops out, the places where it leaves and re-enters the photosphere are cooler than the rest of the Sun’s surface. These cool places appear darker, and therefore are called “sunspots”.

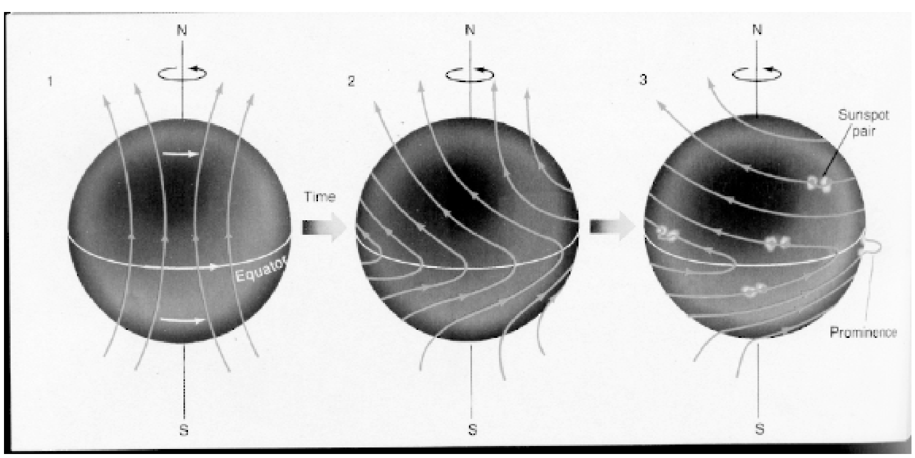


Figure 11.3: Sunspots are a result of the Sun’s differential rotation.

The number of sunspots rises and falls over an 11 year period. This is the amount of time it takes for the magnetic lines to tangle up and then become untangled again. This is called the *Solar Cycle*. Look in your textbook for more information on sunspots and the solar cycle.

11.4 Solar Phenomenon

The Sun is a very exciting place. All sorts of activity and eruptions take place in it and around it. We will now briefly discuss a few of these interesting phenomena. You will be analyzing pictures of prominences during this lab.

Prominences are huge loops of glowing gas protruding from the chromosphere. Charged particles spiral around the magnetic field lines that loop out over the surface of the Sun, and therefore we see bright loops above the Sun's surface. Very energetic prominences can break free from the magnetic field lines and shoot out into space.

Flares are brief but bright eruptions of hot gas in the Sun's atmosphere. These eruptions occur near sunspot groups and are associated with the Sun's intertwined magnetic field lines. A large flare can release as much energy as 10 billion megatons of TNT! The charged particles that flares emit can disrupt communication systems here on Earth.

Another result of charged particles bombarding the Earth is the Northern Lights. When the particles reach the Earth, they latch on to the Earth's magnetic field lines. These lines enter the Earth's atmosphere near the poles. The charged particles from the Sun then excite the molecules in Earth's atmosphere and cause them to glow. Your textbook will have more fascinating information about these solar phenomena.

11.5 Lab Exercises

There are three main exercises in this lab. The first part consists of a series of "stations" in a three ring binder where you examine some pictures of the Sun and answer some questions about the images that you see. Use the information that you have learned from lectures and your book to give explanations for the different phenomena that you see at each station. In the second exercise you will learn about magnetic fields using a bar magnet and some iron filings. Finally, for those labs that occur during daylight hours (i.e., starting before 5 pm!), you will actually look at the Sun using a special telescope to see some of the phenomena that were detailed in the images in the first exercise of this lab (for those students in nighttime labs, arrangements might be made so as to observe the Sun during one of your lecture sessions). During this lab you will use your own insight and knowledge of basic physics and astronomy to obtain important information about the phenomena that we see on the Sun, just as solar astronomers do. As with all of the other exercises in this lab manual, if there is not sufficient room to write in your answers into this lab, do not hesitate to use additional sheets of paper. Do not try to squeeze your answers into the tiny blank spaces in this lab description if you need more space then provided! Don't forget to

SHOW ALL OF YOUR WORK.

One note of caution about the images that you see: the colors of the pictures (especially those taken by SOHO) are *not* true colors, but are simply colors used by the observatories' image processing teams to best enhance the features shown in the image.

11.5.1 Exercise #1: Getting familiar with the Size and Appearance of the Sun

Station 1: In this first station we simply present some images of the Sun to familiarize yourself with what you will be seeing during the remainder of this lab. Note that this station has no questions that you have to answer, but you still should take time to familiarize yourself with the various features visible on/near the Sun, and get comfortable with the specialized, filtered image shown here.

- The first image in this station is a simple "white light" picture of the Sun as it would appear to you if you were to look at it in a telescope that was designed for viewing the Sun. Note the dark spots on the surface of the Sun. These are "sunspots", and are dark because they are cooler than the rest of the photosphere.

- When we take a very close-up view of the Sun's photosphere we see that it is broken up into much smaller "cells". This is the "solar granulation", and is shown in picture #2. Note the size of these granules. These convection cells are about the size of New Mexico!

- To explore what is happening on the Sun more fully requires special tools. If you have had the spectroscopy lab, you will have seen the spectral lines of elements. By choosing the right element, we can actually probe different regions in the Sun's atmosphere. In our first example, we look at the Sun in the light of the hydrogen atom ("H-alpha"). This is the red line in the spectrum of hydrogen. If you have a daytime lab, and the weather is good, you will get to see the Sun just like it appears in picture #3. The dark regions in this image is where cool gas is present (the dark spot at the center is a sunspot). The dark linear, and curved features are "prominences", and are due to gas caught in the magnetic field lines of the underlying sunspots. They are above the surface of the Sun, so they are a little bit cooler than the photosphere, and therefore darker.

- Picture #4 shows a "loop' prominence located at the edge (or "limb") of the Sun (the disk of the Sun has been blocked out using a special telescope called a "coronograph" to allow us to see activity near its limb). If the Sun cooperates, you may be able to see several of these prominences with the solar telescope. You will be returning to this image in Exercise #2.

Station 2: Here are two images of the Sun taken by the SOHO satellite several days apart (the exact times are at the top of the image). **(8 points)**

- Look at the sunspot group just below center of the Sun in **image 1**, and then note that it has rotated to the western (right-hand) limb of the Sun in **image 2**. Since the sunspot group has moved from center to limb, you then know that the Sun has rotated by one quarter of a turn (90°).

- Determine the precise time difference between the images. Use this information plus the fact that the Sun has turned by 90 degrees in that time to determine the rotation rate of the Sun. If the Sun turns by 90 degrees in time t, it would complete one revolution of 360 degrees in how much time?

- Does this match the rotation rate given in your textbook or in lecture? Show your work.

In the second photograph of this station are two different images of the Sun: the one on the left is a photo of the Sun taken in the near-infrared at Kitt Peak National Observatory, and the one on the right is a "magnetogram" (a picture of the magnetic field distribution on the surface of the Sun) taken at about the same time. (Note that black and white areas represent regions with different *polarities*, like the north and south poles of the bar magnet used in the second part of this lab.) **(7 points)**

- What do you notice about the location of *sunspots* in the photo and the location of the *strongest magnetic fields*, shown by the brightest or darkest colors in the magnetogram?

- Based on this answer, what do you think causes sunspots to form? Why are they dark?

Station 3: Here is a picture of the *corona* of the Sun, taken by the SOHO satellite in the extreme ultraviolet. (An image of the Sun has been superimposed at the center of the picture. The black ring surrounding it is a result of image processing and is not real.) **(10 points)**

- Determine the diameter of the Sun, then measure the minimum extent of the corona (diagonally from upper left to lower right).

- If the photospheric diameter of the Sun is 1.4 million kilometers (1.4 x 10^6 km), how big is the corona? (HINT: use unit conversion!)

- How many times larger than the Earth is the corona? (Earth diameter=12,500 km)

Station 4: This image shows a time-series of exposures by the SOHO satellite showing an *eruptive prominence.* **(15 points)**

- As in station 3, measure the diameter of the Sun and then measure the distance of the top of the prominence from the edge of the Sun in the first (earliest) image. Then measure the distance of the top of the prominence from the edge of the Sun in the last image.

- Convert these values into real distances based on the linear scale of the images. Remember the diameter of the Sun is 1.4 x 10^6 kilometers.

- The velocity of an object is the distance it travels in a certain amount of time (vel=dist/time). Find the velocity of the prominence by subtracting the two distances and dividing the answer by the amount of time between the two images.

- In the most severe of solar storms, those that cause flares, and "coronal mass ejections" (and can disrupt communications on Earth), the material ejected in the prominence (or flare) can reach velocities of 2,000 kilometers per second. If the Earth is 150 x 10^6 kilometers from the Sun, how long (hours or days) would it take for this ejected material to reach the Earth?

Station 5: This is a plot of where sunspots tend to occur on the Sun as a function of *latitude* (top plot) and time (bottom plot). What do you notice about the distribution sunspots? How long does it take the pattern to repeat? What does this length of time correspond to? **(3 points)**

11.5.2 Exercise #2: Exploring Magnetic Fields

The magnetic field of the Sun drives most of the solar activity. In this subsection we compare the magnetic field of sunspots to that of a bar magnet (and an optional exercise that shows that a magnetic field is generated by an electric current). During this exercise you will be using a plastic tray in which you will sprinkle iron filings (small bits of iron) to trace the magnetic field of a bar magnet. This can be messy, so be careful as we only have a finite supply of these iron filings, and the other lab subsections will need to re-use the ones supplied to you.

- First, let's explore the behavior of a compass in the presence of a magnetic field. Grab the bar magnet and wave the "north pole" (the red end of the bar magnet with the large "N") of the magnet by the compass. Which end of the compass needle (or arrow) seems to be attracted by the north pole of the magnet? **(1 point)**

- Ok, reverse the bar magnet so the south pole (white end) is the one closest to the compass. Which end of the compass needle is attracted to the south pole of the bar magnet? **(1 point)**

- The compass needle itself is a little magnet, and the pointy, arrow end of the compass needle is the north pole of this little magnet. Knowing this, what does this say about magnets? Which pole is attracted to which pole (and vice versa)? **(1 point)**

- As you know, a compass can be used to find your way if you are lost because the needle always points towards the North Pole of the Earth. The Earth has its own magnetic field generated deep in its molten iron core. This field acts just like that of a bar magnet. But given your answer to the last question, and the fact that the "north pole" of the compass needle points to the North Pole of the Earth, what is the actual "polarity" of the Earth's "magnetic North" pole? **(1 point)**

We have just demonstrated the power of attraction of a magnetic field. What does a magnetic field look like? In this subsection we use some iron filings, a plastic tray, and the bar magnet to explore the appearance of a magnetic field, and compare that to what we see on the Sun.

- Place the bar magnet on the table, and center the plastic tray on top of the bar magnet. Gently sprinkle the iron filings on to the plastic tray so that a thin coating covers the entire tray. Sketch the pattern traced-out by the magnetic filings below, and describe this pattern. **(2 points)**

- The iron filings trace the magnetic field lines of the bar magnet. The field lines surround the magnet in all dimensions (though we can only easily show them in two dimensions). Your TA will show you a device that has a bar magnet inside a plastic case to demonstrate the three dimensional nature of the field. Compare the pattern of the iron filings around the bar magnet to the picture of the sunspot shown in Figure 11.4. They are similar! What does this imply about sunspots? **(3 points)**

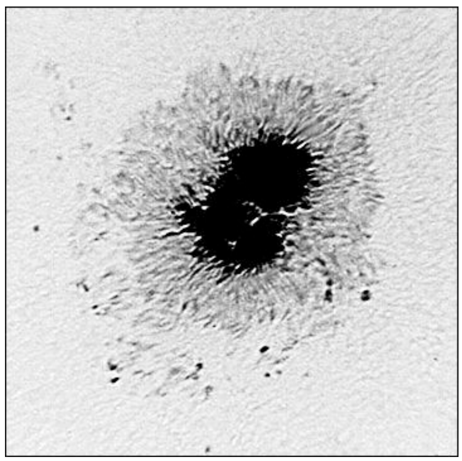


Figure 11.4: The darker region of this double sunspot is called the "umbra", while the less dark, filamentary region is called the "penumbra". For this sunspot, one umbra has a "North polarity", while the other has a "South polarity".

- Now, lets imagine what a fully three dimensional magnetic field looks like. The pattern of the iron filings around the bar magnet would also exist into the space *above* the bar magnet, but we cannot suspend the iron filings above the magnet. Complete Figure 11.5 by drawing-in what you imagine the magnetic field lines look like *above* the bar magnet. **(3 points)**

Figure 11.5: Draw in the field lines above this bar magnet.

- Compare your drawing, above, to the image of the loop prominence seen in station #1 of Exercise #1. What are their similarities—imagine if the magnetic field lines emitted light, what would you expect to see? **(2 points)**

If a sunspot pair is like a little bar magnet on the surface of the Sun, the field extends up into the atmosphere, and along the magnetic field charged particles can collect, and we see light emitted by these moving particles (mostly ionized hydrogen). Note that we do not always see the complete set of field lines in prominences because of the lack of material high in the Sun's atmosphere—but the bases of the prominences are visible, and are located just above the sunspot.

*************If the weather is clear, and your TA is ready, you can proceed to Exercise #3 to look at the Sun with a special solar telescope.************

11.5.3 Optional Exercise: Generating a magnetic field with an electric current

If yours is a nighttime lab, or the weather is poor, you may not be able to complete exercise #3. If this is the case, we offer this alternative exercise on how magnetic fields are created.

How are magnetic fields generated? There are two general categories of magnetism, one is due to intrinsically magnetic materials such as the bar magnet you have been playing with, and the other are magnetic fields generated by electric currents. The mechanism for why some materials are magnetic is complicated, and requires an understanding of the atomic/molecular structure of materials, and is beyond the scope of this class. The second type of magnetism, that caused by electric currents, is more relevant for understanding solar activity.

Electricity and magnetism are intimately related, in fact, scientists talk about the theory of "Electromagnetism". An electric current, which is (usually) composed of moving electrons, generates a magnetic field. A moving magnetic field, can generate an electric current. The magnetic fields of both the Earth and the Sun are generated because they have regions deep inside them that act as electromagnetic fluids. In the Earth's core, it is very hot, and the iron there is molten. Due to the rotation of the Earth, this molten iron fluid is rotating very quickly. Thus, the liquid iron core acts like a current flowing around a wire and can generate a magnetic field. A similar process occurs in the Sun. The gas in the interior of the Sun is "ionized" (the electrons are no longer bound to the protons), and thus the rotation of the Sun spins this ionized gas around generating an electric current that, in turn, generates a magnetic field.

In this exercise you will be using a voltage source (either a battery or low voltage transformer) to generate an electric current to produce a magnetic field. For our "electromagnet" we will simply use a bolt wound with wire. The current flows through the wire, which generates a magnetic field that is carried by the nail. **(Warning: the wire and/or bolt can get fairly hot if you leave the current on too long, so be careful!)**

- Take the two ends of the wire that is wound around the bolt and hook them to the terminals of the lantern battery (or 6V transformer). You now have an electromagnet. Move the compass slowly around the electromagnet. Describe its behavior, does it act like the bar magnet? **(2 points)**

- Using the experience gained from Exercise #2, which end of the nail is the "North" pole of the electromagnet? Switch the wire leads so that they wires are connected in an opposite way. What happens? **(2 points)**.

- Just as you did for the bar magnet, place the white plastic tray on top of the electromagnet and gently sprinkle the iron filings into the tray (sprinkle them very lightly, and gently tap the white tray to get them to align–your electromagnet is not quite as strong as the bar magnet). Draw the resulting pattern below. **(2 points)**

- Does the pattern you have just drawn resemble the one generated by the magnetic field? Describe your results. **(2 points)**

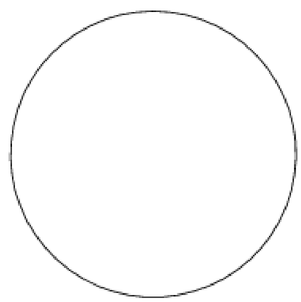
11.5.4 Exercise #3: Looking at the Sun

The Sun is very bright, and looking at it with either the naked eye or any optical device is dangerous—special precautions are necessary to enable you to actually look at the Sun. To make the viewing safe, we must eliminate 99.999% of the light from the Sun to reduce it to safe levels. In this exercise you will be using a very special telescope designed for viewing the Sun. This telescope is equipped with a hydrogen light filter. It only allows a tiny amount of light through, isolating a single emission line from hydrogen ("H-alpha"). In your lecture session you will learn about the emission spectrum of hydrogen, and in the spectroscopy lab you get to see this red line of hydrogen using a spectroscope. Several of the pictures in Exercise #1 were actually obtained using a similar filter system. This filter system gives us a unique view of the Sun that allows us to better see certain types of solar phenomena, especially the "prominences" you encountered in Exercise #1.

- In the "Solar Observation Worksheet" below, draw what you see on and near the Sun as seen through the special solar telescope. **(8 points)**

Note: Kitt Peak Vacuum Telescope images are courtesy of KPNO/NOAO. SOHO Extreme Ultraviolet Imaging Telescope images courtesy of the SOHO/EIT consortium. SOHO Michelson Doppler Imager images courtesy of the SOHO/MDI consortium. SOHO is a project of international cooperation between the European Space Agency (ESA) and NASA.

Solar Observation Worksheet



Name: ____________________ Lab Sec.: __________

Date: ____________________ TA: ________________

11.6 Summary (35 points)

Please summarize the important concepts discussed in this lab.

- Discuss the different types of phenomena and structures you looked at in the lab
- Explain how you can understand what causes a phenomenon to occur by looking at the right kind of data
- List the six layers of the Sun (in order) and give their temperatures.
- What causes the Northern (and Southern) Lights, also known as "Aurorae"?

Use complete sentences and, proofread your summary before turning it in.

Possible Quiz Questions
1) What are sunspots, and what leads to their formation?
2) Name the three interior regions of the Sun.
3) What is differential rotation?
4) What is the "photosphere"?
5) What are solar flares?

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

Look-up a plot of the number of sunspots versus time that spans the last four hundred years. For about 50 years, centered around 1670, the Sun was unusually "quiet", in that sunspots were rarely seen. This event was called the "Maunder minimum" (after the discoverer). At the same time as this lack of sunspots, the climate in the northern hemisphere was much colder than normal. The direct link between sunspots and the Earth's climate has not been fully established, but there must be some connection between these two events. Near 1800 another brief period of few sunspots, the "Dalton minimum" was observed. Looking at recent sunspot numbers, some solar physicists have suggested the Sun may be entering another period like the Dalton minimum. Search for the information these scientists have used to make this prediction. Describe the climate in the northern hemisphere during the last Dalton minimum. Are there any good ideas on the link between sunspot number and climate that you can find?

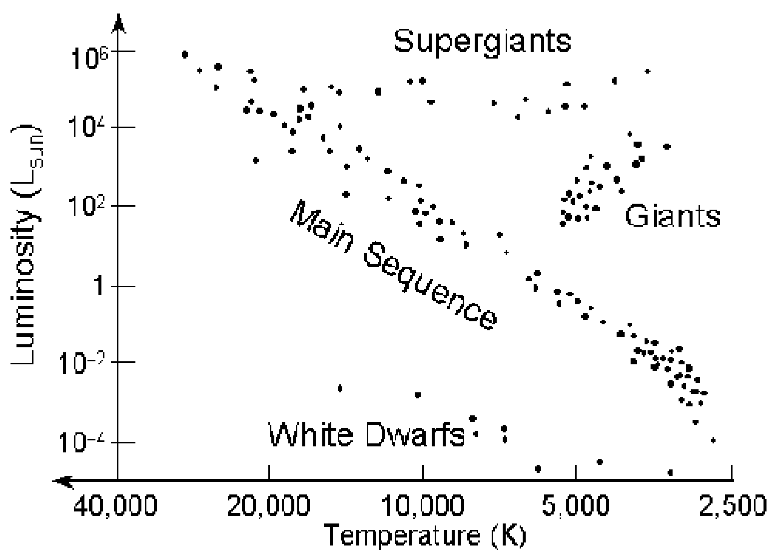
Name:______________________

Date:______________________

12 The Hertzsprung-Russell Diagram

12.1 Introduction

As you may have learned in class, the Hertzsprung-Russell Diagram, or the "HR diagram", is one of the most important tools used by astronomers: it helps us determine both the ages of star clusters and their distances. In your Astronomy 110 textbooks the type of HR diagram that you will normally encounter plots the Luminosity of a star (in solar luminosity units, L_{Sun}) versus its temperature (or spectral type). An example is shown here:



The positions of the various main types of stars are labeled in this HR diagram. The Sun has a temperature of 5,800 K, and a luminosity of 1 L_{Sun}. The Sun is a main sequence "G" star. All stars cooler than the Sun are plotted to the right of the Sun in this diagram. Cool main sequence stars (with spectral types of K and M) are plotted to the lower right of the Sun. Hotter main sequence stars (O, B, A, and F stars) are plotted to the upper left of the Sun's position. As the Sun runs out of hydrogen fuel in its center, it will become a red giant star–a star that is cooler than the Sun, but 100× more luminous. Red giants are plotted to the upper right of the Sun's position. As the Sun runs out of all of its fuel, it sheds its atmosphere and ends its days as a white dwarf. White dwarfs are hotter, and much less luminous than the Sun, so they are plotted to the lower left of the Sun's position in the HR diagram.

The HR diagrams for clusters can be very different depending on their ages. In the following examples, we show the HR diagram of a hypothetical cluster of stars at a variety of different ages. When the star cluster is very young, (see Fig. 12.1) only the hottest stars have made it to the main sequence. In the HR diagram below, the G, K, and M stars (stars that have temperatures below 6,000 K) are still not on the main sequence, while those stars hotter than 7,000 K (O, B, A, and F stars) are already fusing hydrogen into helium at their cores:

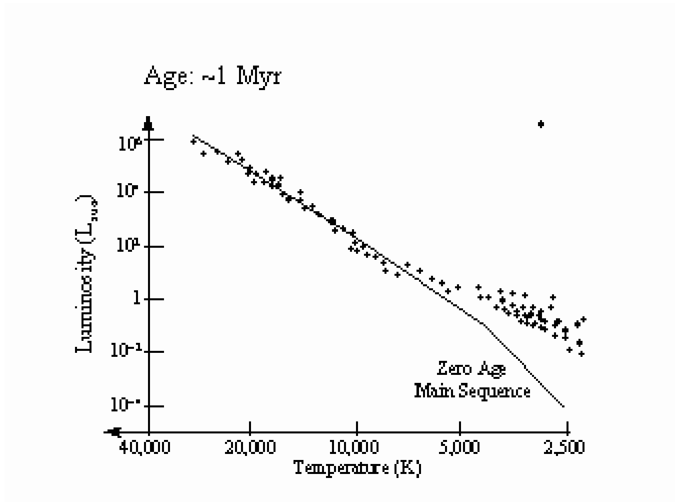


Figure 12.1: The HR diagram of a cluster of stars that is 1 million years old.

In the next HR diagram, Figure 12.2, we see a much older cluster of stars (100 million years = 100 Myr). In this older cluster, some of the hottest and most massive stars (the O and B stars) have evolved into red supergiants. The position of the "main sequence turn off" allows us to estimate the age of a cluster.

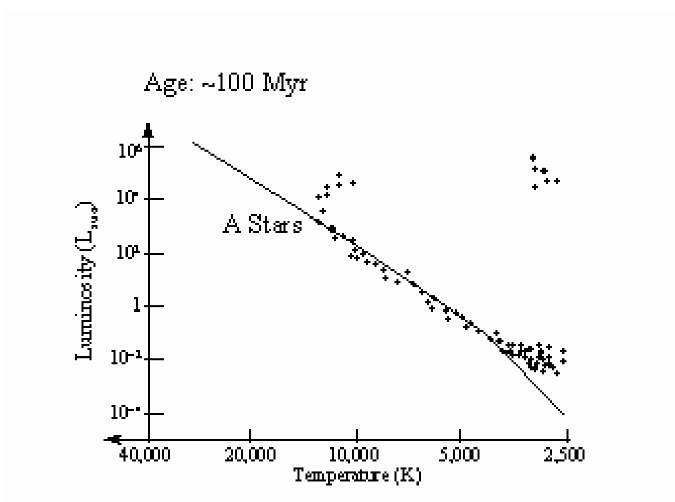


Figure 12.2: The HR diagram of a cluster of stars that is 100 million years old.

In the final HR diagram, Figure 12.3, we have a much older cluster (10 billion years old = 10 Gyr), now stars with one solar mass are becoming red giants, and we say the main sequence turn-off is at spectral type G (T = 5,500 K).

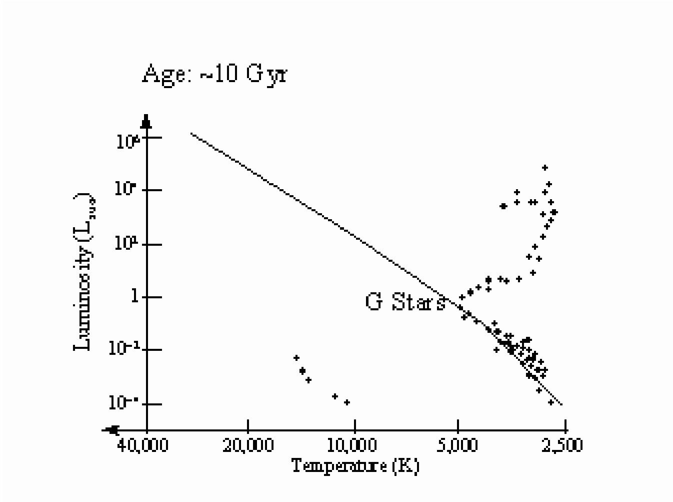


Figure 12.3: The HR diagram of a cluster of stars that is 10 billion years old.

Some white dwarfs (produced by evolved A and F stars) now exist in the cluster. Thus, the HR diagram for a cluster of stars is useful for determining its age.

12.2 Magnitudes and Color Index

While the HR diagrams presented in your class lectures or textbook allow us to provide a very nice description of the evolution of stars and star clusters, astronomers do not actually directly measure either the temperatures or luminosities of stars. Remember that luminosity is a measure the total amount of energy that a star emits. For the Sun it is 10^{26} Watts. But how much energy appears to be coming from an object depends on how far away that object is. Thus, to determine a star's luminosity requires you to know its distance. For example, the two brightest stars in the constellation Orion (see the "Constellation Highlight" for February from the Ast110 homepage link), the red supergiant Betelgeuse and the blue supergiant Rigel, appear to have about the same brightness. But Rigel is six more times luminous than Betelgeuse–Rigel just happens to be further away, so it appears to have the same brightness even though it is pumping out much more energy than Betelgeuse. The "Dog star" Sirius, located to the southeast of Orion, is the brightest star in the sky and appears to be about 5 times brighter than either Betelgeuse or Rigel. But in fact, Sirius is a nearby star, and actually only emits 22× the luminosity of the Sun, or about $1/2000^{\text{th}}$ the luminosity of Rigel!

Therefore, without a distance, it is impossible to determine a star's luminosity–and remember that it is very difficult to measure the distance to a star. We can, however, measure the relative luminosity of two (or more) stars if they are at the same distance: for example if they are both in a cluster of stars. If two stars are at the same distance, then the difference in their apparent brightness is a measurement of the true differences in their luminosities. To measure the apparent brightness of a star, astronomers use the ancient unit of "magnitude". This system was first developed by the Greek astronomer Hipparcos (*ca.* 190 to 120 BC). Hipparcos called the brightest stars "stars of the first magnitude". The next brightest were called "stars of the second magnitude". His system progressed all the way down to "stars of the sixth magnitude", the faintest stars you can see with the naked eye from a dark location.

Astronomers adopted this system and made it more rigorous by defining a five magnitude difference to be exactly equal to a factor of 100 in brightness. That is, a first magnitude star is 100X brighter than a sixth magnitude star. If you are good with mathematics, you will find that a difference of one magnitude turns out to be a factor of 2.5 ($2.5 \times 2.5 \times 2.5 \times 2.5 \times 2.5 = 100$, we say that the fifth root of $100 = 100^{1/5} = 2.5$). Besides this peculiar step size, it is also important to note that the magnitude system is upside down: usually when we talk about something being bigger, faster, or heavier, the quantity being measured increases with size (a car going 100 mph is going faster than one going 50 mph, etc.). In the magnitude system, the brighter the object, the smaller its magnitude! For example, Rigel has an apparent magnitude of 0.2, while the star Sirius (which appears to be 4.5 times brighter than Rigel) has a magnitude of -1.43.

Even though they are a bit screwy, and cause much confusion among Astronomy 110 students, astronomers use magnitudes because of their long history and tradition. So, when astronomers measure the brightness of a star, they measure its apparent magnitude. How bright that star appears to be on the magnitude scale. Usually, astronomers will measure the brightness of a star in a variety of different color filters to allow them to determine its temperature. This technique, called "multi-wavelength photometry", is simply the measurement of how much light is detected on Earth at a specific set of wavelengths from a star of interest. Most astronomers use a system of five filters, one each for the ultraviolet region (the "U filter"), the blue region (the "B filter"), the visual ("V", or green) region, the yellow-red region ("R"), and the near-infrared region ("I"). Generally, when doing real research, astronomers measure the apparent magnitude of a star in more than one filter. [Note: because the name of the filter can some times get confused with spectral types, filter names will be *italicized* to eliminate any possible confusion.]

To determine the temperature of a star, measurements of the apparent brightness in at least two filters is necessary. The difference between these two measurements is called the "color index". For example, the apparent magnitude in the B filter minus the apparent magnitude in the V filter, $(B - V)$, is one example of a color index (it is also the main color index used by astronomers to measure the temperature of stars, but any two of the standard filters can be used to construct a color index). Let us take Polaris (the "North Star") as an example. Its apparent B magnitude is 2.59, and

Table 12.1: The $(B-V)$ Color Index for Main Sequence Stars

Spectra Type	$(B-V)$	Spectral Type	$(B-V)$
O and B Stars	−0.40 to −0.06	G Stars	0.59 to 0.76
A Stars	0.00 to 0.20	K Stars	0.82 to 1.32
F Stars	0.31 to 0.54	M Stars	1.41 to 2.00

its apparent V magnitude is 2.00, so the color index for Polaris is $(B-V) = 2.59 - 2.00 = 0.59$. In Table 12.1, we list the $(B-V)$ color index for main sequence stars. We see that Polaris has the color of a G star.

In Table 12.1, we see that O and B stars have negative $(B-V)$ color indices. We say that O and B stars are "Blue", because they emit more light in the B filter than in the V filter. We say that K and M stars are very red, as they emit much more V light than B light (and even more light in the R and I filters!). A-stars emit the same amount of light at B and V, while F and G stars emit slightly more light at V than at B . With this type of information, we can now figure out the spectral types, and hence temperatures of stars by using photometry.

12.3 The Color-Magnitude HR Diagram

To construct HR diagrams of star clusters, astronomers measure the apparent brightness of stars in two different color filters, and then plot the data into a "Color-Magnitude" diagram, plotting the apparent V magnitude versus the color index $(B-V)$ as shown below. Figure 13.11 shows a color-magnitude diagram for a globular cluster. You might remember from class (or will soon be told!) that globular clusters are old, and that the low mass stars are evolving off the main sequence and becoming red giants. The main sequence turnoff for this globular cluster is at a color index of about $(B-V) = 0.4$, the color of F stars. An F star has a mass of about 1.5 M_{Sun}, thus stars with masses near 1.5 M_{Sun} are evolving off the main sequence to become red giants, so this globular cluster is about 7 billion years old.

12.4 The Color-Magnitude Diagram for the Pleiades

In today's lab, you and your lab partners will construct a color magnitude diagram for the Pleiades star cluster. The Pleiades, sometimes known as the "Seven Sisters" (see the constellation highlight for January at the back of this lab manual), is a star cluster located in the wintertime constellation of Taurus, and can be seen with the naked eye. A wide-angle photograph of the Pleiades is shown below (Fig. 12.4). Many people confuse the Pleiades with the Little Dipper because the brightest stars form a small dipper-like shape.

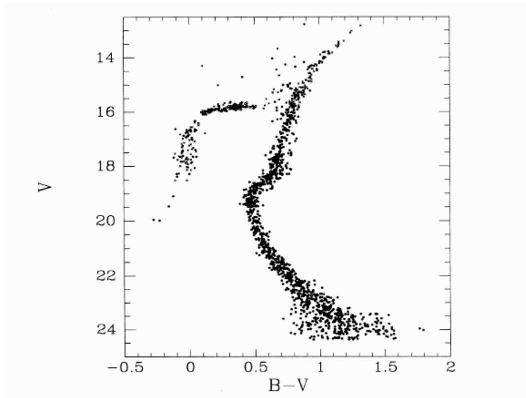


Figure 12.4: The HR diagram for the globular cluster M15.

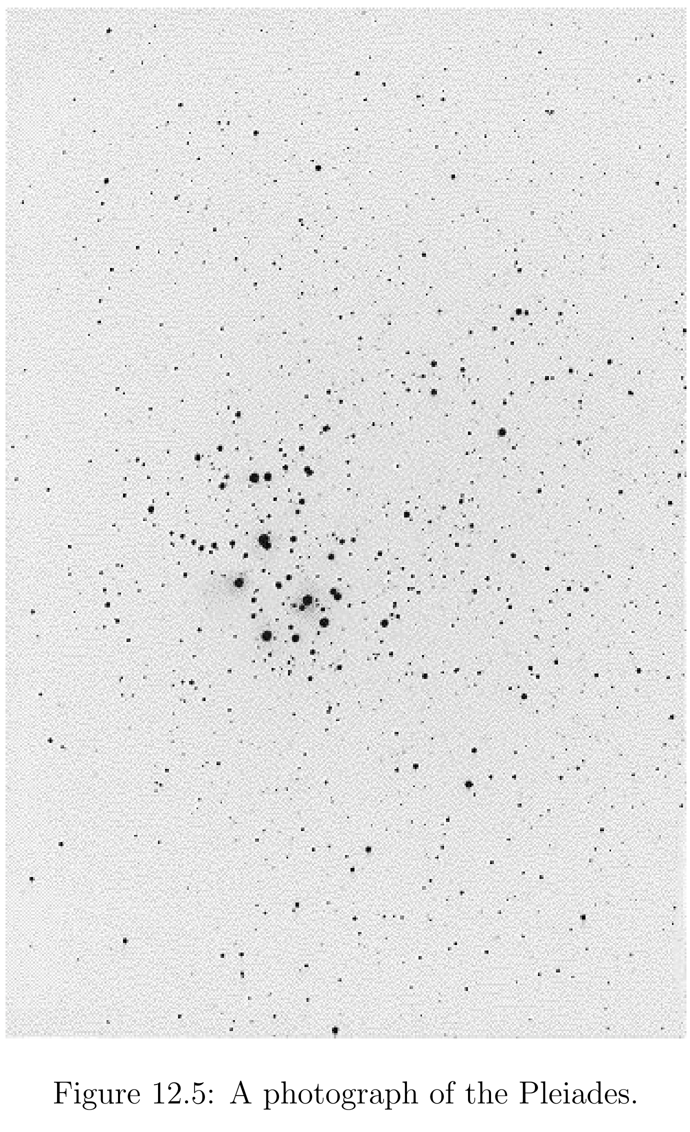
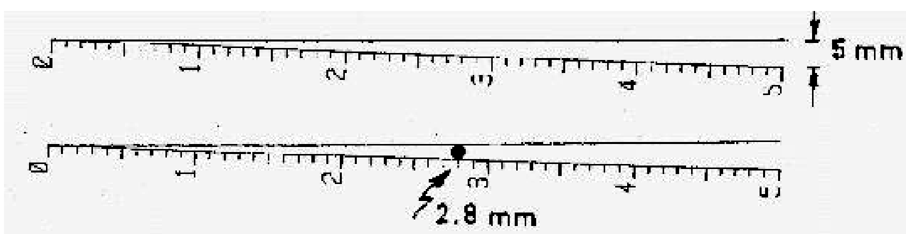


Figure 12.5: A photograph of the Pleiades.

As you will find out, the Pleiades is a relatively young group of stars. We will be using photographs of the Pleiades taken using two different color filters to construct a Color-Magnitude diagram. If you look closely at the photograph of the Pleiades, you will notice that the brighter stars are larger in size than the fainter stars. Note: you are not seeing the actual disks of the stars in these photographs. Brighter stars appear bigger on photographs because more light from them is detected by the photograph. As the light from the stars accumulates, it spreads out. Think of a pile of sand. As you add sand to a pile, it develops a conical, pyramid shape. The addition of more sand to the pile raises the height of the sand pile, but the *base* of the sand pile has to spread more to support this height. The same thing happens on a photograph. The more light there is, the larger the spread in the *image* of the star. In reality, *all* of the stars in the sky are much to far away to be seen as little disks (like those we see for the planets in our solar system) when viewed/imaged through *any existing telescope*. We would need to have a space-based telescope with a mirror 1.5 miles across to actually be able to see the stars in the Pleiades as little, resolved disks! [However, there are some special techniques astronomers have developed to actually measure the diameters of stars. Ask your TA about them if you are curious.]

Thus, we can use the sizes of the stars on a photograph to figure out how bright they are, we simply have to measure their diameters! A special tool, called a "dynameter", is used to measure sizes of circles. You will be given a clear plastic dynameter in class. A replica of this dynameter is shown here:



As demonstrated, a dynameter allows you to measure the diameter of a star image by simply sliding the dynameter along until the edges of the star just touch the lines. In the example above, the star image is 2.8 mm in diameter. On the following two pages are digitized scans of two photographs of the Pleiades taken through B and V filters. These photographs were digitized to allow us to put in an X-Y scale so that you can keep track of which star is which in the two different photographs. You should be able to compare the digitized photographs with the actual photo shown above and see that most of the brighter stars are on all three images.

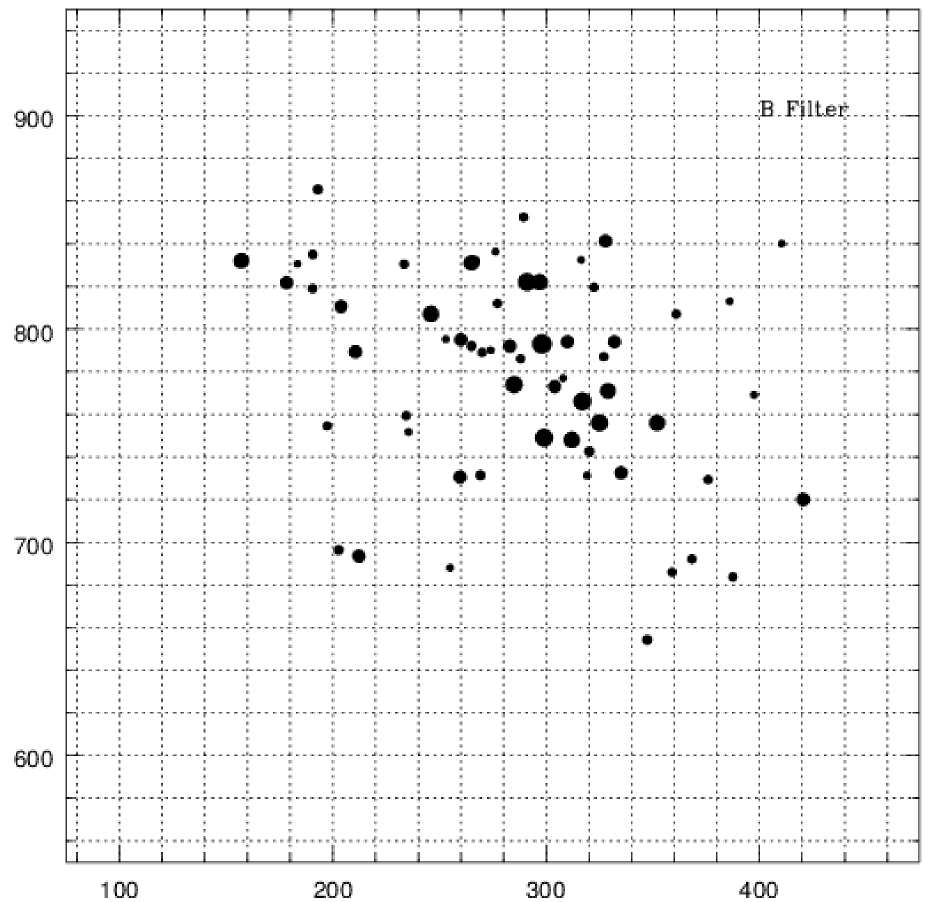


Figure 12.6: This is not the right figure for use in this lab–your TA will give you the correctly scaled version. (Go to: http://astronomy.nmsu.edu/astro/hrlabB.ps)

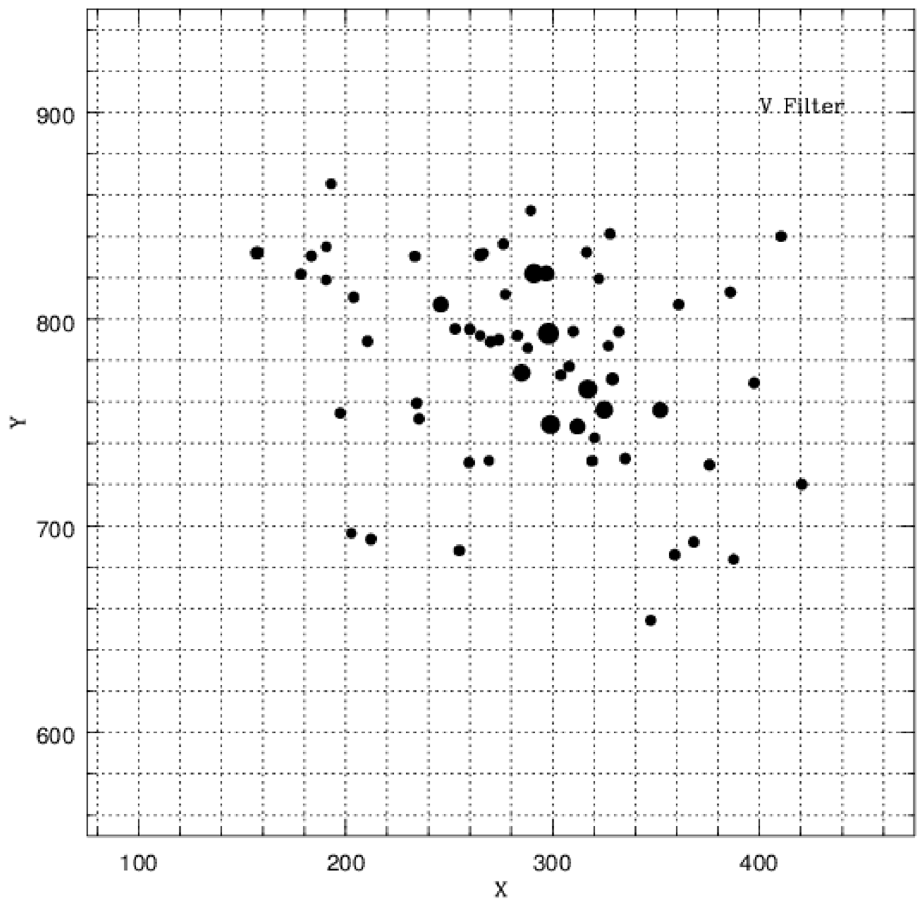


Figure 12.7: This is not the right figure for use in this lab–your TA will give you the correctly scaled version. (Go to: http://astronomy.nmsu.edu/astro/hrlabB.ps)

12.4.1 Procedure

The first task for this lab is to collect your data. What you need to do for this lab is to measure the diameters of ten of the 63 stars on both digitized photographs. At the end of this lab there is a data table that has the final data for 53 of the 63 stars. It is missing the information for ten of the stars (#'s 7, 8, 13, 18, 30, 39, 53, 55, 61, and 63). You must collect the data for these ten stars.

Task #1: First, identify the stars with the missing data on *both* of the digitized photographs (use their X,Y positions to do this). Then measure their diameters of these ten stars on both photographs using the dynameter. Write the V and B diameters into the appropriate spaces within the data table. [Note: You will probably not be able to measure the diameters to the same precision as shown for the other stars in the data table. Those diameters were measured using a computer. Do the best you can—make several measurements of each star and average the results.] (**15 points**)

12.4.2 Converting Diameters to Magnitudes

Obviously, the diameter you measure of a star on a photograph has no obvious link to its actual magnitude. For example, we could blow the photograph up, or shrink it down. The diameters of the stars would change, but the relative change in size between stars of different brightnesses would stay the same. To turn diameters into magnitudes requires us to "calibrate" the two photographs. For example, the brightest star in the Pleiades, "Alcyone" (star #35), has a V magnitude of 2.92, and has a V diameter of 4.4 mm. We have used this star to calibrate our data. Once you have completed measuring the diameters of the stars, you must convert those diameters (in millimeters) into V magnitudes and $(B - V)$ color index. To do so, requires you to use the following two equations:

$$V(\text{mag}) = -2.95\times(\text{V mm}) + 15.9 \text{ (Eq. \# 1)}$$

and

$$(B - V) = -1.0\times(\text{B mm} - \text{V mm}) + 0.1 \text{ (Eq. \#2)}$$

These equations might seem confusing to you because of the negative number in front of the diameters. But if you remember, the brighter the star, the smaller its magnitude. Brighter stars appear bigger, so bigger diameters mean smaller magnitudes! That is why there is a negative sign. Using the example of Alcyone, its V diameter is 4.4 mm and it has a B diameter of 4.7 mm. Putting the V diameter into equation #1 gives: $V\,(\text{mag}) = -2.95\times(4.4\text{ mm}) + 15.9 = -13.0 + 15.9 = 2.9$. So, the V magnitude of Alcyone is correct: $V = 2.9$, and we have calibrated the photograph. Its color index can be found using Eq. #2: $(B - V) = -\,1.0\times(4.7 - 4.4) + 0.1 =$

$-1.0\times(0.4) + 0.1 = -0.20$. Alcyone is a B star!

Task #2: Convert all of the B and V diameters into V magnitudes and $(B - V)$ color index, entering them into the proper column in your data table. Use any of the other stars in the table to see how it is done. Make sure all students in your group have complete tables with all of the data entered. **(15 points)**

12.4.3 Constructing a Color-Magnitude Diagram

The collection of the data is now complete. In this lab you are getting exactly the same kind of experience in "reducing data" that real astronomers do. Aren't you glad you didn't have to measure the diameters of all 63 stars? Obtaining and reducing data can be very tedious, tiring, or even boring. But it is an essential part of the scientific process. Because of the possibility of mis-measurement of the star diameters, a real astronomer doing this lab would probably measure all of the star diameters at least three times to insure that they had not made any errors. Today, we will assume you did everything exactly right, but we will provide a check shortly.

Now we want to finally get to the goal of the lab: constructing a Color-Magnitude diagram. In this portion of the lab, we will be plotting the V magnitudes vs. the $(B - V)$ color index. On the following page is a blank grid that has V magnitude on the Y axis, and the $(B - V)$ color index on the X axis. Now we want to plot your data onto this blank Color-Magnitude diagram to closely examine what kind of stars are in the Pleiades.

Task #3: For each star in your table, plot its position where the $(B - V)$ color index is the X coordinate, and the V magnitude is the Y coordinate. Note that some stars will have very similar magnitudes and colors because they are the same types of star. When this happens, simply plot them as close together as possible, making sure they are slightly separated for clarity. All students must complete their own Color-Magnitude diagram. (**15 points**)

Error checking: All of your stars should fit within the boundaries of the Color-Magnitude diagram! If not, go back and re-measure the problem star(s) to see if you have made an error in the B or V diameter or in the calculations.

12.5 Results

If you have done everything correctly, you should now have a Color-Magnitude diagram in which your plotted stars trace out the main sequence for the Pleiades. Use your Color-Magnitude diagram to answer the following questions:

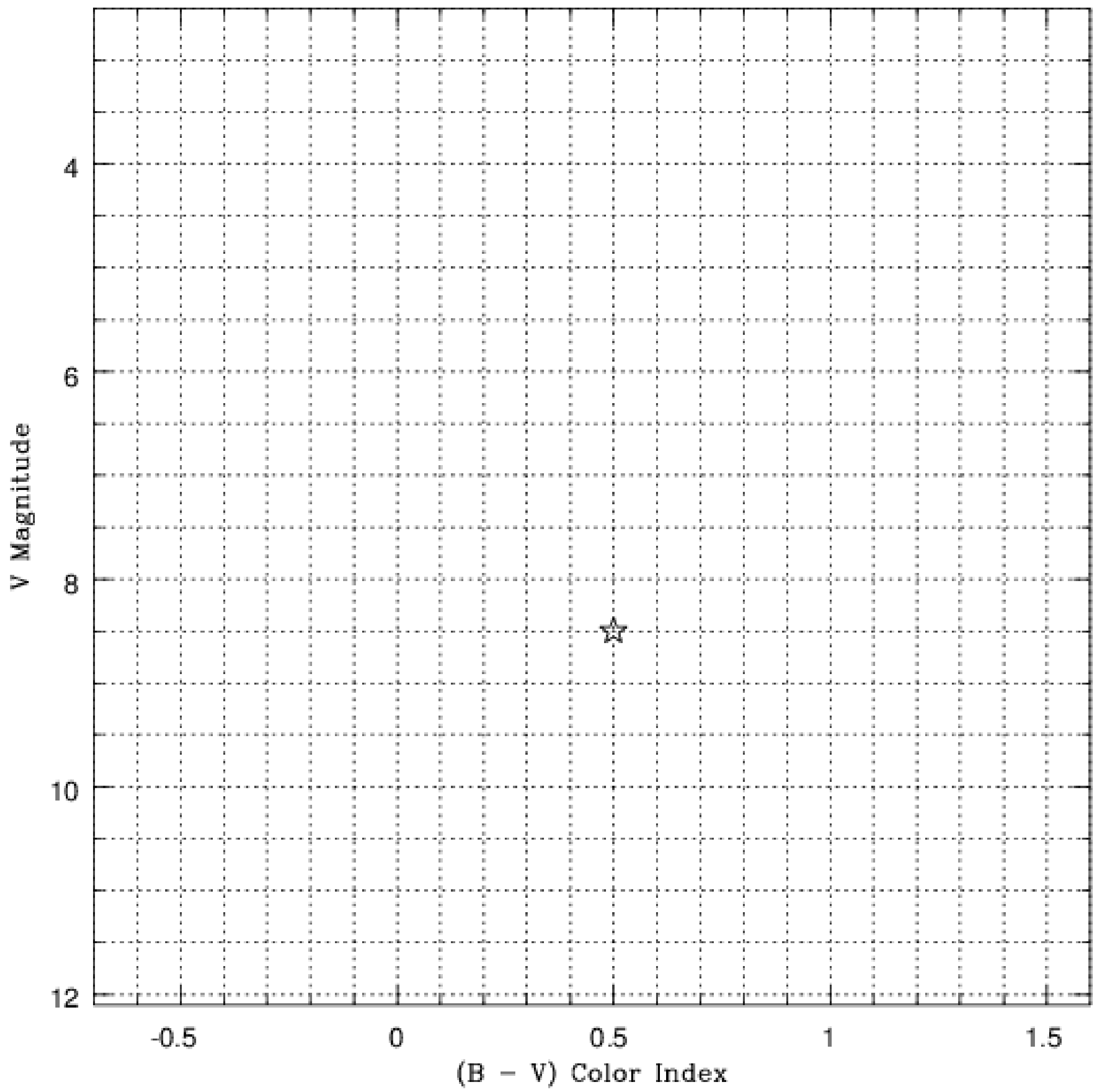


Figure 12.8: The Color-Magnitude Diagram for the Pleiades

1. Are there more B stars in the Pleiades, or more K stars? (**5 points**)

2. Given that the Sun is a main sequence G star, draw an "X" to mark the spot where the Sun would be in your Color-Magnitude diagram for the Pleiades (**5 points**)

3. The faintest stars that the human eye can see on a clear, dark night is $V = 6.0$. If the Sun was located in the Pleiades, could you see it with the naked eye? (**5 points**)

4. Are there any red giants or supergiants in the Pleiades? What does this tell you about the age of the Pleiades? (**5 points**)

12.6 Summary (35 points)

Please summarize the important concepts of this lab.

- Describe how an HR diagram is constructed.
- If you have plotted your HR Diagram for the Pleiades correctly, you will notice that the faint, red stars seem to have a spread when compared to the brighter, bluer stars. Why do you think this occurs? How might you change your observing or measuring procedure to fix this problem? [Hint: is it harder or easier to measure big diameters vs. small diameters?]
- Why are HR diagrams important to astronomers?

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

12.7 Possible Quiz Questions

1. What is a magnitude? Which star is brighter, a star with V = -2.0, or one with V = 7.0?

2. In an HR Diagram, what are the two quantities that are plotted?

3. What are the properties of a white dwarf?

4. What are the properties of a red giant?

5. What is a Color Index, and what does it tell you about a star?

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

White dwarfs are 100× less luminous than the Sun, but are hot, and have a negative color index $(B - V) = -0.2$. Given that a factor of 100 = 5 magnitudes, is it possible to plot the positions of white dwarfs on your Color-Magnitude diagram for the Pleiades?

Table 12.2: Data Table

#	X	Y	V(mm)	B(mm)	V(mag)	$(B-V)$
01	157.00	832.00	3.10	2.89	6.76	0.31
02	157.61	832.20	2.49	2.00	8.50	0.59
03	178.33	821.70	2.37	1.70	8.91	0.77
04	183.40	830.51	2.32	1.60	9.06	0.82
05	190.53	818.94	2.24	1.52	9.29	0.82
06	190.62	834.99	2.23	1.52	9.32	0.81
07	192.98	865.44				
08	197.37	754.50				
09	202.78	696.35	2.23	1.46	9.32	0.87
10	203.87	810.57	2.36	1.72	8.94	0.74
11	210.57	789.29	2.32	1.62	9.06	0.80
12	212.22	693.49	2.48	1.97	8.58	0.61
13	233.44	830.40				
14	234.34	759.27	2.35	1.57	8.97	0.88
15	235.50	751.74	2.40	1.85	8.82	0.65
16	246.00	807.00	3.26	3.07	6.28	0.29
17	252.95	795.24	2.75	2.35	7.78	0.50
18	254.95	688.02				
19	259.60	730.54	2.39	1.74	8.85	0.75
20	260.00	795.00	2.35	1.77	8.97	0.68
21	265.00	792.00	2.24	1.48	9.29	0.86
22	265.00	831.00	2.95	2.65	7.20	0.40
23	266.66	831.82	2.20	1.36	9.41	0.94
24	269.27	731.47	2.18	1.33	9.47	0.95
25	270.00	789.00	2.31	1.62	9.09	0.79
26	274.00	790.00	2.32	1.70	9.06	0.72
27	276.28	836.35	2.50	1.98	8.53	0.62
28	277.19	811.96	2.22	1.55	9.35	0.77
29	283.00	792.00	2.35	1.75	8.97	0.70
30	285.00	774.00				
31	288.00	786.00	2.20	1.42	9.41	0.88
32	289.50	852.50	2.18	1.54	9.47	0.74
33	291.00	822.00	4.24	4.46	3.39	−0.12
34	297.00	822.00	3.46	3.38	5.69	0.18
35	298.00	793.00	4.40	4.70	2.92	−0.20
36	299.00	749.00	4.09	4.23	3.83	−0.04
37	304.00	773.00	2.39	1.79	8.85	0.70
38	308.00	777.00	2.31	1.67	9.09	0.74
39	310.00	794.04				
40	312.00	748.00	3.35	3.20	6.02	0.25

Table 12.3: Data Table (cont.)

#	X	Y	V(mm)	B(mm)	V(mag)	$(B-V)$
41	316.46	832.35	2.52	2.01	8.47	0.61
42	317.00	766.00	3.93	4.00	4.31	0.03
43	319.14	731.31	2.38	1.81	8.88	0.67
44	320.29	742.55	2.17	1.46	9.50	0.81
45	322.43	819.50	2.17	1.52	9.50	0.75
46	325.00	756.00	3.62	3.57	5.22	0.15
47	327.00	787.00	2.20	1.47	9.41	0.83
48	327.80	841.25	2.34	1.68	8.99	0.76
49	329.00	771.00	2.87	2.52	7.43	0.45
50	332.00	794.00	2.62	2.14	8.17	0.58
51	335.13	732.56	2.28	1.54	9.17	0.84
52	347.41	654.23	2.15	1.43	9.55	0.82
53	352.00	756.00				
54	359.05	685.95	2.35	1.70	8.97	0.75
55	361.00	807.00				
56	368.31	692.12	2.35	1.69	8.96	0.76
57	375.90	729.41	2.20	1.50	9.41	0.80
58	375.90	729.41	2.36	1.73	8.94	0.73
59	386.00	813.00	2.37	1.72	8.91	0.75
60	387.50	683.69	2.20	1.54	9.41	0.76
61	397.48	769.11				
62	410.49	839.98	2.34	1.62	8.99	0.82
63	420.52	720.04				

Name:________________________

Date:________________________

13 Mapping the Galaxy

13.1 Introduction

When we look up at the night sky we see many different kinds of objects. Objects you can see with the naked eye are mostly stars and planets, although in the Southern Hemisphere, two nearby galaxies are visible. With a small telescope, one can see "globular clusters", "open clusters", "gaseous nebulae" and "galaxies". One very prominent feature which can be seen without the use of a telescope (in a dark location), is a swath of light that sweeps across the sky in a broad arc, the Milky Way. We know the Milky Way is a vast collection of stars that orbit about the center of our Galaxy in a flattened distribution resembling a plate or disk. This disk is often called the Milky Way or the Milky Way disk. It is but one of the components that make up our Galaxy.

In this lab, we will try to determine the shape of the Milky Way and our location in it based on observations of the distribution of several different types of objects in the sky.

- *Goals:* to determine the shape of our Galaxy and our place in it by observing patterns in the distributions of star clusters and nebulae
- *Materials:* Galaxy map, colored pencils or markers, scissors, tape, skewer

13.2 Getting used to the ideas

We are trying to determine the shape of our galaxy and our location in it. Since the Galaxy is so large, we cannot go outside of it and see what it looks like; instead, we have to infer what it looks like from our vantage point within the Galaxy.

The situation is even more complicated because, when we look at astronomical objects from the Earth, we cannot easily distinguish *how far away* the objects are. We only see in what direction they appear, but two objects which appear in the same direction are not necessarily at the same distance.

13.3 Map Projections

A hard aspect for some students to grasp is the idea of map projections. If you have completed the "Terrestrial Planets" lab, we discussed the idea of how a spherical object (such as the Earth) can be represented on a flat sheet of paper. In Figure 13.1

is a standard map of the Earth called a "Mercator Projection". Near the equatorial regions, this type of projection is not too bad, but as you move to the poles, the projection is terrible! Antarctica appears to have more land then all of the other continents combined, but in reality is much smaller than North America. This is because you cannot perfectly plot a sphere on a rectangular grid.

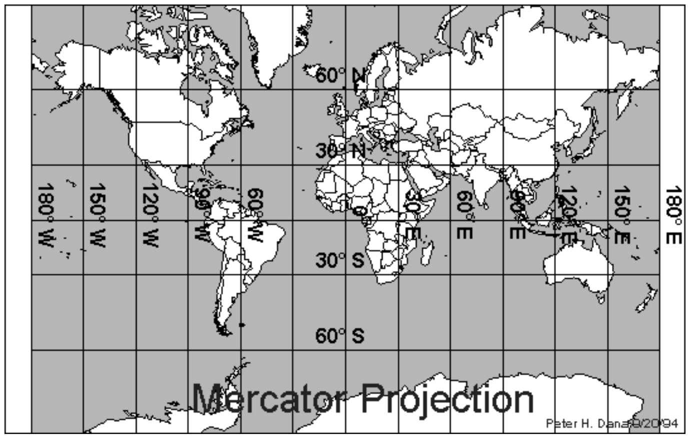


Figure 13.1: A "Mercator" projection of the Earth.

Map makers have come up with a variety of ways to make better maps that more correctly represent the actual sizes of objects on a sphere. For example, the "Mollweide" projection seen in Figure 13.2 uses a complex formula to *do a better job* at rendering the sizes and shapes of the Earth's continents, though it also fails really close to the poles.

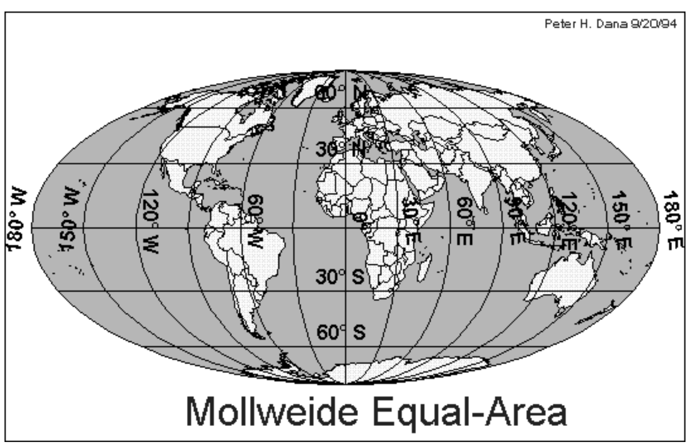


Figure 13.2: A "Mollweide" projection of the Earth.

A clever way to make a map of a globe is to mentally start with a spherical globe of paper, and then peel off segments of that sphere (like peeling an orange) so that we end up with a ragged, but more accurate representation of the Earth's surface.

An example is shown in Figure 13.3. Here it is slightly more difficult to make out the continents, but we could cut out this map with scissors and tape the pieces back together to construct a spherical globe!

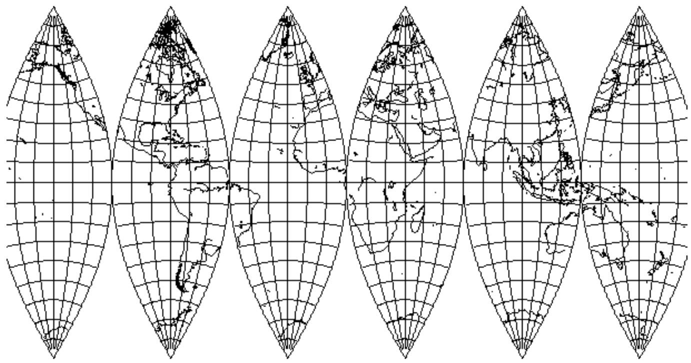


Figure 13.3: A map of the Earth made by "peeling" a sphere apart and plotting the result on a flat sheet of paper.

On such a map, objects on the far left are actually very near to objects on the far right. This is the type of map we will use in this exercise. Sitting on the Earth's surface, the sky appears to be a spherical entity that surrounds us–it is like a globe surrounding the globe of the Earth (ask your TA to show you the "celestial sphere" we have in the back room if they haven't brought it out for you to look at).

To develop your intuition about this sort of map, let's each make a map of the directions of all of your fellow students. Let's imagine that we are each standing inside of a globe and you can see all the other students in different directions. Let's all agree that "north" should be up towards the ceiling, that the left-most panel in the map is looking towards the front of the classroom, and that panels to the right move in a clockwise fashion around the classroom (so the right most panel is almost all the way back to the front again). Remember that we are imagining that you don't know anything about the distance to each student, only what direction they are seen in.

Now let's compare the maps. How do the maps differ for students in the middle of the classroom from those of students at the edge of the classroom?

Now let's imagine we can reconfigure the students so they are distributed uniformly throughout the room. This means there are students above and below you as well as around you! However, there may be more students in some directions than in others, depending on where you are located in the classroom. Again, make a map of the directions of your fellow students.

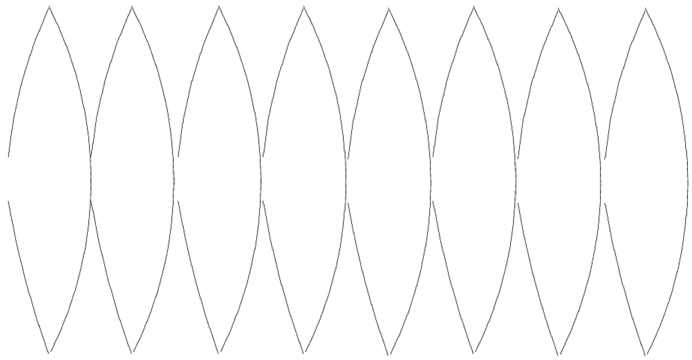


Figure 13.4: Map of students in this classroom.

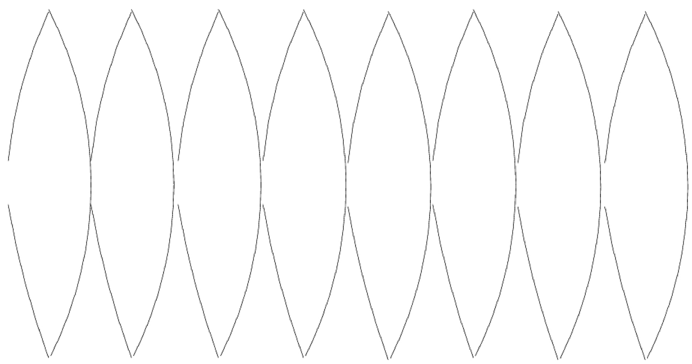


Figure 13.5: The map if students were distributed uniformly in every direction.

Again, let's compare the maps. How do the maps differ for students in the middle of the classroom from those of students at the edge of the classroom?

Let's summarize by drawing maps for four different idealized situations:

You are at the center of a uniform distribution of objects.

You are at the edge of a uniform distribution of objects.

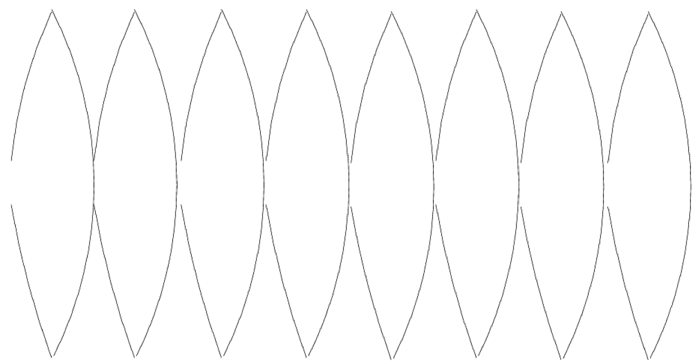


Figure 13.6: You are at the center of a uniform distribution of objects.

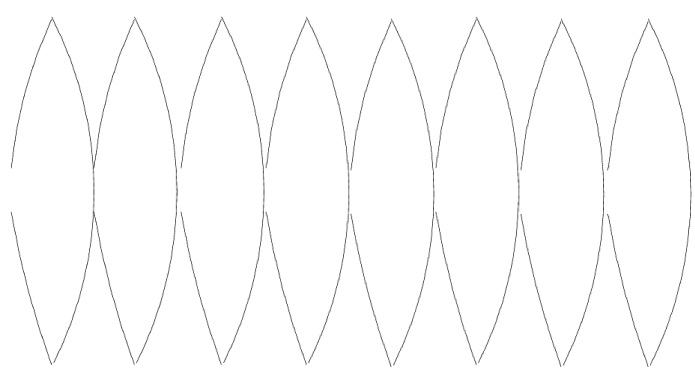


Figure 13.7: You are at the edge of a uniform distribution of objects.

You are at the center of a flattened distribution of objects.

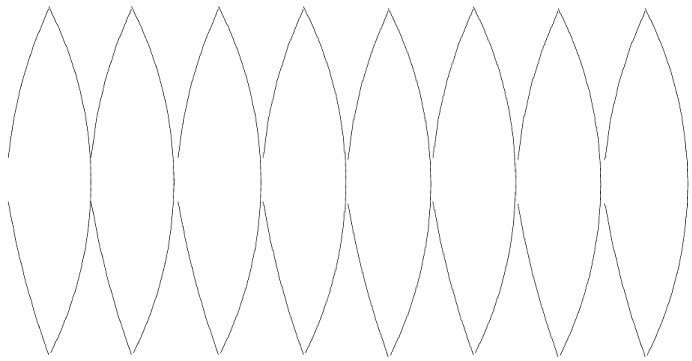


Figure 13.8: You are at the center of a flattened distribution of objects.

You are at the edge of a flattened distribution of objects.

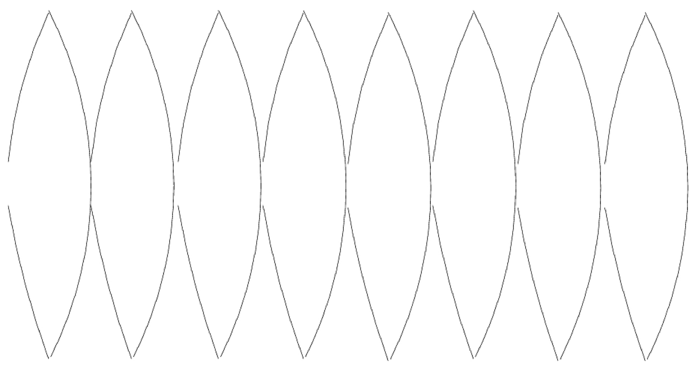


Figure 13.9: You are at the edge of a flattened distribution of objects.

One final thing to consider for the flattened distribution of objects: how does the appearance of objects on the map depend on the choice of where you put the North Pole?

13.4 The Contents of Our Milky Way Galaxy

Before we begin this lab, we should briefly introduce (or re-introduce) you to the various types of objects we will be plotting on our map. The band of light we call the Milky Way is in fact the sum of the light from billions of faint, and distant stars. Stars, and objects containing stars, are what we see with our eye, and those are the types of objects we will be plotting today. As you have/will find out in your lecture sessions, the Milky Way and other galaxies like it contain a number of objects that are not stars (such as molecular gas clouds), but these do not emit light that the human eye can detect (though we can infer their presence since they can absorb light!), and we will not be plotting those types of objects. Besides the band of light called the

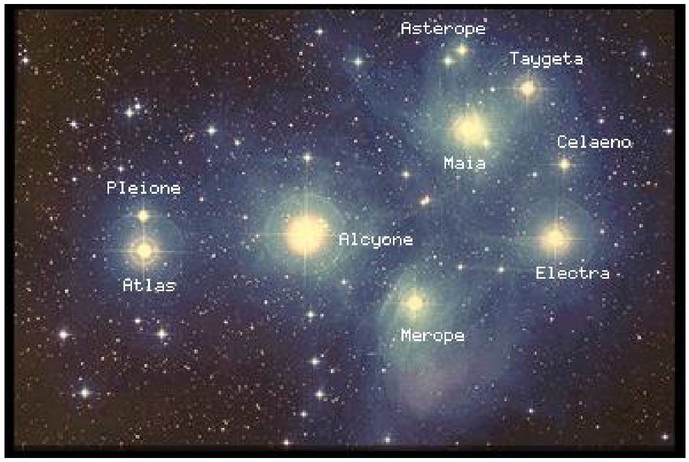


Figure 13.10: The Pleiades, an "Open Cluster" of relatively young stars.

Milky Way, there are four types of objects we will plot today: Open clusters, Gaseous nebulae, Globular clusters and Galaxies. The first three of these all belong to our Milky Way galaxy, while galaxies are "Milky Ways" in their own rite, and are located far beyond the boundaries of the Milky Way.

Depending on which labs your professor has chosen, you might have already encountered an "Open" cluster: the HR Diagram lab deals with the Pleiades, a well known Open cluster. A picture of the Pleiades is shown in Figure 13.10. The Pleiades consists of about 250 stars that are about 100 million years old. All of the stars in the Milky Way form in clusters. This is because they condense-out of cold molecular gas that is found in large clouds. Sometimes the gas cloud is small and produces a handful of stars, sometimes the gas cloud is large ($> 10^6$ M_{Sun}) and produces thousands of stars. Eventually, however, such a cluster will slowly fall apart, and the stars will wander off and circle the galaxy with unique orbits (when in a cluster, however, all of the stars orbit around the galaxy together as a single unit). This is why astronomers call them "Open", they eventually fall apart. If the were "Closed", they would not fall apart. Why do they fall apart? Because the gravity from very massive objects (such as molecular clouds) can pull Open clusters apart because they have relatively small ($<$ 5,000 M_{Sun}) total masses.

In contrast, "Globular clusters" are "Closed". Globular star clusters do not fall apart. An example is M15 shown in Figure 13.11. Globular star clusters contain 100,000 stars or more, and thus have large masses, and the gravity from all of these stars keeps them "bound": Even as they pass by very massive objects, they cannot be pulled apart. Globular clusters are made up of some of the oldest stars found in our galaxy–in fact, most astronomers believe that Globular clusters were among the first objects that formed as the large gas cloud that was the "proto-Milky Way" collapsed.

"Gaseous nebulae" are closely related to Open clusters. When a cluster of stars first forms, much of the gas left over from the formation of stars is still present. The

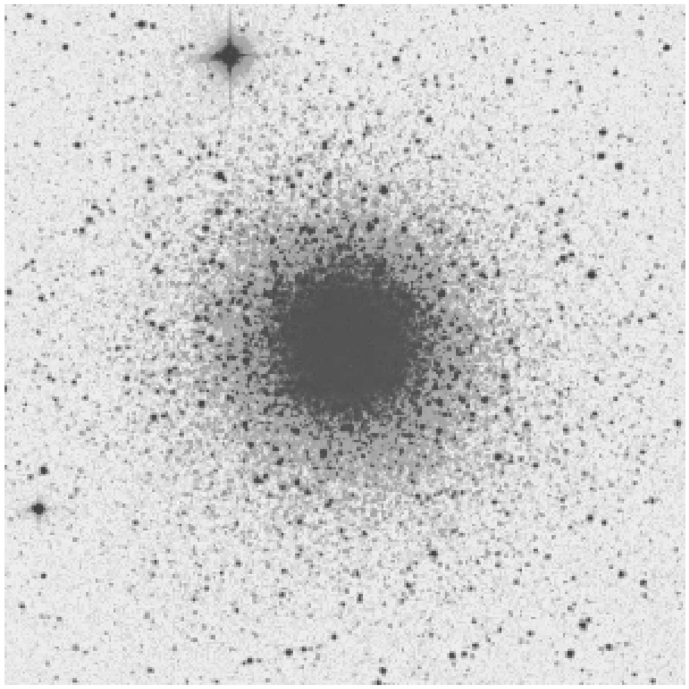


Figure 13.11: M15, a "Globular Cluster" which contains about 100,000 very old stars.

hotter stars in the cluster can "ionize" this gas (see the Spectroscopy lab), and cause it to glow. We see this gas as glowing knots and wisps of material surrounding the stars. The "Lagoon" Nebula, shown in Figure 13.12, is where several hundred young stars are being born. There is a lot of gas and dust that surrounds the very young open cluster at the center of the Lagoon, and such regions have complex structures.

As noted earlier, galaxies are large collections of objects mostly composed of stars, star clusters, gas, and dust. They are the hosts of Open clusters, Globular clusters and Gaseous nebulae (as well as molecular clouds, and some other objects we have not mentioned). To see some pretty pictures of galaxies, skip ahead to the "Galaxy Morphology" lab (the next lab in this manual), where images of several different types of galaxies are presented.

13.5 Exercises

Now we will create maps which show the distribution of different types of celestial objects in the sky. In Table 13.1 is a list of constellations within which bright objects can be observed using a small telescope. The list is separated into four subsections, one for each type of object: globular clusters, open cluster, gaseous nebulae and galaxies. For each object type we have listed names of constellations and the number of objects of each type which can be found within the constellations.

The figure at the end of this lab write-up has a blank map of the sky with the

Table 13.1: Location of different objects in the sky

Constellation Name	Number of Globular Clusters	Number of Galaxies	Number of Open Clusters	Number of Gaseous Nebulae
Cepheus			3	6
Pegasus	4	2		
Aquarius	1			
Capricornus	4			
Grus		2		
Draco		5		
Cygnus			7	6
Vulpecula				4
Aquila			3	2
Sagittarius	20		2	3
Telescopium	8			
Hercules	4			
Ophiuchus	8			
Scorpius			6	
Lupus			2	1
Norma			4	
Ursa Majoris		16		
Canes Venatici		10		
Bootes	2			
Coma Bernaices	3	12		
Virgo	2	11		
Centaurus	2	5	1	4
Leo		8		
Hydra	1	2		
Camelopardalis		4		
Monoceros				8
Canis Major			6	3
Puppis			5	1
Perseus			4	5
Taurus			3	3
Orion			3	6
Eriadanus		8		
Dorado	3	4		
Cassiopeia			8	7
Andromeda		4		
Triangulus		7		
Pisces		3		
Cetus		7		
Fornax		2		
Sculptor	1	5		

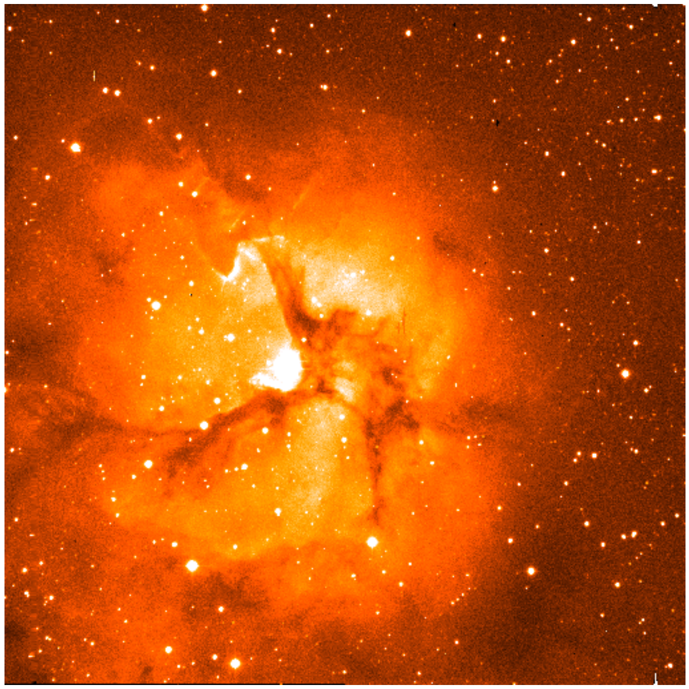


Figure 13.12: The Lagoon nebula, a gaseous nebula that contains several hundred young stars, some of which are so hot they ionize the hydrogen gas, causing it to glow.

boundaries of all the constellations marked on it. This map is a bit like a map of the world that shows the borders between countries but nothing else. Remember however, when we are looking at the sky we are looking up at the inside of a sphere that completely surrounds us, not down onto the outside of the Earth. *The continuous band of stars already marked on the map is the Milky Way.*

For each type of object, your group will construct a separate celestial sphere. *In the end, you should have four celestial spheres, each with one type of object marked on it.*

Complete the following steps to construct each sphere:

1. Mark the location of each object in your set on the celestial sphere map. As an approximation, just place the marks near the center of the constellation the objects are in. The marks should be dark and large enough so that you can see the marks on the other side of the sheet.

2. Use a different color for each type of object. This will help you distinguish the different types of celestial spheres. (Remember that each sphere will have only one type of object marked on it.)

3. Cut out the map by cutting along the outside bold-face lines. Be sure it NOT

to cut off the tabs at the top and bottom of each of the map subsections. These are essential for the proper construction of the globes.

4. A celestial sphere can be constructed using tape and skewers (be careful!). Your TA will give you more detailed instructions. Be sure that the skewers go through the small circles on the tabs at the top and bottom of each of the subsections of the map.

5. Be sure to construct your celestial sphere inside out because the Earth is really at the center of this "globe". The objects we see are above and around us so when we construct these spheres, the marks should be on the inside surface of the sphere.

Describe the distribution of each type of object. Work as a group with each celestial globe and describe the distribution you observe for each type of object. Be as detailed as possible and make references to the plane of the Milky Way which has already been marked on each map and also the *center of the Milky Way Galaxy which is toward the constellation Sagittarius.* This information will be used to complete the questions so make sure you take good notes! **(20 points)**
Milky Way:

Open Clusters:

Gaseous Nebulae:

Globular Clusters:

Galaxies:

13.6 Questions

The following questions are intended to help you reconstruct the shape of our galaxy based on the exercises done in the lab. Be sure to answer all parts of the questions and use complete sentences as always.

1. Do any of the descriptions of the idealized distributions of objects discussed in subsection 13.2 (i.e. center of flattened distribution, edge of flattened distribution, center of uniform distribution, edge of uniform distribution) match the descriptions of the distributions of the celestial objects? If so, which ones? Explain your reasoning. **(10 points)**

2. Considering the answer to the previous question, where do you think we are located with respect to the system of globular clusters? open clusters? gaseous nebulae? Explain your reasoning. **(10 points)**

3. Draw a sketch of the Galaxy based on your answers to Questions 1 and 2. Draw your picture showing our location relative to the distributions of the four types of objects. Be sure to include all four types of objects and label them. **(15 points)**

4. What do you think the distribution of galaxies, as compared with the distributions of the other objects, tells you about where galaxies are located? **(10 points)**

13.7 Summary (35 points)

Please summarize the concepts you learned from this lab. You might wish to discuss:

- Describe each of the 4 types of objects discussed in the lab.
- When you look up into the sky and see a band of stars, what does that tell you about the structure of the Galaxy you live in?
- Describe the difference (in terms of the 4 objects discussed in lab) in what you would see if you were *a)* standing in the center of our Galaxy, and *b)* standing at the edge of our Galaxy.
- What conclusions can you draw about the distribution of objects in our galaxy and beyond?

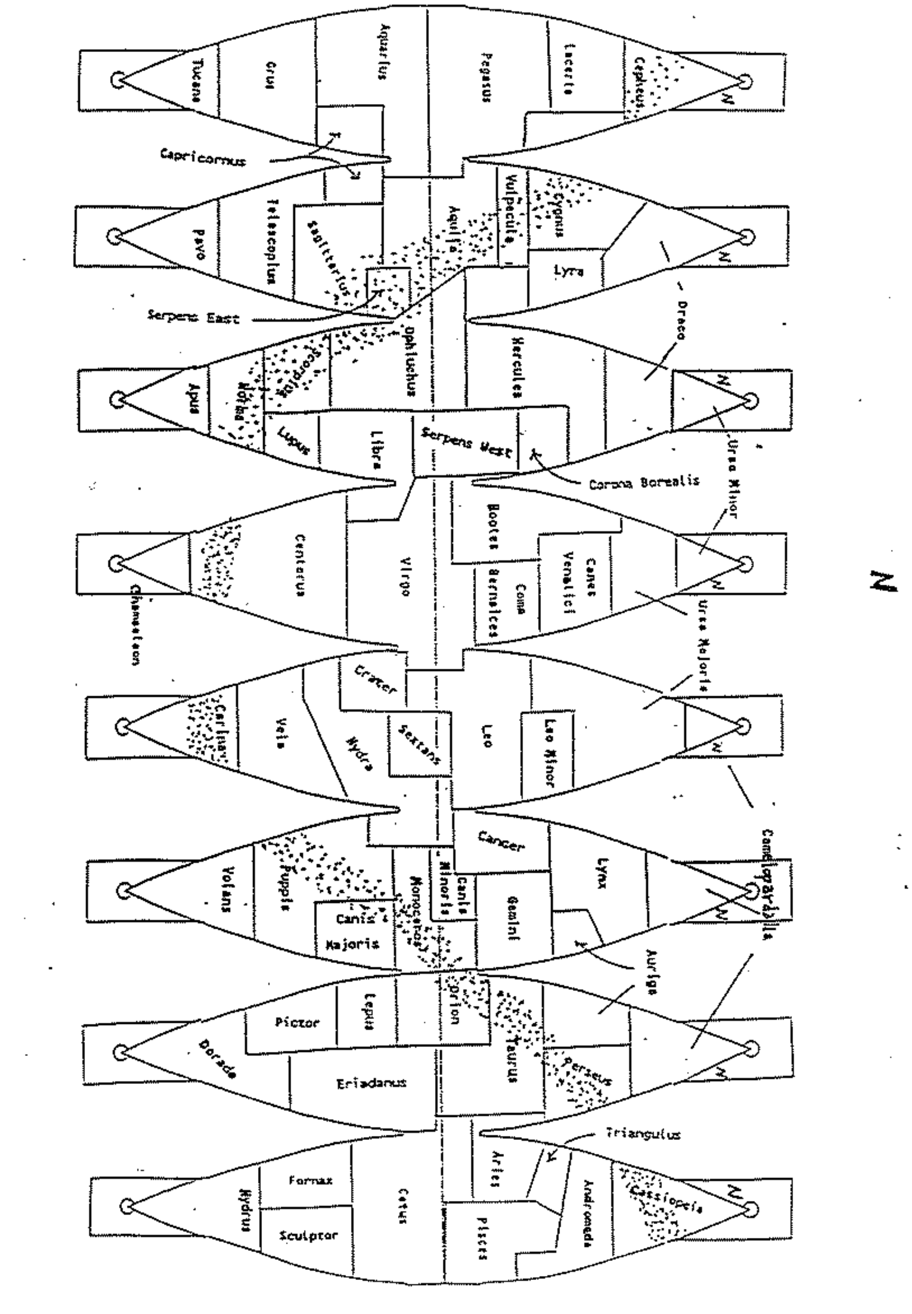
Use complete sentences, and proofread your summary before handing in the lab.

13.8 Possible Quiz Questions

1. What is an open cluster?
2. What is an HII region?
3. What is a map projection?
4. Why are map projections used?

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

In this lab we have plotted objects that are in the Milky Way galaxy. What would the plot look like if we plotted external galaxies? Make sure to research this topic so that you have confidence in what you are plotting, and make a rough sketch of the distribution of external galaxies (or photocopy one of the "orange peel" diagrams and plot your galaxies on that)


Tucana
Grus
Aquarius
Pegasus
Lacerta
Cepheus
N
Capricornus
Pavo
Telescopium
Sagittarius
Aquila
Vulpecula
Cygnus
Lyra
Draco
Serpens East
Apus
Norma
Scorpius
Ophiuchus
Hercules
Lupus
Libra
Serpens West
Corona Borealis
Ursa Minor
Centarus
Virgo
Bootes
Canes Venatici
Coma Bernaices
Chamaeleon
Ursa Majoris
Carina
Vela
Crater
Hydra
Sextans
Leo
Leo Minor
Camelopardalis
Volans
Puppis
Canis Majoris
Monoceros
Canis Minoris
Cancer
Gemini
Lynx
Auriga
Dorado
Pictor
Lepus
Orion
Taurus
Perseus
Eriadanus
Triangulus
Aries
Andromeda
Cassiopeia
Hydrus
Fornax
Sculptor
Cetus
Pisces

Name:______________________________

Date:______________________________

14 Galaxy Morphology

14.1 Introduction

Galaxies are enormous, "gravitationally bound" collections of millions, upon millions of stars. In addition to these stars, galaxies also contain varying amounts of gas and dust from which stars form, or from which they *have* formed. In the centers of some galaxies live enormous black holes that are sucking-in, and ripping apart stars and clouds of atomic and molecular gas. Galaxies come in a variety of shapes and sizes. Some galaxies have large numbers of young stars, and star forming regions, while others are more quiescent, mostly composed of very old, red stars. In today's lab you will be looking at pictures of galaxies to become familiar with the appearances, or "morphology", of the various types of galaxies, and learn how to classify galaxies into one of the three main categories of galaxy type. We will also use photographs/images of galaxies obtained using different colors of light to learn how the appearances of galaxies depend on the wavelength of light used to examine them.

- *Goals:* to learn about galaxies
- *Materials:* a pen to write with, a ruler, a calculator, and one of the notebooks of galaxy pictures

14.2 Our Home: The Milky Way Galaxy

During the summertime, if you happen to be far from the city lights, take a look at the night sky. During the summer, you will see a faint band of light that bisects the sky. In July, this band of light runs from the Northeast down to the Southwest horizon (see Fig. 14.1). This band of light is called the Milky Way, our home galaxy. Because we are located within the Milky Way galaxy, it is actually very hard to figure out its exact shape: we cannot see the forest for the trees! Thus, it is informative to look at other galaxies to attempt to compare them to ours to help us understand the Milky Way's structure.

Galaxies are collections of stars, and clouds of gas and dust that are bound together by their mutual gravity. That is, the mass of all of the stars, gas and dust pull on each other through the force of gravity so that they "stick together". Just like the planets in our Solar System orbit the Sun, the stars (and everything else) in a galaxy orbit around the central point of the galaxy. The central point in a galaxy is referred to as the "nucleus". In some galaxies, there are enormous black holes that sit right at the center. These black holes can have a mass that is a billion times that of the Sun (10^9 $M_\odot$)! But not all galaxies have these ferocious beasts at their

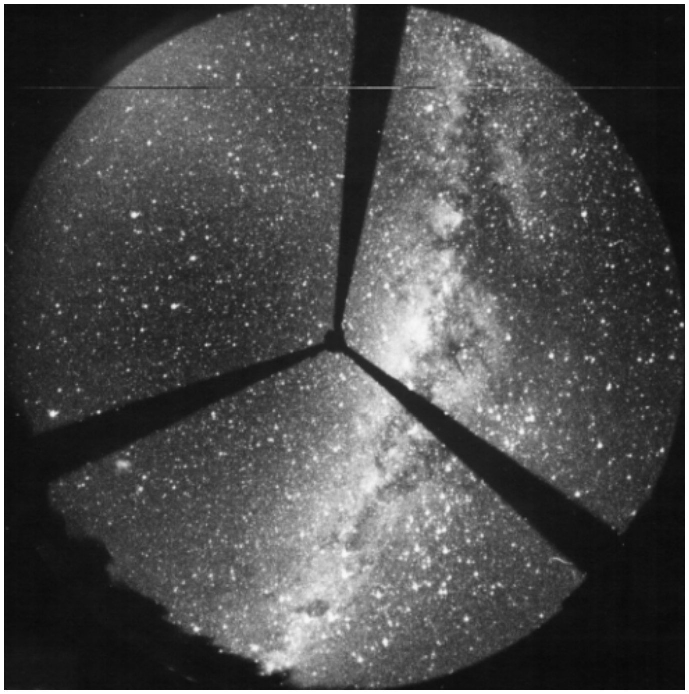


Figure 14.1: A fisheye lens view of the summertime sky showing the band of light called the Milky Way. This faint band of light is composed of the light from thousands and thousands of very faint stars. The Milky Way spans a complete circle across the celestial sphere because our solar system is located within the "disk" of the galaxy.

cores, some merely have large clusters of young stars, while others have a nucleus that is dominated by large numbers of old stars. The Sun orbits around the nucleus of our Milky Way galaxy (Fig. 14.2) in a similar fashion to the way the Earth orbits around the Sun. While it only takes one year for the Earth to go around the Sun, it takes the Sun more than 200 million years to make one trip around our galaxy!

Note that the central region ("bulge" and nucleus) of the Milky Way has a higher density of stars than in the outer regions. In the neighborhood of the Sun, out in the "disk", the mass density is only 0.002 $M_{\odot}/ly^3$ (remember that density is simply the mass divided by the volume: M/V, here the Mass is solar masses: $M_{\odot}$, and Volume is in cubic light years: ly^3). In the central regions of our Milky Way galaxy (within 300 ly of the center), however, the mass density is 100 times higher: 0.200 $M_{\odot}/ly^3$. What does this mean? The nearest star to the Sun is Alpha Centauri at 4.26 ly. If we were near the nucleus of our Milky Way galaxy, there would be 200 stars within 4.26 ly of the Sun. Our sky would be ablaze with dozens of stars as bright as Venus, with some as bright as the full moon! It would be a spectacular sight.

Our Milky Way galaxy is a spiral galaxy that contains more than 100 billion stars. While the Milky Way is a fairly large galaxy, there are much larger galaxies out there, some with 100 times the mass of the Milky Way. But there are an even larger number of very small "dwarf" galaxies. Just like the case for stars, nature prefers to produce

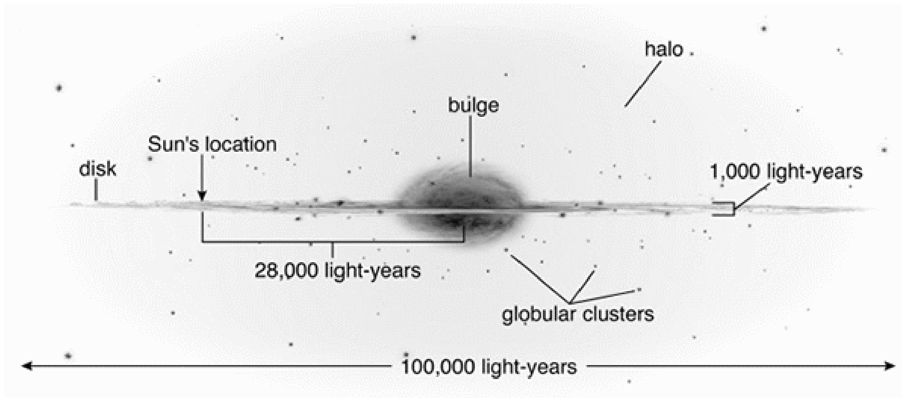


Figure 14.2: A diagram of the size and scale of our "Milky Way" galaxy. The main regions of our galaxy, the "bulge", "disk", and "halo" are labeled. Our Milky Way is a spiral galaxy, with the Sun located in a spiral arm 28,000 ly from the nucleus. Note that the disk of the Milky Way galaxy spans 100,000 ly, but is only about 1,000 ly thick. While the disk and spiral arms of the Milky Way are filled with young stars, and star forming regions, the bulge of the Milky Way is composed of old, red stars.

lots of little galaxies, and many fewer large galaxies. The smallest galaxies can contain only a few million stars, and they are thousands of times smaller than the Milky Way.

14.3 Galaxy Types: Spirals Ellipticals, and Irregulars

Shortly after the telescope was invented, astronomers started scanning the sky to see what was out there. Among the stars, these first astronomers would occasionally come across a faint, fuzzy patch of light. Many of these "nebulae" (Latin for cloud-like) appeared similar to comets, but did not move. Others of these nebulae were resolved into clusters of stars as bigger telescopes were constructed, and used to examine them. Some of these fuzzy nebulae, however, did not break-up into stars no matter how big a telescope was used to look at them. While many of these nebulae are clouds of glowing hydrogen gas within the Milky Way galaxy (HII regions), others (some of which resembled pinwheels) were true galaxies–similar to the Milky Way in size and structure, but millions of light years from us. It was not until the 1920's that the actual nature of galaxies was confirmed–they were true "Island Universes", collections of millions and billions of stars. As you will find out in your lecture sessions, the space between galaxies is truly empty, and thus most of the matter in the Universe resides inside of galaxies: *They are islands of matter in an ocean of vacuum.*

Like biologists or other scientists, astronomers attempt to associate similar types of objects into groups or classes. One example is the spectral classification sequence (*OBAFGKM*) for stars. The same is true for galaxies–we classify galaxies by their observed properties. It was quickly noticed that there were two main types of galaxies, those with pinwheel shapes, "spiral galaxies", and smooth, mostly round or oval galaxies, "elliptical" galaxies. While most galaxies could be classified as spirals or ellipticals, some galaxies shared properties of both types, or were irregular in shape. Thus, the classification of "irregular". This final category is a catch-all for any galaxy that cannot be easily classified as a spiral or elliptical. Most irregular galaxies are small, messy, unorganized clumps of gas and stars (though some irregular galaxies result from the violent collisions of spiral and/or elliptical galaxies).

14.3.1 Spiral Galaxies

The feature that gives spiral galaxies their shape, and leads to their classification are their spiral arms. An example of a beautiful spiral is M81 shown in Fig. 14.3. A spiral galaxy like M81 resembles a whirlpool, or pinwheel: arms of stars, gas and dust that radiate in curving arcs from the central "bulge".

Figure 14.3: The Sb spiral galaxy M81. Notice the nice, uniform spiral arms that are wound tightly around the large, central bulge. Inside the spiral arms, there are large regions of glowing gas called HII regions–where stars are being born. These stand out as knots or clumps in the spiral arms. The dark spots, lanes, and arcs are due to dust clouds that are associated with these star forming regions.

Other spiral galaxies, like M51 shown in Fig. 14.4, have less tightly wound spiral arms, and much smaller bulges. Finally, there are spiral galaxies with very tightly wound spiral arms that are dominated by their bulge, like the Andromeda galaxy (M31) shown in Fig. 14.5. The arms are so tightly wound, that it is hard to tell where one ends and the other begins. These types of galaxies also have much less star formation.

Spiral galaxies are classified by how tightly their arms are wound, and how large their central bulges are. There are three main types of spirals: Sa, Sb, and Sc. Sa spirals have large bulges and tightly wound arms, while Sc's have very loosely wound

Figure 14.4: The Sc spiral galaxy M51. Notice the large, clumpy spiral arms that are loosely wound around the small, central bulge. Inside the spiral arms of M51 there are very many large HII regions–M51 has many young star forming regions. Notice that there is also a lot more dust in M51 than in M81.

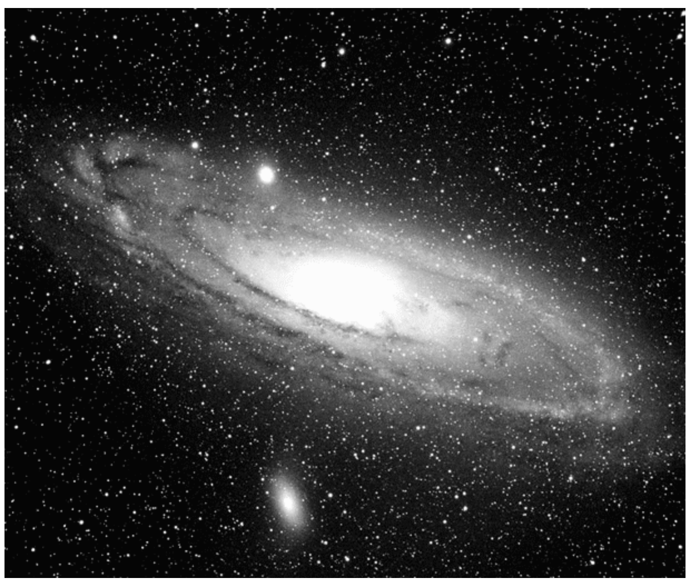


Figure 14.5: The Sab spiral galaxy M31. Notice the very large bulge, and very tightly wound spiral arms. Like the Milky Way, the Andromeda Galaxy has several small galaxies in orbit around it (just like planets orbit the Sun, some small galaxies can be found orbiting around large galaxies). Two of these galaxies can be seen as the round/elliptical blobs above and below the disk of the Andromeda galaxy shown here. Both are elliptical galaxies, discussed in the next subsection.

arms, and small bulges. Sb's are intermediate between Sa's and Sc's (of course, like M31, there are galaxies that fall halfway between two classes, and they are given names like Sab, or Sbc). The spiral classification sequence is shown in Fig. 14.6.

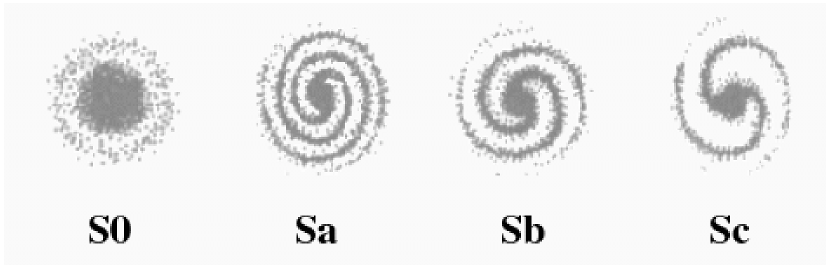


Figure 14.6: The classification sequence for spirals. S0 spirals are galaxies that show a small disk that is composed of only old, red stars, and have no gas, little dust and no star forming regions. They are mostly a large bulge with a weak disk, with difficult-to-detect spiral arms. They actually share many properties with elliptical galaxies. Sa galaxies have large bulges, and tightly wound spiral arms. Sb's have less tightly wound arms, while Sc's have very loosely wound arms, and have tiny bulges.

14.3.2 Elliptical Galaxies

Elliptical galaxies do not have as much structure as spiral galaxies, and are thus less visually interesting. They are smooth, round to elliptical collections of stars that are highly condensed in their centers, that slowly fade out at their edges. Unlike spiral galaxies, where all of the stars in the disk rotate in the same direction, the stars in elliptical galaxies do not have organized rotation: the individual stars orbit the nucleus of an elliptical galaxy like an individual bee does in a swarm. While they have random directions, all of the billions of stars have well-defined orbits around the center of the galaxy, and take many millions of years to complete an orbit. An example of an elliptical galaxy is shown in Fig. 14.7.

Elliptical galaxies can appear to be perfectly round, or highly elongated. There are eight categories, ranging from round ones (E0) to more football-shaped ones (E7). This classification scheme is diagrammed in Fig. 14.8.

It is actually much easier to classify an elliptical galaxy, as the type of elliptical galaxy can be determined by measuring the major and minor axes of the ellipse. The definitions of the major and minor axes of an ellipse are shown in Fig. 14.9. To determine which type of an elliptical galaxy you are looking at, you simply measure the major axis ("a") and the minor axis ("b"), and calculate: $10\times(a - b)/a$. You will do this for several elliptical galaxies, below.

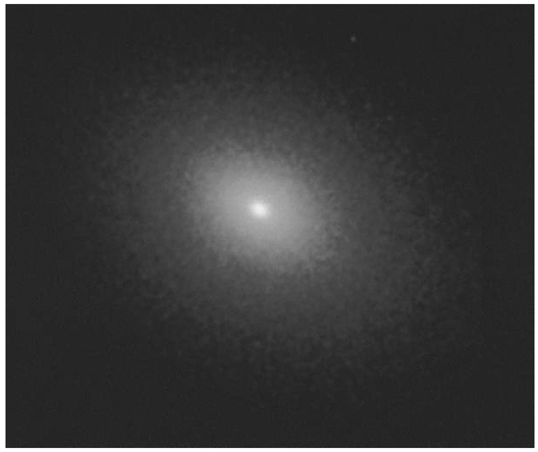


Figure 14.7: A typical elliptical galaxy, NGC205, one of the small elliptical galaxies in orbit around the Andromeda galaxy shown in Fig. ??. Most elliptical galaxies have a small, bright core, where millions of stars cluster around the nucleus. Just like the Milky Way, the density of stars increases dramatically as you get near the nucleus of an elliptical galaxy. Many elliptical galaxies have black holes at their centers. NGC205 is classified as an E5.

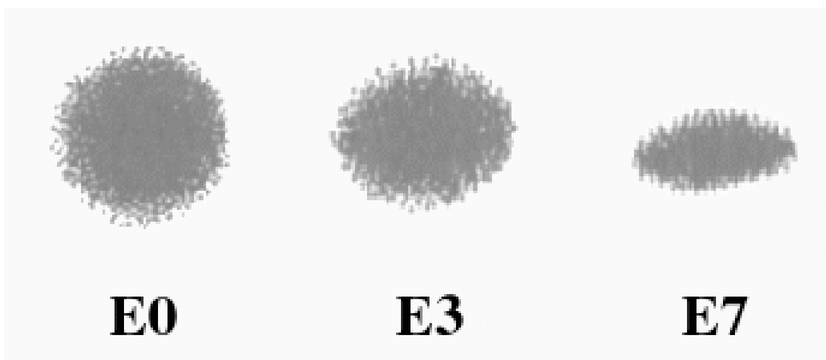


Figure 14.8: The classification scheme for elliptical galaxies. Elliptical galaxies range from round (E0), to football shaped (E7).

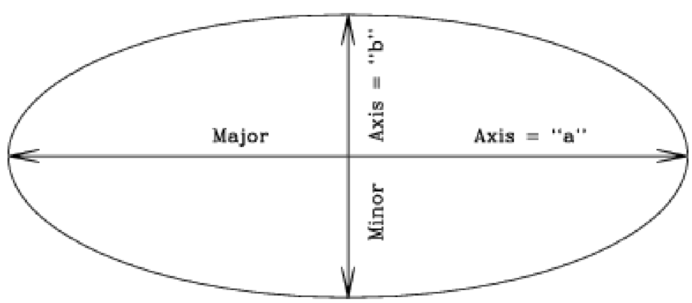


Figure 14.9: The definition of the major ("a") and minor ("b") axes of an ellipse.

14.3.3 Irregular Galaxies

As noted above, the classification of a galaxy as an "irregular" usually stems from the fact that it cannot be conclusively categorized as either a spiral or elliptical. Most irregular galaxies, like the LMC shown in Fig. 14.10, are small, and filled with young stars, and star forming regions. Others, however, result when two galaxies collide, as shown in Fig. 14.11.

Figure 14.10: The Large Magellanic Cloud (LMC). The LMC is a small, irregular galaxy that orbits around the Milky Way galaxy. The LMC (and its smaller cousin, the SMC) were discovered during Magellan's voyage, and appear as faint patches of light that look like detached pieces of the Milky Way to the naked eye. The LMC and SMC can only be clearly seen from the southern hemisphere.

14.3.4 Galaxy Classification Issues

We have just described how galaxies are classified, and the three main types of galaxies. Superficially, the technique seems straightforward: you look at a picture of a galaxy, note its main characteristics, and render a classification. But there are a few complications that make the process more difficult. In the case of elliptical galaxies, we can never be sure whether a galaxy is truly a round E0 galaxy, or an E7 galaxy seen from an angle. For example, think of a football. If we look at the football from one angle it is long, and pointed at both ends. But if we rotate it by 90^o, it appears to be round. This is a "projection effect", and one that we can never remove since we cannot go out and look at elliptical galaxies from some other angle.

As we will find out, spiral galaxies suffer from a different classification issue. When the Sa/Sb/Sc classification scheme was first devised, only photographs sensitive to blue light were used. If you actually look at spiral galaxies at other wavelengths, for example in the red or infrared, the appearance of the galaxy is quite different. Thus it is important to be consistent with what kind of photograph is used to make a galaxy classification. We will soon learn that the use of galaxy images at other wavelengths besides that which our eyes are sensitive to, results in much additional information.

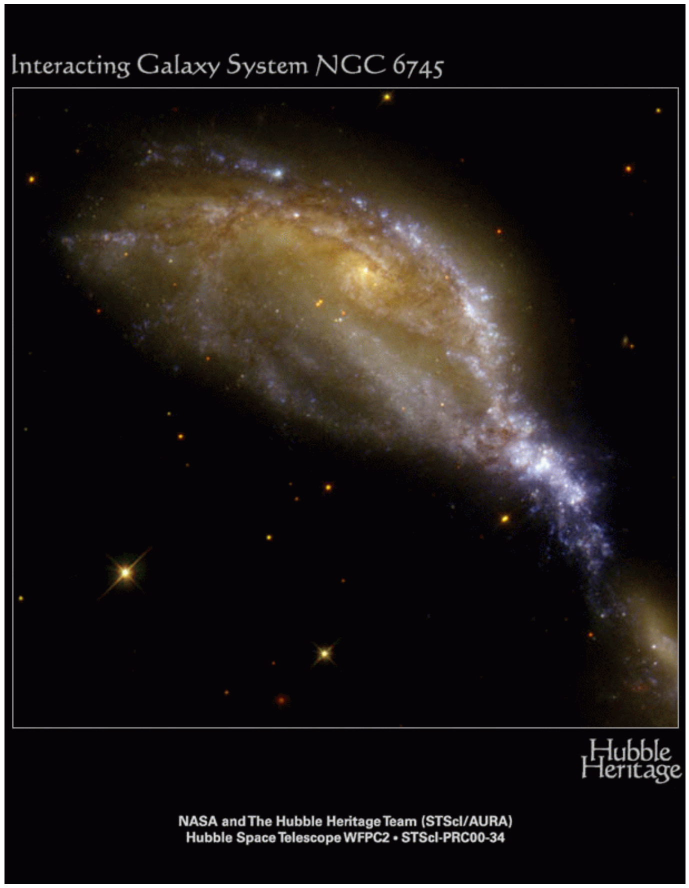


Figure 14.11: An irregular galaxy that is the result of the collision between two galaxies. The larger galaxy appears to have once been a normal spiral galaxy. But another galaxy (visible in the bottom right corner) ran into the bigger galaxy, and destroyed the symmetry typically found in a spiral galaxy. Galaxy collisions are quite frequent, and can generate a large amount of star formation as the gas and dust clouds are compressed as they run into each other. Some day, the Milky Way and Andromeda galaxies are going to collide—it will be a major disruption to our galaxy, but the star density is so low, that very few stars will actually run into each other!

14.4 Lab Exercises

For this lab, each group will be getting a notebook containing pictures of galaxies. *These notebooks are divided into five different subsections.* Below, there are *five subsections* with exercises that correspond to each of the five subsections in the notebook. Make sure to answer all of the questions fully, and to the best of your ability.

Section #1: Classification of Spiral Galaxies
In this subsection we look at black and white photographs of spiral galaxies. First you will see three standard spiral galaxies that define the Sa, Sb, and Sc subtypes, followed by more classification exercises.

Exercise #1: In pictures 1 through 3 are standard spiral galaxies of types Sa, Sb, Sc. Using the discussion above, and Figures 14.3 to 14.6, classify each of the spiral galaxies in these three pictures and describe what properties led you to decide which subclass each spiral galaxy fell into. **(3 points)**

Exercise #2: The pictures of the galaxies that you have seen so far in this lab are "positive" images, just like you would see if you looked at those galaxies through a large telescope—white means more light, black means less light. But working with the negative images is much more common, as it is much easier to see fine detail when presented as dark against a light background versus bright against a dark background. For example, Picture #4 is the negative image for Picture #1. Detail that is overlooked in a positive image can be seen in a negative image. For most of the rest of this lab, we will look at negative images like those shown in Picture #4.

Classify the spiral galaxies in Pictures #5, 6, 7 and 8. In each case, describe what led you to these classifications. **(4 points)**

Exercise #3: So far, we have looked at spiral galaxies that have favorable orientations for classification. That is, we have seen these galaxies from a direction that is almost perpendicular to the disk of the galaxy. But since the orientation of galaxies to our line of sight is random, many times we see galaxies from the side view. In this exercise, you will look at some spiral galaxies from a less favorable viewing angle.

In pictures #9, 10, and 11 are three more spiral galaxies. Try to classify them. Use the same techniques as before, but try to visualize how each subtype of spiral galaxy would change if viewed from the side. (Remember that in a negative image, bright white means no light, and dark means lots of light–so dusty regions show up as white!) **(3 points)**

Section #2: Elliptical Galaxies As described earlier, elliptical galaxies do not show very much detail–they are all brighter in the center, and fade away at the edges. The only difference is in *how* elliptical they are, ranging from round (E0) to football-shaped (E7). In this subsection will learn how to classify elliptical galaxies.

Exercise #4: In pictures #12, 13, 14, and 15 are some elliptical galaxies. Using Figure 14.8 as a guide, classify each of these four galaxies as either E0, E1, E2, E3, E4, E5, E6, or E7. Describe how you made each classification. **(4 points)**

Exercise #5: In our discussion about elliptical galaxy classification, we mentioned that there was a *quantitative* method to classify elliptical galaxies: you use the equation $10\times(a - b)/a$ to derive the subclass number. In this equation "a" is the major axis (long diameter) and "b" is the minor axis (the short diameter). Go back to Figure 14.9 to see the definition of these two axes. For example, if you measured a value of a = 40 mm, and b = 20 mm, than the subclass is $10\times(40 - 20)/40 = 10\times(20/40) = 10\times(0.5) = 5$. So that this particular elliptical galaxy is an E5.

If the measurements for an elliptical galaxy are a = 30 mm and b= 20 mm, what subclass is that galaxy? (Round to the nearest integer.) **(2 points)**

Measure the major and minor axes for each of the galaxies in pictures #12, 13, 14, and 15, and calculate their subtypes. Note: it can sometimes be hard to determine where the "edge" of the galaxy is–try to be consistent and measure to the same level of brightness. **(4 points)**

It is pretty hard to measure the major and minor axes of elliptical galaxies on black and white photographs! Usually, astronomers use digital images, and then use some sort of image processing to make the task easier. Picture #16 is a digitized version of picture #15, processed so that similar light levels have the same color. As you can see, this process makes it much easier to define the major and minor axes of an elliptical galaxy.

Exercise #6: Measure the major and minor axes of the two elliptical galaxies shown in Pictures #16 and #17, and classify them using the same equation/technique as before. **(2 points)**

Section #3: Irregular Galaxies While most large galaxies in our Universe are either spirals or ellipticals, there are a large number of very strange looking galaxies. If we cannot easily classify a galaxy as a spiral or elliptical, we call it an Irregular galaxy. Some irregular galaxies appear to show some characteristics of spirals and/or ellipticals, others are completely amorphous blobs. Many of the most unusual looking galaxies are the result of the interactions between two galaxies (such as a collision). Sometimes the two galaxies merge together, other times they simply pass through each other (see Fig. 14.11). Pictures 18 through 22 are of irregular galaxies.

Exercise #7: The peculiar shapes and features of the irregular galaxies shown in Pictures #18, 19 and 20 are believed to be caused by galaxy collisions or galaxy-galaxy interactions (that is, a close approach, but not a direct collision). Why do you think astronomers reached such a conclusion for these three galaxies? **(4 points)**

Exercise #8: In Pictures #21 and 22 are images of two "dwarf" irregular galaxies. Note the general lack of any structure in these two galaxies. Unlike the collision-caused irregular galaxies, these objects truly have no organized structures. It is likely that there are hundreds of dwarf galaxies like these in our Universe for every single large spiral galaxy like the Milky Way. So, while these dwarf irregular galaxies only have a few million stars (compared to the Milky Way's 100+ billion), they are a significant component of all of the normal ("baryonic") mass in our Universe. One common feature of dwarf irregular galaxies is their abundance of young, hot stars. In fact, more young stars are produced each year in some of these small galaxies than in our Milky Way, even though the Milky Way is 10,000 times more massive! Why this occurs is still not fully understood.

In the two dwarf irregular galaxies shown in Pictures #21 and 22, the large numbers of blue stars, and the high number of *bright* red supergiants (especially in NGC 1705) indicate a high star formation rate–that is lots of new, young stars. Why are large numbers of hot, luminous blue stars, and red supergiants linked to young stars? [Hint: If you have learned about the HR diagram, try to remember how long hot, blue O and B stars live. As their internal supply of hydrogen runs out, they turn into red supergiants.] **(4 points)**

Section #4: Full Color Images of Galaxies

As we have just shown, color images of galaxies let us look at the kinds of stars that are present in them. A blue color indicates hot, young O and B stars, while a predominantly red, or yellow color indicates old, cool stars (mostly red giants). In this subsection we explore the kinds of stars that comprise spiral and elliptical galaxies.

Exercise #9: Comparison of Spirals and Ellipticals

In Pictures #23 through 27 we show some color pictures of elliptical and spiral galaxies. Describe the average color of an elliptical galaxy (i.e., #23 & #24) compared to the colors of spiral galaxies (#25 to #27). **(3 points)**

Now, let's look more closely at spirals and ellipticals. When examining the color pictures of the spiral galaxies you should have noticed that the spiral arms are generally bluer in color than their bulges. Hot young stars are present in spiral arms! That is where all of the young stars are. But in the bulges of spirals, the color is much redder—the bulge is made up of mostly old, red stars. In fact, the bulges of spiral galaxies look similar to elliptical galaxies. Compare the large bulge of the Sombrero galaxy (Picture #27) to the giant E0 galaxy M87 (Picture #23). **(3 points)**

If the bulges of spiral galaxies are made-up of old, red giant stars, what does this say about elliptical galaxies? **(3 points)**

It is likely that you have learned about the emission of light by hydrogen atoms in your lecture sessions (or during the spectroscopy lab). Hydrogen is the dominant element in the Universe, and can be found everywhere. The brightest emission line in the visual spectrum of hydrogen is a red line at 656 nm. This gives glowing hydrogen gas a pinkish color. When we take pictures of glowing clouds of hydrogen gas they are dominated by this pink light. During the course of this semester, you will also hear about 'HII" regions (such as the "Orion Nebula", see the monthly skycharts for February found in the back of this lab manual). HII regions form when hot O and B stars are born. These stars are so hot that they ionize the nearby hydrogen gas, causing it to glow. When we look at other spiral galaxies, we see many HII regions in them, just like those found in our Milky Way.

Of the spiral galaxies shown in Pictures 25 to 27, which has the most HII regions? Which appears to have the least? What does this imply about M51? **(3 points)**

Section #5: Multi-wavelength Views of Galaxies

We now want to explore what galaxies look like at ultraviolet and infrared wavelengths. "Multi-wavelength" data provides insights that cannot be directly gleaned from visual images.

We have just finished looking at some color images of galaxies. Those color pictures were actually made by taking several images, each through a different color filter, and then combining them to form a true-color image. Generally astronomers take pictures through a red, green, and blue filter to generate an "RGB" color picture. Many computer programs, such as Adobe Photoshop, allow you to perform this type of processing. Sometimes, however, it is best not to combine several single-color images into a color picture–subtle detail is often lost. Also, astronomers can take pictures of galaxies in the ultraviolet and infrared (or even X-ray and radio!), light which your eye cannot detect. There is no meaningful way to represent the true colors of a galaxy in an ultraviolet or infrared picture. Why would astronomers want to look at galaxies in the ultraviolet or infrared? Because different types of stars have different colors, decomposing the light of galaxies into its component colors allows us to determine how such stars are distributed (as well as gas and dust). In Pictures #28 and 29 we present blue and red images of the spiral galaxy M81. As you have just learned, the bulges of spiral galaxies are red, and the spiral arms (and disks) of spiral galaxies are blue. Note how the red image highlights the bulge region, while the blue image highlights the disk. Hot stars emit blue light, so if we want to see how many blue stars there are in a galaxy, it is best to use blue, or even ultraviolet light.

In this part of the lab, we will look at some multi-wavelength data. Let's remind ourselves first about the optical part of the electromagnetic spectrum. It runs from ultraviolet ("U", 330 nm), to blue ("B", 450 nm), through green/visual ("V", 550 nm), to yellow, red ("R" 600 nm) and infrared ("I", 760 nm and longer). The high energy photons have shorter wavelengths and are ultraviolet/blue, while the low energy photons have longer wavelengths and are red/infrared. If we go to shorter wavelengths than those that can penetrate our atmosphere, we enter the true ultraviolet (wavelengths of 90 to 300 nm). These are designated by UV or FUV (FUV means "far" ultraviolet, below 110 nm). We will now see what galaxies look like at these wavelengths–but note that we will switch back to black and white photos.

Exercise #10: Comparison of Optical and Ultraviolet Images of Galaxies
In Picture #30 are three separate images of two spiral galaxies. In the left hand column are FUV, U and I images of the Sc galaxy NGC 1365, and in the right hand column are FUV, U and R images of the Sa galaxy NGC 2841. Remember that images in the FUV, UV, U and B filters look at hot stars, while images in V, R, and I look at cooler stars. The ultraviolet really only sees hot stars! Compare the number of hot stars in NGC 1365 with NGC 2841. Describe the spiral arms of NGC 2841. What do you think is happening in the nucleus of NGC 2841? **(4 points)**

In Picture #31 are FUV, U and R images of two more galaxies: the Sc galaxy NGC 2403, and the irregular galaxy IC 2574. Compare the number of red and blue stars in these two galaxies–are they similar? What is the main difference? **(3 points)**

In Picture #32 is a similar set of images for two elliptical galaxies, NGC 5253 and NGC 3115 (which can also be seen in Pictures #15 and 16) Compare these two galaxies. While NGC 3115 is a normal elliptical galaxy, NGC 5253 seems to have something interesting going on near its nucleus. Why do we believe that? Describe how we might arrive at this conclusion? **(3 points)**

Exercise #11: Comparison of Optical and Infrared Images of Galaxies
Ok, now let's switch to the infrared. Remember that cool stars emit most of their energy in the red, and infrared portions of the electromagnetic spectrum. So if we want to trace where the cool, red (and old) stars are, we use red or infrared images. Another benefit of infrared light is its power to penetrate through dust, allowing us to see through dusty molecular gas clouds.

In Pictures #33 through #35 are blue ("B", 450 nm) and infrared ("H", 1650 nm) images of spiral galaxies. In Picture #33 we have Sa galaxies, in #34 we have Sb galaxies, and in #35 we have Sc galaxies. Compare how easy/hard it is to see the spiral arms in the B images versus the H images. Where are the blue stars? Where are the red stars? Note that while the hot O and B stars are super-luminous (1 million times the Sun's luminosity), they are very rare. For each O star in the Milky Way galaxy there are millions of G, K, and M stars! Thus, while an O star may have 60 times the Sun's mass, they are tiny component of the total mass of a spiral galaxy. Thus, what does the infrared light trace? **(5 points)**

Finally, let's take a look at the Milky Way galaxy. As we mentioned in the introduction, we are embedded in the disk of the Milky Way galaxy, and thus it is hard to figure out the exact shape and structure of our galaxy. In Picture #36 is an optical picture that spans the entire sky–we see that our Milky Way galaxy has a well-defined disk. But in the optical photograph, it is difficult to ascertain the bulge of the Milky Way, or the symmetry of our galaxy–there is just too much dust in the way! Picture #37 is an infrared view that is identical to the previous optical image. What a difference! We can now see through all of that dust, and clearly make out the bulge–note how small it is. We think that the Milky Way is an Sc galaxy. Make an argument in support of this claim, compare it to the photographs of other tilted spiral galaxies from Exercise #3. [Note: both of these images are special "projections" of the celestial sphere onto a two-dimensional piece of paper. This "Aitoff" projection makes sure the sizes and shapes of features are not badly distorted. For proper viewing, the right hand edge of these pictures should be wrapped around so that it touches the left hand edge, and you would have to be viewing the picture from inside to get a proper perspective. It is hard to take a three dimensional picture of the sky and represent it in two dimensions! A similar problem is encountered when using a rectangle to make a map of our globe (see the Terrestrial planet lab # 5.) **(8 points)**

14.5 Summary (35 points)

Summarize the important concepts of this lab, including the following topics.

- Describe the process for classifying a spiral galaxy.
- Describe the process for classifying an elliptical galaxy.
- What are the main difficulties in classifying these two main types of galaxies (they may not be the same issues!).
- What kind of information does multi-wavelength data (images) on galaxies provide? How is it useful? What does it tell us?
- What types of stars are found in spiral galaxies? In ellipticals? What does this tell us about elliptical galaxies?
- What types of stars are found in dwarf irregular galaxies?

14.6 Possible Quiz Questions

1. What are the three main types of galaxies?
2. What are the major components of the Milky Way and other Spiral galaxies?
3. How big is the Milky Way, and how many stars does it contain?
4. What are O and B stars like? How long do they live? What are red supergiants?
5. What are HII regions?
6. Draw the electromagnetic spectrum and identify the visual, infrared and ultraviolet regions.

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

In the introduction we mentioned that many galaxies (including the Milky Way) have large black holes at their centers. These black holes rip apart stars and suck in the gas. As the gas falls in, it gets very hot, and emits a lot of X-rays, ultraviolet and blue light. Compared to the galaxy, this hot gas region is tiny, and shows up as a small bright spot at the nucleus of the galaxy in the ultraviolet. Go back to Pictures 30 to 32 and list which of the galaxies appear to have black holes at their centers. How did you reach your conclusion?

Name:________________________

Date:________________________

15 How Many Galaxies are there in the Universe?

15.1 Introduction

Measurements, calculations, physical principles and estimations (or educated guesses) lie at the heart of all scientific endeavors. Measurements allow the scientist to quantify natural events, conditions, and characteristics. However, measurements can be hard to make for practical reasons. We will investigate some of the issues with taking measurements in this lab.

In addition, an important part about the measurement of something is an understanding about the *uncertainty* in that measurement. No one, including scientists, ever make measurements with perfect accuracy, and estimating the degree to which a result is uncertain is a fundamental part of science. Using a result to prove or disprove some theory can only be done after a careful consideration of the uncertainty of the result.

- *Goals*: to discuss the concepts of estimation, measurement and measurement error, and to use these, along with some data from the Hubble Space Telescope, to estimate the number of observable galaxies in the Universe
- *Materials*: Hubble Deep Field image

15.2 Exercise Section

15.2.1 Direct Measurement, Measurement Error

We will start out by counting objects much closer to home than galaxies!

How many chairs do you think there are in your classroom? You have one minute!

How did you determine this?

How does your number compare with that of other groups? What does this say about the uncertainty in the results?

Now do an exact count of the number of chairs - you have three minutes. Note the advantage of working with a group! By comparing results from different groups, what is the uncertainty in the result?

15.2.2 Estimation

Now we extend our measurement to a larger system where practical considerations limit us from doing a direct count.

How many chairs do you think there are in the entire University? You might wish to consider the campus map shown in Figure 15.1.

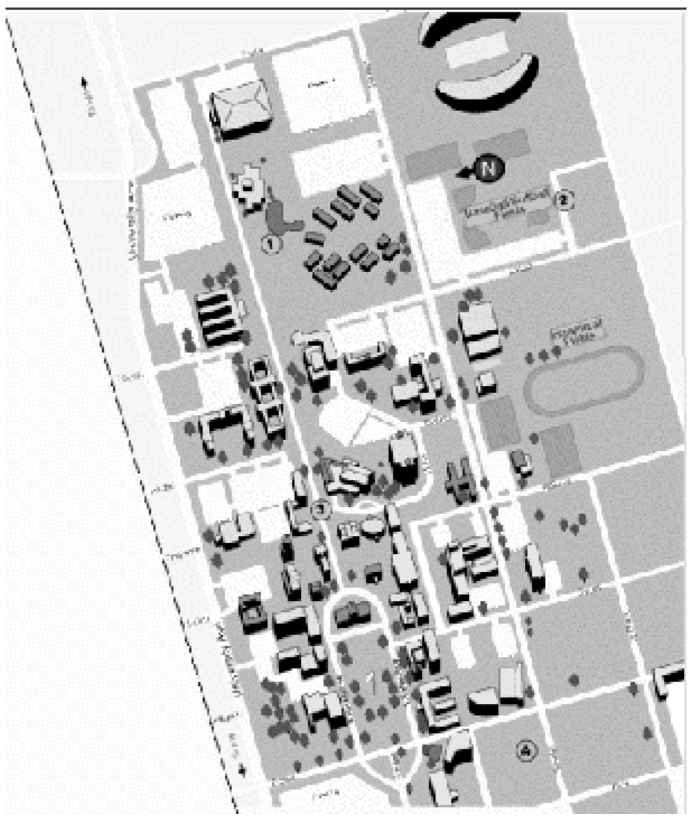


Figure 15.1: A map of the NMSU campus from the NMSU WWW site

How did you determine your number?

How accurate do you think your number is?

How might you estimate the uncertainty in your number?

15.3 How many galaxies are there in the Universe?

Considering how you estimated the number of chairs in the classroom and on campus, consider and write down several alternative ways of estimating the number of galaxies in the Universe.

Let's consider the issue by looking at a picture of the sky taken with the Hubble Space Telescope. This telescope is the most capable of existing telescopes for viewing very faint objects. In an effort to observe the faintest galaxies, astronomers decided to spend 10 entire days training this telescope on one small region of the sky to observe the faintest galaxies and learn about them. The image that was obtained is shown in

Figure 15.2.

First, let's figure out how long it would take for the Space Telescope to take pictures like this over the entire sky.

To do this, we need to talk about how we measure distances and areas on the sky, concepts that we have used in some of the other labs this semester. When one measures, for example, the distance between two stars as seen from Earth, one measures what is known as an angular distance. A standard unit of this angular distance is the familiar unit of the degree; there are 360 degrees in a full circle. As an example, the distance between an object which is straight overhead and one which is on the horizon is 90 degrees. However, when one makes astronomical observations with big telescopes, one usually sees an area which is only a small fraction of a degree on a side. To make things easier to write, astronomers sometimes use units known as arcminutes and arcseconds. There are 60 arcminutes in a degree, and 60 arcseconds in an arcminute.

1. We can now use this information to calculate how many pictures the Space Telescope would have to make to cover the entire sky. The picture from the Space Telescope covers a region that is about 1 arcminute on a side. Our first conversion is from arcminutes to degrees (this has been partially done for you): (**3 points**)

$$1\ arcminute \times \frac{1\ degree}{60\ arcminutes} = \underline{\hspace{6cm}}\ degrees \qquad (12)$$

2. The *area* of the entire picture is measured in square degrees, so we take the number of degrees found in question 1 and square it to get: (**3 points**)

3. Now there are 4.13×10^4 square degrees in the sky. From this you can figure out how many pictures you would need to take to cover the whole sky: (**5 points**)

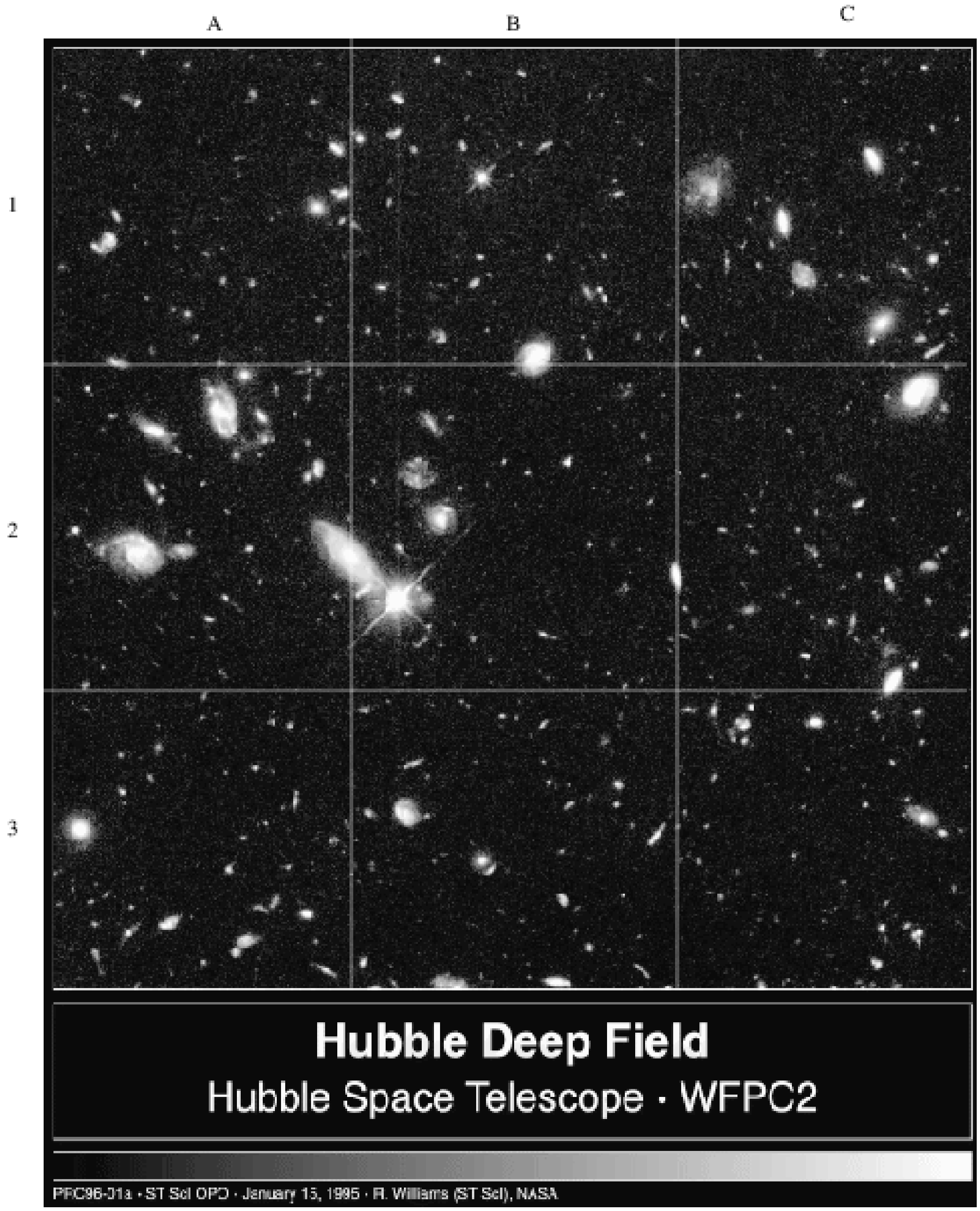


Figure 15.2: A reproduction of the Hubble Deep Field image.

4. Finally if it takes 10 days for each picture, we can figure out how long it would take to cover the whole sky with similar pictures: (**4 points**)

5. With a unit conversion of 365 days/year, we can determine the number of years it would take: (**4 points**)

Clearly, this is a very long time! This is an interesting point to note: astronomers can only take deep pictures of a small fraction of the sky. So it is not practical to count galaxies by taking pictures of the entire sky.

So how can we proceed to figure out how many total galaxies there are? We can make an *estimate* by guessing that the number of galaxies in any particular picture will be the same regardless of where we point. We can then estimate the total number of galaxies in the sky by counting the number of galaxies in this one picture, and multiplying it by the number of pictures that it would take to cover the whole sky.

6. Take a look at the image of the Hubble Deep Field given to you by your TA. Almost every one of the objects you see in this picture is a distant galaxy. Count up all the galaxies in each subsection then add them up to get an estimate of the number of galaxies in this one field. Again, you can proceed quicker by taking advantage of the multiple members of your group; however, you might wish to have everyone in the group count one region independently to get some idea of the measurement uncertainty. (**10 points**)

Region A1:________________________
Region A2:________________________
Region A3:________________________
Region B1:________________________
Region B2:________________________
Region B3:________________________

Region C1:________________________

Region C2:________________________

Region C3:________________________

There are a total of ________________________galaxies in Hubble Deep Field.

7. Now estimate the total number of galaxies in the whole sky, using our calculation of the number of pictures it takes to cover the sky which we did above. (**7 points**)

   This is a pretty amazingly large number. Consider that each galaxy has billions of stars, and think just for minute about how many total stars there are in the Universe! It makes you feel pretty small.... but, on the other hand, think how cool it is that humans have evolved to the point where they can even make such an estimation!

8. As we've discussed, an estimate of the *uncertainty* in a result is often as important as the result itself. Discuss several reasons why your result may not be especially accurate. You may wish to compare the number of galaxies in any given region which you counted with the number counted by other groups, or consider the variation in the number of galaxies from one region to another. Also, remember a fundamental assumption that we made for getting our estimate, namely, that the number of galaxies we would see in some other portion of the sky is the same as that which we see in this Hubble deep field. (**8 points**)

9. Finally, there's one more caveat to our calculated total number of galaxies. To make our estimate, we *assumed* that the 10 day exposure sees every single

galaxy in this portion of the sky. With this in mind, how would the calculation you just conducted compare to the real number of galaxies in the Universe? Back up your answer with a short explanation. (**8 points**)

15.4 The Mass and Density of the Universe (Contained in Galaxies)

In the preceding we have estimated the number of galaxies in the Universe. In the final subsection of this lab, we now want to explore the implications of this calculation by making an estimate of the matter density of the Universe. In your lecture subsections, and some of the earlier labs (like in Table 5.1 in the Terrestrial Planet lab) you have probably encountered the concept of density: density = Mass/Volume. Astronomers usually use the unit of gm/cm^3 for density. We can now make an estimate for the density of matter contained in all of the galaxies in our Universe. We will start with very large numbers, and end up with an extremely tiny number. It is quite likely that your calculator cannot handle such numbers. To make this calculation easier, we will use some round numbers so that you can do the calculation by hand using the techniques outlined in Lab 1 (if you get stuck with how to multiply numbers with exponents, refer back to subsection 1.4 in the introductory lab). This is a challenging exercise, but one that gives you an answer that you might not expect!

10. In question 7 above, you estimated the total number of galaxies in the sky. If we assume that these galaxies are similar to (though probably somewhat smaller than) our Milky Way galaxy, we can calculate the total mass of all of the galaxies in the Universe. Over the course of this semester you will learn that the Milky Way has about 100 billion stars, and most of these stars are about the mass of the Sun, or somewhat smaller. The mass of the Sun is 2×10^{33} gm. Let's assume that the average galaxy in the Universe has 1/2 the number of stars that the Milky Way has: 50 billion. Fifty billion in scientific notation is 5 x 10^{10}. To calculate the mass (in gm) of all of the galaxies in the Universe, we need to solve this equation:

Mass of Galaxies in Universe = (# of Galaxies)×(Average Mass of a Galaxy)

You calculated the # of Galaxies in question 7. We need to multiply that number by the Average Mass of a Galaxy. The Average Mass of a Galaxy (in gm) is simply:

Average Mass of a Galaxy = (# of stars in a galaxy)×(average mass of a star)

If the number of stars in a galaxy is 5 x 10^{10}, and the average mass of a star is 2 X 10^{33} gm, what is the average mass of a galaxy? **(2 points)**

Average Mass of a Galaxy = (__________________)×(__________________)

= ________________________ gm

With this number, you can now calculate the total mass of all of the galaxies in the Universe **(2 points)**:

Mass of Universe = (__________________)×(__________________) =

________________________ gm

11. We have just calculated the total mass of galaxies in the Universe, and are halfway to our goal of figuring out the density of galactic matter in the Universe. Since density = M/V, and we now have M, we have to figure out V, the Volume of the Universe. This is a little more difficult than getting M, so make sure you are confident of your answer to each of the following steps before proceeding to the next. We are going to make some assumptions that will simplify the calculation of V. First off, we will assume that the Universe is a sphere. The volume of a sphere is simply four thirds "pi" R cubed: $V_{sphere} = 4\pi R^3/3$. To figure out the volume of the Universe we need to calculate "R", the radius of the Universe.

    So, how can we estimate R? In your lecture class you will find out that the most distant parts of the Universe are moving away from us at nearly the speed of light (the observed expansion of the Universe is covered in the Hubble's Law lab). Let's assume that the largest distance an object can have in our Universe is given by the speed of light × the age of the Universe. Remember, if a car travels at 50 mph for one hour it will cover 50 miles: Distance = velocity × time. We can use this equation to estimate the radius of the Universe: $R_{Universe}$ = velocity × time = (speed of light) × (age of Universe).

The speed of light is a very large number: 3 X 10^{10} cm/s, and the age of the Universe is also large: 13 billion years. To calculate the radius of the Universe in cm, we must convert the age of the Universe in years to an age in seconds (s). First, how many seconds are there in a year? Let's do the calculation:

Seconds in year = (seconds in day) × (days in year) = (60 × 60 × 24) × 365 =

__________________ s/yr

Since this is only estimate, feel free to round off any decimals to whole numbers. Now that we have the number of seconds in a year, we can convert the age of the Universe from years to seconds:

Age of Universe in seconds = (Age of Universe in Years) × (seconds in a year)

= (13×10^9 yr) × __________________ s/yr = __________________ s.

Ok, we now have the "time" part of the equation distance = velocity × time. And we have already set the velocity to the speed of light: 3×10^{10} cm/s. Now we can figure out the Radius of the Universe **(3 points)**:

Radius of Universe (in cm) = (speed of light) × (Age of Universe in seconds) =

(3×10^{10} cm/s) × ________________________ s =

________________________ cm.

In these calculations, notice how the *units* cancel. The units on a distance or radius is length, and astronomers generally use centimeters (cm) to measure lengths. Velocities have units of length per time, like cm/s. So when calculating a radius in cm, we multiply a velocity with units of cm/s × a time measured in seconds, and the units of seconds cancels, leaving a length unit (cm).

We are now ready to calculate the Volume of the Universe, $V = 4\pi R^3/3$. It may be easier for you to break this into two parts, multiplying out $4/3 \times \pi$, and then taking R^3, and then multiplying those two numbers. [Remember, $\pi = 3.14$.]

Volume of Universe = $4/3 \times \pi \times R^3$ =

________________________ × ________________________ =

________________________ cm^3

12. Tying it all together: figuring out the average density of the Universe (at least that contained within galaxies–astronomers believe there is more "dark" matter in the Universe than the regular matter that we can see contained in galaxies!). We have just calculated the Volume of the Universe, and we have already calculated the Mass of all of the galaxies in the Universe. Now we take the final step, and calculate the Average Galactic Matter Density of the Universe **(3 points)**:

Average Density of the Universe = $M_{Universe}/V_{Universe}$ =

(________________________ gm)/(________________________ cm^3) =

________________________ gm/cm^3

13. The mass of a single hydrogen atom is 1.7 x 10^{-24} gm. Compare your answer for the average density of the Universe to the mass of a single hydrogen atom. [Hint: the average amount of mass (*in gm*) of 1 cm^3 of the Universe is simply the density you just calculated, but you drop the cm^3 of the units on density to get *gm*.] Are they similar? What does this imply about the Universe, is it full of stuff, or mostly empty?
(3 points)

15.5 Summary (35 points)

Please summarize the important concepts discussed in this lab. Your summary should include a brief discussion of

- direct measurement vs. estimation
- error estimates in both direct measurement and estimation
- Consider the importance of the galaxy counting results discussed in lab. Since the Hubble Deep Field was taken in a presumably empty part of the sky, what is the significance of finding so many galaxies in this picture?
- Use the concepts discussed in this lab to estimate the total number of stars that you can see in the night sky by going out at night and doing some counting and estimating. Describe your method as well as the number you get and provide some estimate of your uncertainty in the number.
- Think back to a time before you did this lab, would you have expected the answer to question #13? Our Universe has many surprises!

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

15.6 Possible Quiz Questions

1. What is meant by the term "estimation"?
2. Why do scientists use estimation?
3. How many degrees are in a circle?
4. What is an "arcminute"?
5. What is the "Hubble Deep Field"?

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

In question #7, you estimated the number of galaxies in the Universe. In question #10 you found that a typical galaxy contains 50 billion stars. Thus, you can now estimate how many stars there are in the Universe. Recently, some mathematicians have estimated that there are between 7×10^{19} and 7×10^{22} grains of sand on all of the Earth's beaches–that is every single beach on every single island and continent on the Earth. Obviously, this is a difficult estimate to make, and thus their estimate is quite uncertain. How would you begin to estimate the number of sand grains on the Earth's beaches? What factors need to be taken into account?

Compare the number of stars in the Universe, with the number of grains of sand on the planet Earth. How do they compare? We still do not know the average number of planets that are found around an average star. It is probably safe to assume that 10% of all stars have at least one planet orbiting them. If so, how many planets are there in the Universe?

Name:____________________________

Date:____________________________

16 Hubble's Law: Finding the Age of the Universe

16.1 Introduction

In your lecture sessions (or the lab on spectroscopy), you will find out that an object's spectrum can be used to determine the temperature and chemical composition of that object. A spectrum can also be used to find out how fast an object is moving by measuring the Doppler shift. In this lab you will learn how the velocity of an object can be found from its spectrum, and how Hubble's Law uses the Doppler shift to determine the distance scale of the Universe.

- *Goals:* to discuss Doppler Shift and Hubble's Law, and to use these concepts to determine the age of the Universe
- *Materials:* galaxy spectra, ruler, calculator

16.2 Doppler Shift

You have probably noticed that when an ambulance passes by you, the sound of its siren changes. As it approaches, you hear a high, whining sound which switches to a deeper sound as it passes by. This change in pitch is referred to as the Doppler shift. To understand what is happening, let's consider a water bug treading water in a pond, as in Figure 16.1.

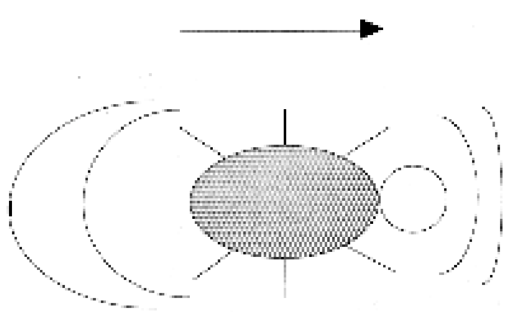


Figure 16.1: A waterbug, treading water.

The bug's kicking legs are making waves in the water. The bug is moving forward relative to the water, so the waves in front of him get compressed, and the waves behind him get stretched out. In other words, the frequency of waves increases in front of him, and decreases behind him. In wavelength terms, the wavelength is shorter in front of him, and longer behind him. Sound also travels in waves, so when the ambulance is approaching you, the frequency is shifted higher, so the pitch (not the volume) is higher. After it has passed you, the frequency is Doppler shifted to a lower pitch as the ambulance moves away from you. You hear the pitch change because to your point of view the relative motion of the ambulance has changed. First it was moving toward you, then away from you. The ambulance driver won't hear any change in pitch, because for her the relative motion of the ambulance hasn't changed.

The same thing applies to light waves. When a light source is moving away from you, its wavelength is longer, or the color of the light moves toward the red end of the spectrum. A light source moving toward you shows a ________________________(color) shift.

This means that we can tell if an object is moving toward or away from us by looking at the change in its spectrum. In astronomy we do this by measuring the wavelengths of spectral lines. We've already learned how each element has a unique fingerprint of spectral lines, so if we look for this fingerprint and notice it is displaced slightly from where we expect it to be, we know that the source must be moving to produce this displacement. We can find out how fast the object is moving by using the Doppler shift formula:

$$\frac{\Delta\lambda}{\lambda_o} = \frac{v}{c}$$

where $\Delta\lambda$ is the wavelength shift you measure, λ_o is the rest wavelength[1] (the one you'd expect to find if the source wasn't moving), v is the radial velocity (velocity toward or away from us), and c is the speed of light (3×10^5 km/s).

In order to do this, you just take the spectrum of your object and compare the wavelengths of the lines you see with the rest wavelengths of lines that you know should be there. For example, we would expect to see lines associated with hydrogen so we might use this set of lines to determine the motion of an object. Here is an example:

Exercise 1. Doppler Shift (10 points)
If we look at the spectrum of a star, we know that there will probably be hydrogen lines. We also know that one hydrogen line always appears at 6563Å, but we find the line in the star's spectrum at 6570Å. Let's calculate the Doppler shift:

a) First, is the spectrum of the star redshifted or blueshifted (do we observe a longer or shorter wavelength than we would expect)?

[1]For this lab we will be measuring wavelengths in Ångstroms. 1.0 Å= 1.0×10^{-10} m.

b) Calculate the wavelength shift: $\Delta\lambda = (6570\text{Å} - 6563\text{Å})$

$\Delta\lambda =$ ________________________Å

c) What is its radial velocity? Use the Doppler shift formula:

$$\frac{\Delta\lambda}{\lambda_o} = \frac{v}{c}$$

$v =$________________________km/s

A way to check your answer is to look at the sign of the velocity. Positive means redshift, and negative means blueshift.

Einstein told us that nothing can go faster than the speed of light. If you have a very high velocity object moving at close to the speed of light, this formula would give you a velocity faster than light! Consequently, this formula is not always correct. For very high velocities you need to use a different formula, the *relativistic* Doppler shift formula, but in this lab we won't need it.

16.3 Hubble's Law

In the 1920's Hubble and Slipher found that there is a relationship between the redshifts of galaxies and how far away they are (don't confuse this with the ways we find distances to stars, which are much closer). This means that the further away a galaxy is, the faster it is moving away from us. This seems like a strange idea, but it makes sense if the Universe is expanding.

The relation between redshift and distance turns out to be very fortunate for astronomers, because it provides a way to find the distances to far away galaxies. The formula we use is known as Hubble's Law:

$$v = H \times d$$

where v is the radial velocity, d is the distance (in Mpc), and H is called the Hubble constant and is expressed in units of km/(s × Mpc). Hubble's constant is basically the expansion rate of the Universe.

The problem with this formula is that the precise value of H is not known! If we take galaxies of known distance and try to find H, the values range from 50 to 100 km/(s $\times$ Mpc). By using the incredible power of the Hubble Space Telescope, the current value of the H is near 75 km/(s $\times$ Mpc). Let's do an example illustrating how astronomers are trying to determine H.

Exercise 2. The Hubble Constant (15 points)
In this exercise you will determine a value of the Hubble constant based on direct measurements. The figure at the end of this lab has spectra from five different galaxy clusters. At the top of this figure is the spectrum of the Sun for comparison. For each cluster, the spectrum of the brightest galaxy in the cluster is shown to the right of the image of the cluster (usually dominated by a single, bright galaxy). Above and below these spectra, you'll note five, short vertical lines that look like bar codes you might find on groceries. These are comparison spectra, the spectral lines which are produced for elements here on earth. If you look closely at the galaxy spectra, you can see that there are several dark lines going through each of them. The left-most pair of lines correspond to the "H and K" lines from calcium (for the Sun and for Virgo = Cluster #1, these can be found on the left edge of the spectrum). Are these absorption or emission lines? (Hint: How are they appearing in the galaxies' spectra?)

Now we'll use the shift in the calcium lines to determine the recession velocities of the five galaxies. We do this by measuring the change in position of a line in the galaxy spectrum with respect to that of the comparison spectral lines above and below each galaxy spectrum. For this lab, measure the shift in the "K" line of calcium (the left one of the pair) and write your results in the table below (Column B). At this point you've figured out the shift of the galaxies' lines as they appear in the picture. Could we use this alone to determine the recession velocity? No, we need to determine what shift this corresponds to for actual light. In Column C, convert your measured shifts into Ångstroms by using the conversion factor **19.7 Å/mm** (this factor is called the "plate scale", and is similar to the scale on a map that allows you to convert distances from inches to miles–you can determine this yourself using the separation of the H and K lines = 34.8 Å).

Earlier in the lab we learned the formula for the Doppler shift. Your results in Column C represent the values of $\Delta\lambda$. We expect to find the center of the calcium K line at λ_o = **3933.0 Å**. Thus, this is our value of λ. Using the formula for the Doppler shift along with your figures in Column C, determine the recession velocity for each galaxy. The speed of light is, $c = \mathbf{3 \times 10^5}$ **km/sec**. Write your results in Column D. For each galaxy, divide the velocity (Column D) by the distances provided in Column E. Enter your results in Column F.

The first galaxy cluster, Virgo, has been done for you. Go through the calculations for Virgo to check and make sure you understand how to proceed for the other

A Galaxy Cluster	B Measured shift (mm)	C Redshift (Angstroms)	D Velocity (km/s)	E Distance (Mpc)	F Value of H (km/s/Mpc)
1. Virgo	*0.9*	*17.7*	*1,352*	20	*67.6*
2. Ursa Major				110	
3. Corona Borealis				180	
4. Bootes				300	
5. Hydra				490	

galaxies. **Show all of your work on a separate piece of paper and turn in that paper with your lab.**

Now we have five galaxies from which to determine the Hubble constant, H. Are your values for the Hubble constant somewhere between 50 and 100 km/(s $\times$ Mpc)? Why do you think that all of your values are not the same? The answer is simple: *human error*. It is only possible to measure the shift in each picture to a certain accuracy. For Virgo the shift is only about 1 mm, but it is difficult with a ruler and naked eye to measure such a small length to a high precision. A perfect measurement would give the "correct" answer (but note that there is always another source of uncertainty: the accuracy of the distances used in this calculation!).

16.4 The Age of the Universe

The expansion of the Universe is a result of the Big Bang. Since everything is flying apart, it stands to reason that in the past everything was much closer together. With this idea, we can use the expansion rate to determine how long things have been expanding - in other words, the age of the Universe! As an example, suppose you got in your car and started driving up to Albuquerque. Somewhere around T or C, you look at your watch and wonder what time you left Las Cruces. You know you've driven about 75 miles and have been going 75 miles per hour, so you easily determine you must have left about an hour ago. For the age of the Universe, we essentially do the same thing to figure out how long ago the Universe started. This is assuming that the expansion rate has always been the same, which is probably not true (by analogy, maybe you weren't always driving at 75 mph on your way to T or C). The gravitational force of the galaxies in the Universe pulling on each other would slow the expansion down. However, we can still use this method to get a rough estimate of the age of the Universe.

Exercise 3. Age Calculation (15 points)
The Hubble constant is expressed in units of km/(s $\times$ Mpc). Since km and Mpc are both units of distance, we can cancel them out and express H in terms of 1/sec.

Simply convert the Mpc into km, and cancel the units of distance. The conversion factor is **1 Mpc = 3.086×10^{19} km**.

a) Add up the five values for the Hubble constant written in the table of Exercise 2, and divide the result by five. This represents the average value of the Hubble constant you have determined.

$H =$ ________________________ $\frac{km}{s \times Mpc}$

b) Convert your value of H into units of 1/s:

$H =$ ________________________ $\frac{1}{s}$

c) Now convert this into seconds by inverting it ($1/H$ from part b):

Age of the Universe = ________________________s

d) How many years is this? (convert from seconds to years by knowing there are 60 seconds in a minute, 60 minutes in an hour, etc.)

Age of the Universe=________________________yrs

16.5 How Do we Measure Distances to Galaxies and Galaxy Clusters?

In exercise #2, we made it easy for you by listing the distances to each of the galaxy clusters. If you know the distance to a galaxy, and its redshift, finding the Hubble constant is easy. But how do astronomers find these distances? In fact, it is a very difficult problem. Why? Because the further away an object is from us, the fainter it appears to be. For example, if we were to move the Sun out to a distance of 20 pc, it would no longer be visible to the naked eye! Note that the closest galaxy cluster is at a distance of 20 Mpc, a million times further than this! Even with the largest telescopes in the world, we could not see the Sun at such a great distance (and Virgo is the closest big cluster of galaxies).

Think about this question: Why do objects appear to get dimmer with distance? What is actually happening? Answer: The light from a source spreads out as it travels. This is shown in Fig. 16.2. If you draw (concentric) spheres around a light source, the amount of energy passing through a square meter drops with distance as $1/R^2$. Why? The area of a sphere is $4\pi R^2$. The innermost sphere in Fig. 16.2 has a radius of "1" m, its area is therefore 4π m^2. If the radius of the next sphere out is

"2" m, then its area is 16π m^2. It has 4× the area of the inner sphere. Since all of the light from the light bulb passes through both spheres, its intensity (energy/area) must drop. The higher the intensity, the brighter an object appears to our eyes. The lower the intensity, the fainter it appears. Again, refer to Fig. 16.2, as shown there, the amount of energy passing through 1 square of the inner sphere passes through 4 squares for the next sphere out, and 9 squares (for R = 3) for the outermost sphere. The light from the light bulb spreads out as it travels, and the intensity drops as $1/R^2$.

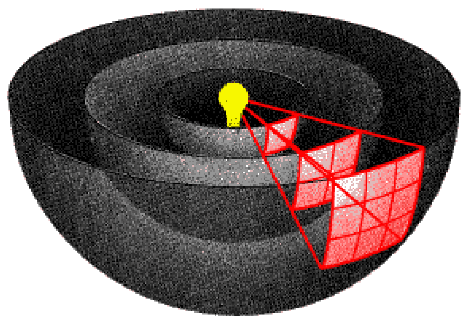


Figure 16.2: If you draw concentric spheres around a light source (we have cut the spheres in half for clarity), you can see how light spreads out as it travels. The light passing through one square on the inner sphere passes through four squares for a sphere that has twice the radius, and nine squares for a sphere that has three times the radius of the innermost sphere. This is because the area of a sphere is $4\pi R^2$.

Exercise 4. Inverse Square Law If the apparent brightness (or intensity) of an object is proportional to $1/R^2$ (where R = distance), how much brighter is an object in the Virgo cluster, compared to a similar object in Hydra? [Hint: how many times further is Hydra than Virgo?] **(2 points)**

An object in Hydra is hundreds of times fainter than the same object in Virgo! Obviously, astronomers need to find an object that is very luminous if they are going to measure distances to galaxies that are as far, or even further away than the Hydra cluster. You have probably heard of a supernova. Supernovae (supernovae is the plural of supernova) are tremendous explosions that rip stars apart. There are two types of supernova, Type I is due to the collapse of a white dwarf into neutron star, while a Type II is the explosion of a massive star that often produces a black hole. Astronomers use Type I supernovae to measure distances since their explosions always release the same amount of energy. Type I supernovae have more than one billion times the Sun's luminosity when they explode! Thus, we can see them a long way.

Let's work an example. In 1885 a supernova erupted in the nearby Andromeda galaxy. Andromeda is a spiral galaxy that is similar in size to our Milky Way located at a distance of about 1 Mpc. The 1885 supernova was just barely visible to the naked eye, but would have been easy to see with a small telescope (or even binoculars). Astronomers use telescopes to collect light, and see fainter objects better. The largest telescopes in the world are the Keck telescopes in Hawaii. These telescopes have diameters of 10 meters, and collect 6 million times as much light as the naked eye (thus, if you used an eyepiece on a Keck telescope, you could "see" objects that are 6 million times fainter than those visible to your naked eye).

Using the fact that brightness decreases as $1/R^2$, how far away (in Mpc) could the Keck telescope see a supernova like the one that blew up in the Andromeda galaxy? **(2 points)**. [Hint: here we reverse the equation. You are given the brightness ratio, 6 million, and must solve for the distance ratio, remembering that Andromeda has a distance of 1 Mpc!]

Could the Keck telescopes see a supernova in Hydra? **(1 point)**

16.6 Questions

1. Explain how the Doppler shift works. **(5 points)**

2. In the water bug analogy, we know what happens to waves in front of and behind the bug, but what happens to the waves directly on his left and right (hint: is the bug's motion compressing these waves, stretching them out, or not

affecting them at all)? With this in mind, what can the Doppler shift tell us about the motion of a star which is moving only at a right angle to our line of sight? **(5 points)**

3. Why did we use an average value for the Hubble constant, determined from five separate galaxies, in our age of the Universe calculation? What other important factor in our determination of the age of the Universe did we overlook? (Hint: It was mentioned in the lab.) **(5 points)**

4. Does the age of the Universe that you calculated seem reasonable? Check your textbook or the World Wide Web for the ages estimated for globular clusters, some of the oldest known objects in the Universe. How does our result compare? Can any object in the Universe be older than the Universe itself? **(5 points)**

16.7 Summary (35 points)

Summarize what you learned from this lab. Your summary should include:

- An explanation of how light is used to find the distance to a galaxy
- From the knowledge you have gained from the last several labs, list and explain *all* of the information that can be found in an object's spectrum.

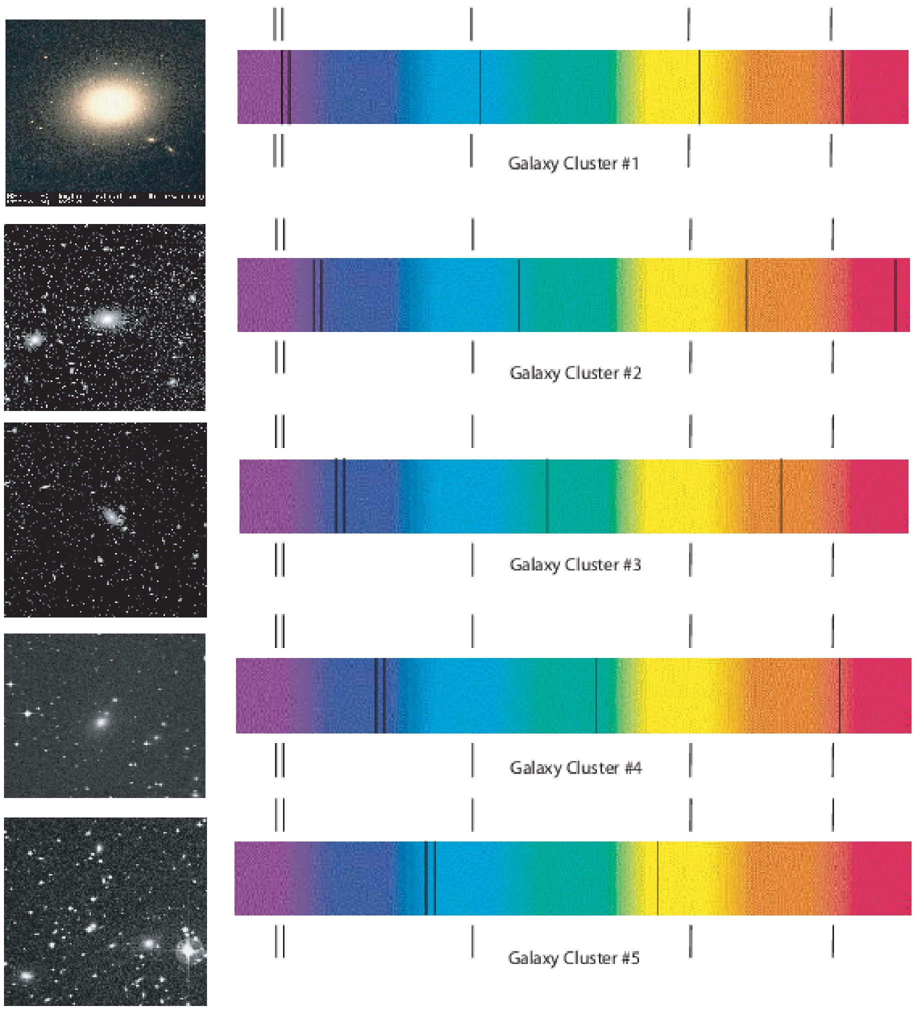
Use complete sentences, and proofread your summary before handing in the lab.

Possible Quiz Questions
1) What is a spectrum, and what is meant by wavelength?
2) What is a redshift?
3) What is the Hubble expansion law?

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

Recently, it has been discovered that the rate of expansion of the Universe appears to be accelerating. This means that the Hubble "constant" is not really constant! Using the world wide web, or recent magazine articles, read about the future of the Universe if this acceleration is truly occurring. Write a short essay summarizing the fate of stars and galaxies in an accelerating Universe.

The Spectrum of the Sun



Name:______________________________

Date:______________________________

17 Discovering Exoplanets

17.1 Introduction

One of the most exciting discoveries in Astronomy over the last twenty years was the conclusive detection of planets orbiting other stars. At last count, we are closing-in on having discovered *two thousand* planets orbiting other stars. Planets orbiting other stars are called "exoplanets." These exoplanets range in size from similar to the Earth, to larger than Jupiter. With much hard work, we now know that small exoplanets are much more common than big exoplanets, and some astronomers believe that Earth-sized planets orbit nearly every normal star. The current goal of astronomers is to find exoplanets that are most similar to Earth (same mass, radius, orbiting their host star at 1 AU, etc.). With improvements in technology, we will one day be able to determine whether such exoplanets support life. In the distant future, maybe we will be able to send a space probe to those exoplanets to investigate the life found there.

Astronomers have been studying the sky with advanced instruments for more than 100 years, but it was only in the early 1990's that the first real exoplanets were found. Why did it take so long? The answer is that compared to their host stars, exoplanets are tiny, and hard to see. We will quantify how hard it is to see them shortly. First though, how might we discover such objects? There are three main techniques: direct imaging, transits (mini-eclipses), and "radial velocity" measurements. As its name suggests, direct imaging is simply taking a picture of a star and looking for its planets. The big problem is that the star is very bright (it generates its own energy), while an exoplanet shines by reflected light from the star. This is by far the hardest method to find exoplanets. To be effective, we will need to launch special telescopes into space where our image-disturbing atmosphere does not exist, allowing us to see much, much more clearly.

The transit method is much easier in that what we monitor is the light output from a star, and if an exoplanet crosses in front of the star, the light briefly dims. As we will learn, this technique also tells us the *diameter* of the exoplanet. The radial velocity method uses the Doppler effect to detect the orbital motion of the planet. The radial velocity technique allows us to determine the *mass* of the exoplanet. If we can combine the transit and radial velocity techniques, we can get the size and mass of a planet, and thus measure its *density*, and therefore constrain its composition. We will investigate all three methods in this lab, and then learn how we can characterize the properties of these objects.

17.2 Why are Exoplanets so hard to see?

In our first experiment, we are simply going to demonstrate how hard it is to directly see an exoplanet. First, however, a diagram to remind you how small the Earth and Jupiter are compared to the Sun (Figure 17.1).

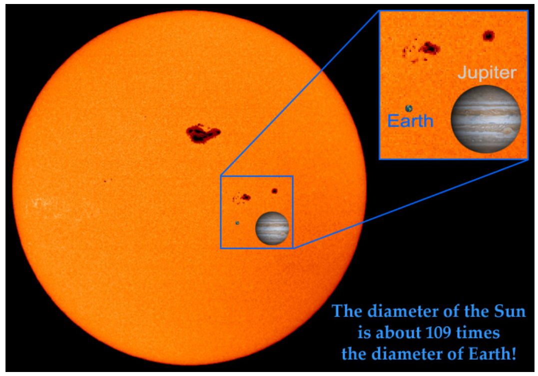


Figure 17.1: Comparison of the size of the Earth and Jupiter to the Sun.

Let's look at some numbers. The radius of the Sun is 695,550 km, the radius of Jupiter is 69,911 km, and the radius of the Earth is 6,371 km. Note that these objects are all spheres, and thus when we look at them from space, they all appear to be circles ("disks"). What is the area of a circle? $A_{\text{circle}} = \pi R^2$.

Exercise #1: Calculate the areas of the circular disks of the Sun, Jupiter, and Earth (if you want make the calculation simpler, just set R_{Sun} = 700,000 km, R_{Jupiter} = 70,000 km, and R_{Earth} = 6000 km). **(3 points)**.

(Area of Earth) = ______________________ km^2

(Area of Jupiter) = ______________________ km^2

(Area of Sun) = ______________________ km^2

If we are going to take a picture of a exoplanet around a star, we have two problems: how much light will the exoplanet reflect compared to its star, and how close-in is it? Let's tackle the first question.

Exercise #2: We are going to keep everything very simple, and just estimate how much sunlight the Earth or Jupiter would reflect compared to that emitted by the Sun. We will assume that these planets reflect 100% of the light that hits them, and we are going to ignore the fact that the amount of sunlight at the orbits of each of these planets is less than at the surface of the Sun (remember, the amount of light passing through a sphere surrounding a light source drops off as $1/R^2$). In this unrealistic scenario, the maximum amount of light that a planet can reflect is simply the ratio of its area to that of the star it orbits. Calculate the following: **(2 points)**.

(Area of Earth)/(Area of Sun) = ________________________

(Area of Jupiter)/(Area of Sun) = ________________________

These already small numbers are actually way too big. As we noted, Earth can only reflect the amount of light it intercepts at the distance it is from the Sun. In fact, the Earth only intercepts 1.67×10^{-9} of the Sun's light output, and the amount of visible light it reflects (its "albedo") is 40%. So, seen from distant space, the Earth is only *one billionth* as bright as the Sun! Jupiter is obviously much bigger than the Earth, but remember, Jupiter is at 5.2 AU, so it actually receives $1/27^{\text{th}}$ the amount of sunlight as does the Earth. Thus, to an observer outside our solar system, Jupiter is only 4.4 times more luminous than the Earth.

Directly detecting exoplanets is going to be hard, besides being very faint, they are located very close to their host stars. We need a way to "turn off" the star. One way to do this is to block its light out with a small, opaque metal disk. As shown in Figure 17.2, we now have the capability to do this, but only for finding big planets located far from their host stars (in fact, to date, only Jupiter-sized planets located at large distances from their host stars have been directly imaged). There is a more complex technique called "nulling interferometry" where you use the star's own light to cancel itself out, but not its planets, that lets astronomers search for planets closer to the host star. While it can be done from the ground, it is better from space. You can more read about this method by searching for the canceled NASA mission "Terrestrial Planet Finder" on the web (it was killed due to budget cuts).

17.3 Exoplanet Transits

The exoplanet transit method of discovery is simple to envision, and the easiest to carry-out. As shown in Figure 17.3, a transit occurs when an exoplanet crosses the disk of its host star as seen by observers on Earth. Since the planet does not emit any light (we are looking at the "nighttime side"), it is completely dark. Thus, the amount of light from the star will dim as the planet blocks out ("eclipses") a small portion of the star's light-emitting disk. The plot of the brightness of a star versus time is called a "light curve". The light curve of the transit is shown below the cartoon of the star and exoplanet in Figure 17.3.

Exercise #3: Simulating an Exoplanet transit

As part of the materials set out for you to use during today's lab is a device to simulate an exoplanet transit. Take a look at the wooden device. It has a light meter attached to the back, and three rods that dangle down in front of the light meter. We will use the desk lamp as our light source ("star"), and move the rods across the

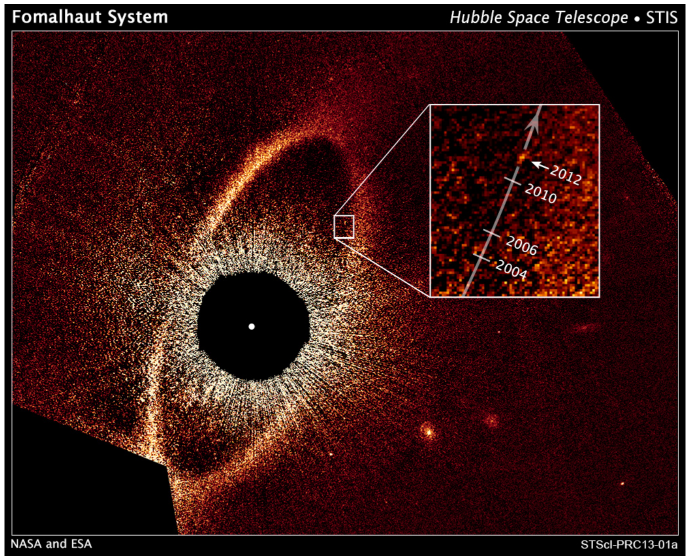


Figure 17.2: A planet orbiting the star Fomalhaut (inside the box, with the arrow labeled "2012"). This image was obtained with the Hubble Space Telescope, and the star's light has been blocked-out using a small metal disk. Fomalhaut is also surrounded by a dusty disk of material—the broad band of light that makes a complete circle around the star. This band of dusty material is about the same size as the Kuiper belt in our solar system. The planet, "Fomalhaut B", is estimated to take 1,700 years to orbit once around the star. Thus, using Kepler's third law ($P^2 \propto a^3$), it is roughly about 140 AU from Fomalhaut (remember that Pluto orbits at 39.5 AU from the Sun).

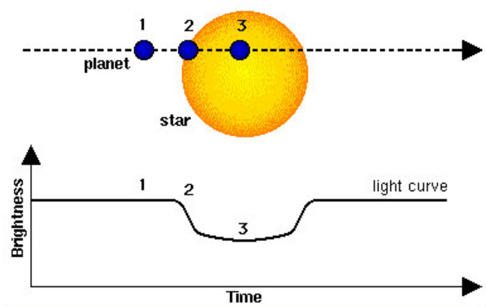


Figure 17.3: The diagram of an exoplanet transit. The planet, small, dark circle/ disk, crosses in front of the star as seen from Earth. In the process, it blocks out some light. The light curve shown on the bottom, a plot of brightness versus time, shows that the star brightness is steady until the exoplanet starts to cover up some of the visible surface of the star. As it does so, the star dims. It eventually returns back to its normal brightness only to await the next transit.

light meter. Note that the dowel rod on top has five notches. The two furthest from the center represent where we will be at the start and end of our simulation. At these positions, no light is blocked (similar to position #1 in Figure 17.3). Note also that we have two planets, one big, one small, and a bare rod without a planet. What do you think the latter is used for? Yes, our planets need to be attached to *something* to allow us to perform this experiment. Thus, this planet-less rod allows us to measure how much light just the bare rod blocks out. We will have to take this into account when we plot our light curves.

The light meter itself is rather simple, it has power, mode, and hold buttons. We only will use the power and mode buttons. Hit the power button (note that to extend battery life, the device automatically shuts off after 45 seconds). At the bottom of the device display window there will either be a "LUX" or "FC" displayed. We want the unit to be in LUX, so click the mode button until LUX is displayed.

Setting things up: Move all of the metal rods to the left end of the dowel rod so that nothing is blocking the lamp light from illuminating the white circle. Turn on the light meter. Note that the number bounces around–this is due to electronic noise. Every electronic device has this type of noise, and it takes much hard work (and expense) to minimize this noise (one way is to chill the device to low temperatures). Here we have to live with it, but this is just like what an astronomer would have to deal with in a real observation. You are going to have to make a mental average of the values at each measurement point. For example, in five seconds, if the numbers are 78, 81, 79, 82, and 78, we would just estimate the count rate as "80". Note: the light meter is very sensitive, so you must keep yourself and your hands well away from the front of the device when making a measurement (the meter will detect light reflected off of *you*, making it hard to figure out what is going on!).

With the room lights turned off, set the desk lamp about two feet in front of the transit device. Power on the light and the light meter. With no rods in front of the glass disk, adjust the *height and direction* of the desk lamp to maximize the number of counts. Make sure the light bulb in the lamp is at roughly the same height as the round, glass disk in front of the light meter. One way to do this is move the big planet in front (putting the rod in the center-most notch) and make sure its shadow hits the center of the glass disk. Move all of the rods out of the way, and then move the transit device closer to the lamp until it gives a reading above 200 counts.

Now we are simply going to move each of the three rods (Bare Rod, Small Planet, Large Planet) into the five notches on the top dowel rod, and write down the average value of the light meter measurement at each position into Table 17.1. We do this one rod at a time. Once done, move that rod to the far right side of the dowel rod to start the process for the next rod. The rods may swing around a bit, just let them stop moving, back away from the front of the device, and take your measurement. It sometimes takes a few seconds for the light meter to settle to the correct value, so give it a few seconds, and then make a estimate of the average light value at this position. Note: if you accidently bump the lamp or transit device you have to start over! Small changes in the separation or lamp height will result in bad data.

Table 17.1: Exoplanet Transit Data

Position	**Bare Rod**	δ	**Small P.**	**S.P.**+δ	**Large P.**	**L.P.**+δ
#1		0.0				
#2						
#3						
#4						
#5		0.0				

Now we have to account for the dimming effect of the rod. First, add the bare rod measurements at positions #1 and #5 together and divide by 2 to create the average unobscured value. Now, in the column labeled "δ", fill in the differences between the average unobscured value you just calculated, and your bare rod measurements at positions 2 through 4 (δ = Ave. − #2, etc.). Then in columns 5 (S.P. + δ) and 7 (L.P. + δ), add the value in column 3 to the measurements in columns 4 and 6, respectively for all five measurements [obviously, you add the value of δ at position #2 to the value of Small P. at position #2 to get the value of (S.P. + δ) at position #2]. **(14 points)**

Making Light Curves

Now we want to plot the data in Table 17.1 to make a light curve for our two planets. Plot your data on the graph paper in the next two windows. We have filled-in the X axis with notation for the five positions you measured. You will have to put values on the Y axis that allow the entire light curve to be plotted. For example if the unobscured value was near 285 (positions #1 or #5), the top Y axis grid line might be set to 300. If the value at position #3 was 223, the bottom of the Y axis could have a value of 200. It depends on your light meter, and how bright the light source was. You will have to decide how to label the Y axis! Plot the data for both planets in Figures 17.4 and 17.5. **(8 points)**.

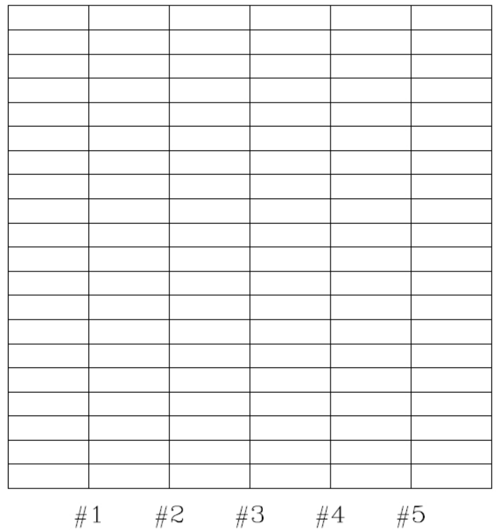


Figure 17.4: The light curve of the transit of the small planet.

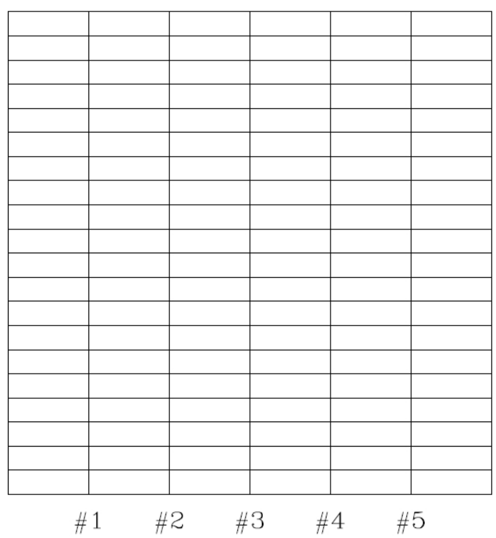


Figure 17.5: The light curve of the transit of the large planet.

17.3.1 Real exoplanet transits

Now that we have seen how one might observe a real exoplanet transit, and construct its light curve. We now want to examine how hard this really is. You probably have already found the dimming signal due to the small planet was quite small. Let's calculate how much the light dimmed in our simulations so we can compare them to real exoplanet transits. First we need to find the difference between the unobscured value, and the value at position #3 for both planets: **(2 points)**

Total dimming small planet = (Position #1) − (Position #3) = _________ counts

Total dimming large planet = (Position #1) − (Position #3) = _________ counts

Now let's put this in the fractional amount of dimming ("ΔF/F"):

Fractional dimming small planet = (Total dimming small planet)/(Position #1) = _____

Fractional dimming large planet = (Total dimming large planet)/(Position #1) = ______

How does this compare to the real world? You actually already calculated the percent dimming for the Earth and Jupiter in Exercise #2. In that exercise we calculated the ratio of the areas of the planets relative to the Sun—this ratio is in fact how much the light from the Sun would dim (in fractional terms) when the Earth or Jupiter transited it as seen from a very distant point in space (or as some alien would measure watching those crazy exoplanets transit the star we call the Sun!).

Questions:

1) Compare the percent dimming of our simulated exoplanets to the values for the Earth and Jupiter found in Exercise #2. Was our simulation very realistic? **(2 points)**

2) Let's imagine an alien pointed their telescope at our Sun to watch a transit of the Earth. If his light meter was measuring 25,000 counts from the Sun before the Earth transited (i.e., Point #1), what would it read at mid-transit (i.e., Point #3)? Show your math. [Hint: remember the dimming is very small, so the mid-transit number will be very close to the unobscured value.] **(2 points)**

As you have now seen, detecting planets around other stars is very hard. The amount of dimming during a transit is only about 1% for a Jupiter-sized exoplanet that orbits another star. To make such high precision measurements, especially to see Earth-sized planets, requires us to get above the Earth's atmosphere and use special detectors that have very low noise. Note that we also have to observe for a very long time—the Earth only has one transit per year! Jupiter would have one every 12 years! These events only last a few hours, so we also have to observe the star continuously so we do not miss the transit. This requires a dedicated instrument, and this need was the genesis of the Kepler mission launched by NASA several years ago. Kepler detected over 1,000 transiting exoplanets during its four year mission. Unfortunately, Kepler is no longer fully functional, and it will not be able to continue searching for Earth-like planets.

Before we leave the subject of transits behind, we want to talk a little more about how we can use light curves to get actual information on the exoplanet. In Figure 17.6 is plotted an exoplanet transit and light curve, with all of the math (scary, eh?) that needs to be taken into account to decipher exactly what is going on (actually the math is not real scary, as it is derived from Kepler's laws). In the preceding we have assumed that the planet crosses the center of the star—but this almost never happens. The orbit is tilted a little bit, so the transit path is shortened. There are ways to figure all of this out, as demonstrated by the many math equations in this figure. But we want to focus your attention on the most important result that a transit tells you: the radius of the exoplanet. In the top corner of Figure 17.6 there is a simple equation: $\Delta F/F = (R_p/R_*)^2$. As we have calculated above, the depth of the eclipse, $\Delta F/F$, allows you to determine the radius of an exoplanet. As all of the math in this figure shows you, if you can estimate the stellar parameters (R_*, M_*), you can also determine other characteristics of the exoplanet orbit (semi-major axis, orbital inclination). It is fairly simple to estimate R_* and M_*. In fact, if we measure the period of the orbiting planet, we can measure the mass of the host star using Kepler's laws (the $P^2 = 4\pi^2/GM_*$ equation). Thus observing transits provides much insight into the nature of an exoplanet, its orbit, and the host star.

17.4 Exoplanet Detection by Radial Velocity Variations

The final method we are going to investigate today, the technique of radial velocity variations, is the most difficult to understand as we have to talk about "center of mass", the Doppler effect, and spectroscopy. You have probably heard about all three of these during the lectures over this past semester, but we are sure you need to have a review of these topics.

You are certainly aware of the concept center of mass, even if you never knew what it was called. Take the pencil or pen that you have with you today and try to balance it across the tip of your finger. The point on the pencil/pen where it balances on your finger tip is its center of mass. A teeter totter is another good way

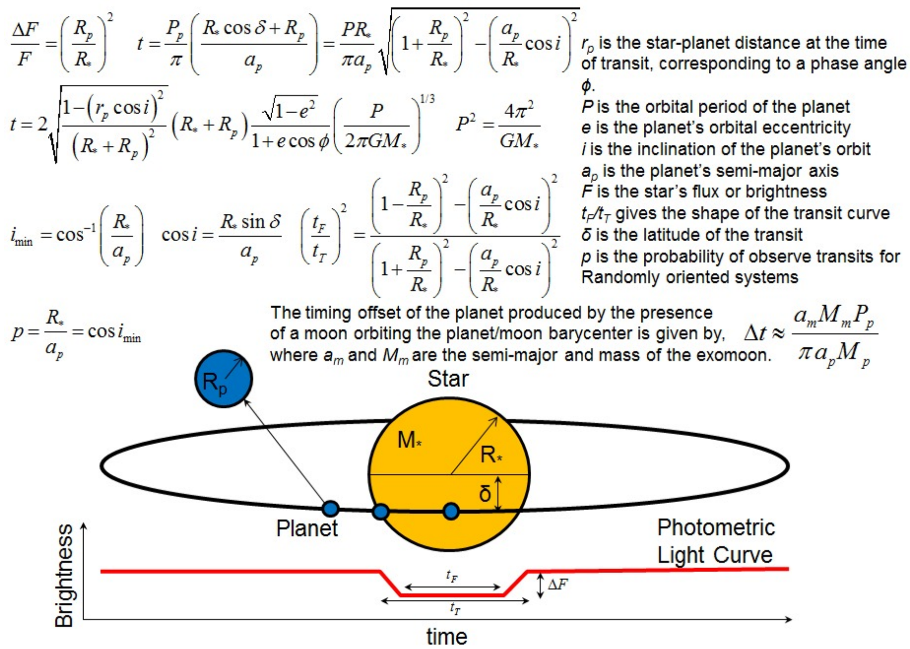


Figure 17.6: An exoplanet transit light curve (bottom) can provide a useful amount of information. As we have shown, the most important attribute is the radius of the exoplanet. But if you know the mass and radius of the exoplanet host star, you can determine other details about the exoplanet's orbit. As the figure suggests, by observing multiple transits of an exoplanet, you can actually determine whether it has a moon! This is because the exoplanet and its moon orbit around the center of mass of the system ("barycenter"), and thus the planet appears to wobble back and forth relative to the host star. We will discuss center of mass, and the orbits of stars and exoplanets around the center of mass, in the next subsection.

to envision the center of mass. If a small kid and a big kid are playing on the teeter totter, the balance is not good, and it is hard to have fun. You need to either adjust the balance point of the teeter totter, or have two kids with the same weight use it.

A diagram for defining the center of mass for two objects with different masses is shown in Figure 17.7. If the two objects had the same mass, the center of mass would be halfway between them. If one object has a much bigger mass, than the center of mass will be located closer to it. You have a device today that clearly demonstrates this type of system.

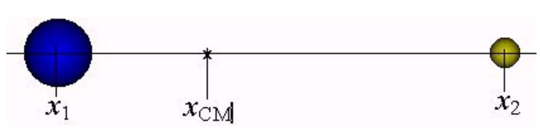


Figure 17.7: Center of mass, "x_{CM}", for two objects that have unequal masses. The center of mass can be thought as being the point where the system would balance on a "fulcrum" if connected by a rod.

Exercise #4: Defining the Center of Mass for a Two Body System

As part of the materials for today's lab, you were given a center of mass demonstrator. It consists of a large black mass connected to a small white mass by a long rod. There is also a wooden handle with a small pin at one end.

Remove the wooden handle from the long rod. Using the meter stick, estimate the length of the entire device, from the **center** of the black sphere (we will call it "M_1"), to the **center** of the white sphere ("M_2"). What is this number in cm? **(1 point)**:

Ok, now find the halfway point from the center of one ball to the next. You need to divide the length you just measured by two, and measure in from one of the balls and note its location (if necessary, use a piece of tape). Is there a hole there? If you try to balance the device on the tip of your finger at this center point/hole, what happens? **(2 points)**

Now put the device on the tip of your finger and find the balance point of the device. There is also a hole there. Use the meter stick to estimate (and write down) the distance between the center of the black ball to this point (we will call this "X_1"), and the distance between the center of the white ball and this point (we will call this "X_2"). This exercise is best done by two people. **(2 points)**

X_1 = ________________________ cm

X_2 = ________________________ cm

This spot on the rod is "the center of mass". The center of mass point is important, as it allows us to determine the "mass ratio", and if we know the mass of one of the objects, we can figure out the mass of the other object. The equation for center of mass is this:

$$M_1X_1 = M_2X_2$$

and the mass ratio is:

$$M_1/M_2 = X_2/X_1$$

Determine the mass ratio for the center of mass device. **(2 points)**

$M_1/M_2 =$

If $M_1 = 250$ grams, what is the mass of M_2? **(2 points)**

$M_2 =$ ___________________________ grams

Now that we have explored the concept of center of mass, let's see how it applies to objects that orbit each other. Inserting the pin on the wooden handle into the center point of the rod (not the center of mass hole!), hold the wooden handle and try to spin the device (watch your head!). Now, move the wooden handle to the center of mass hole. Spin the device. Explain what happened at both locations: **(2 points)**

Any two objects in orbit around each other actually orbit the center of mass of the system. This is diagrammed in Figure 17.8[1]. Thus, the Earth and Sun orbit each other around their center of mass, and Jupiter and the Sun orbit each other around their center of mass, etc. In fact, the motion of the Sun is a complex combination of the orbits of all of the planets in our solar system. For now, we are going to ignore the other planets, and figure out where the center of mass is for the Sun−Earth system.

The Sun has a mass of $M_{Sun} = 2.0 \times 10^{30}$ kg, while the Earth has a mass of $M_{Earth} = 6.0 \times 10^{24}$ kg. We will save you some math and just tell you that the approximate mass ratio is:

$M_{Sun}/M_{Earth} = 330{,}000$

To determine where the center of mass is for the Earth-Sun system, we have to do a little bit of algebra. Remember that the mean distance between the Earth and the

[1] An animation of this can be found at http://astronomy.nmsu.edu/tharriso/ast105/Orbit3.gif

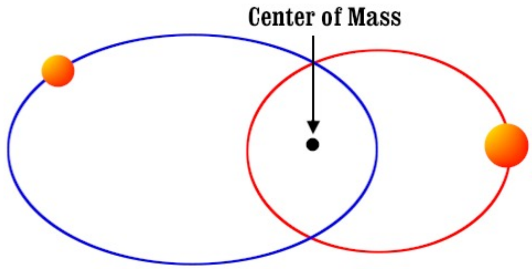


Figure 17.8: If two stars are orbiting around each other, or a planet is orbiting a star, they both *actually* orbit the center of mass. If the two objects have the same mass, the center of mass is exactly halfway between the two objects. Otherwise, the orbits have different sizes.

Sun is 1 AU. Thus, using our notation from above:

$$1 \text{ AU} = X_1 + X_2$$

Therefore,

$$X_1 = 1 \text{ AU} - X_2 \qquad \text{(Equation \#1)}$$

Does that make sense to you? X_1 and X_2 are the distance from the Sun to the center of mass, and the Earth to the center of mass, respectively. As the center of mass demonstration device shows you, the center of mass is located somewhere on the line that connects the two objects. Thus, $X_1 + X_2$ = distance between the two masses. For the Earth and Sun, $X_1 + X_2 = 1$ AU. Now, going back to our center of mass equation:

$$M_1X_1 = M_2X_2 \qquad \text{(Equation \#2)}$$

We can substitute the result for X_1 in equation #1 into Equation #2:

$$M_1(1 \text{ AU} - X_2) = M_2X_2 \qquad \text{(Equation \#3)}$$

Dividing both sides of Equation #3 by M_1 gives:

$$1 \text{ AU} - X_2 = (M_2/M_1)X_2 \qquad \text{(Equation \#4)}$$

But $(M_2/M_1) = 1/330{,}000$ for the Earth-Sun system, and now we can solve to find X_2:

$$1 \text{ AU} = (M_2/M_1)X_2 + X_2 = (1/330{,}000 + 1)X_2$$

Thus,

$$X_2 = 1.0/(1 + 1/330{,}000) = 0.999997 \text{ AU}$$

Essentially, the Earth is 1 AU from the center of mass, how far away is the Sun from the Earth-Sun center of mass? Go back to equation #1:

$$X_1 = 1 - 0.999997 = 0.000003 \text{ AU}$$

The Sun is very close to the center of mass of the Earth-Sun system.

Exercise #5: Determining the Size and Velocity of the Sun's "Reflex Motion"

We are going to calculate the size of the Sun's orbit around the center of mass for the Sun-Earth system, and then determine how fast the Sun is actually moving. The motion of the Sun (or any star) due to an orbiting planet is called the "reflex motion." Like the name suggests, it is the response of the star to the gravitational pull of the planet. Since AU per year is not a normal unit with which to measure velocity, we need to convert the numbers we have just calculated to something more useful.

1 AU = 149,597,871 km. How far from the center of mass is the Sun in km? **(1 point)**:

X_1 (km) = X_1 (AU) × 149,597,871 (km/AU) = ________________ km

Hopefully, you noticed how the units of length canceled in the last equation.

So, we now have the distance of the Sun from the center of mass. Note that this number puts the center of mass of the Earth-Sun system well inside the Sun (actually very close to its core). We now want to figure out what the length of the orbit is that the Sun executes over one year (remember, the Earth takes one year to orbit the Sun, so the "orbital period" of the Sun around the Earth-Sun center of mass will be one year). Referring back to the center of mass device, if you put the handle in the center of mass hole and spin the system, what path do the masses trace? That's right, a circle. Do you remember how to calculate the circumference of a circle? $C = 2\pi R$, where R is the radius of the circle and $\pi = 3.14$.

What is the circumference of the orbit circle (in km) that is traced-out by the Sun? **(2 points)**:

This is how far the Sun travels each year, thus we can turn this into a velocity (km/hr = kph) by dividing the distance traveled (in km) by the number of hours in a year. Show your math **(2 points)**:

$$V_{\rm Sun}\ ({\rm km/hr}) = {\rm C\ (km)} \div (\#\ {\rm hours\ in\ year}) = ???$$

1) Comment on the size of the reflex velocity ($V_{\rm Sun}$) of the Sun. Note that the Earth travels much, much further during the year, so its velocity is much, much higher: 107,000 km/hr! **(3 points)**:

Because all of the math above involved simple, "linear" equations, we can quickly estimate the reflex velocity of the Sun if we replaced the Earth by something more massive. For example, if we put an object with 10 Earth masses in an orbit with R = 1 AU, the reflex velocity of the Sun would be 10 times that which you just calculated for the Earth.

2) Jupiter has a mass that is 318 times that of the Earth. If Jupiter orbited the Sun at 1 AU, what would the reflex velocity of the Sun be? **(2 points)**:

Since Jupiter is at 5.2 AU, and its orbital period is 11.9 yr, the reflex motion of Jupiter is actually: $V_{Jupiter} = 318 \times V_{Earth} \times 5.2 \div 11.9 \approx 45$ km/hr.

Exercise #6: Understanding the Sizes of the Reflex Motions

For the final exercise of today's lab, we want to demonstrate how big these reflex motions are by comparing them to the velocities that you can generate. To do so, we are going to be using radar guns just like those used by the police to catch speeders. These devices are very expensive, so please be extremely careful with them. The radar guns are a bit technical to set-up, so your TA will put them in the correct mode for measuring velocities in km/hr.

Your lab group should head out of the classroom, and into the hallway (or outside) to get a long enough path to execute this part of the lab. The idea is to have one of the lab members move down the hallway, and act as the "speeding car". Note that if there are other people moving around in the hallway, the radar gun might get a confusing signal and not read correctly. So, make sure only one person is moving when doing this.

1) One lab member hold the radar gun, have another lab member walk towards the radar gun. Hold down the trigger a few seconds and then let go. Do this several times to get a good reading. What is the average velocity of the walking speed of this lab member? **(2 points)**:

2) Now, we are going to measure the running speed. **BE CAREFUL!**. Have

everyone participate, and see who can run the fastest. What are the velocities for the various lab members? **(2 points)**:

3) Compare your walking and running velocities to the Sun's reflex velocity caused by the Earth that you calculated above. How massive a planet (in Earth masses) would it take to get your walking reflex motion to be executed by the Sun? How about your running reflex motion? **(5 points)**.

17.5 Radial Velocity and the Doppler Effect

Earlier we called this final exoplanet discovery technique "the radial velocity" method. What do we mean by this term? The radial velocity is a measurement of how fast something is coming towards you, or going away from you. If an object is moving across your line of sight (like the cars on the road as you wait to cross a street at the pedestrian crossing), it has no radial velocity (formally, they would have a "tangential velocity" only). If we were an alien watching the Sun, the Sun would sometimes have a radial velocity coming towards us (normally defined to be a negative number), and a radial velocity going away from us (normally defined as a positive number), due to the reflex motions imparted on it by the planets in our solar system. This gives rise to something called a "radial velocity curve."

So how do we detect the radial velocity of a star? We use something called the Doppler effect. The Doppler effect is the change in frequency of a sound or light *wave* due to motion of the source. Think of an ambulance. When the ambulance is coming towards you, the siren has a high pitch. As it passes by you, the pitch drops (for audio examples, go here: http://www.soundsnap.com/search/audio/doppler/score?page=1"). This is shown in Figure 17.9. The radar guns you just used emit microwaves that are Doppler shifted by moving objects. Stars are too far away to use radar. Fortunately, the same process happens with all types of electromagnetic radiation. Astronomers use visible light to search for Exoplanets. In a source coming towards us the light waves get compressed to higher frequency. When it is receding the light waves are stretched to lower frequency. Compressing the frequency of light adds energy, so it "blueshifts" the light. Lowering the frequency removes energy, so it "redshifts" the light. For an object orbiting the center of mass, sometimes the light is blueshifted (at point #4 in Figure 17.10), sometimes it is redshifted (at point #2 in Figure 17.10).

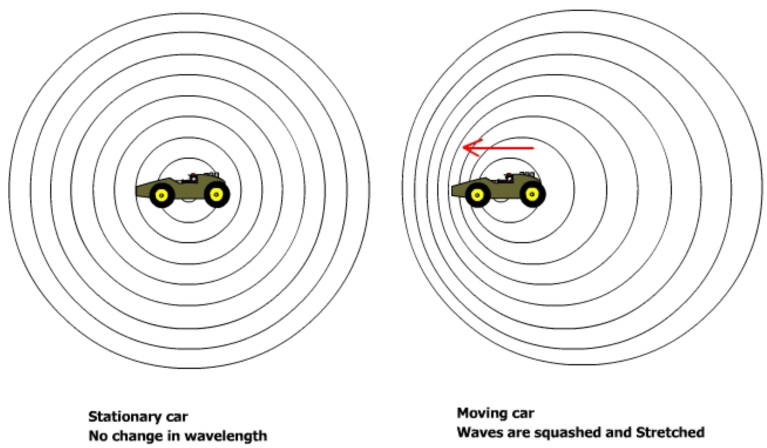


Figure 17.9: For a stationary vehicle emitting sound, there is no Doppler effect. As the vehicle begins to move, however, the sound is compressed in the direction it is moving, and stretched-out in the opposite direction.

This is how astronomers discover exoplanets, they monitor the spectrum of a star and look for a changing radial velocity like that shown in Figure 17.10. What they see is that the absorption lines in the spectrum of the exoplanet host star shift back and forth, red to blue to red to blue. Measuring the shift gives them the velocity. Measuring the time it takes to go from maximum blueshift to maximum redshift and back to maximum blueshift, is the exoplanet's orbital period. Remember, the exoplanet is too faint to detect directly, it is only the reflex velocity of the host star that can be observed. And, now you should understand how we measure the mass of the exoplanet. The amount of reflex velocity is directly related to the mass of the exoplanet and the size of its orbit. We can use the orbital period and Kepler's laws to figure out the size of the exoplanet's orbit. We then measure the radial velocity curve, and if we can estimate the host star's mass, we can directly measure the mass of the exoplanet using the techniques you have learned today.

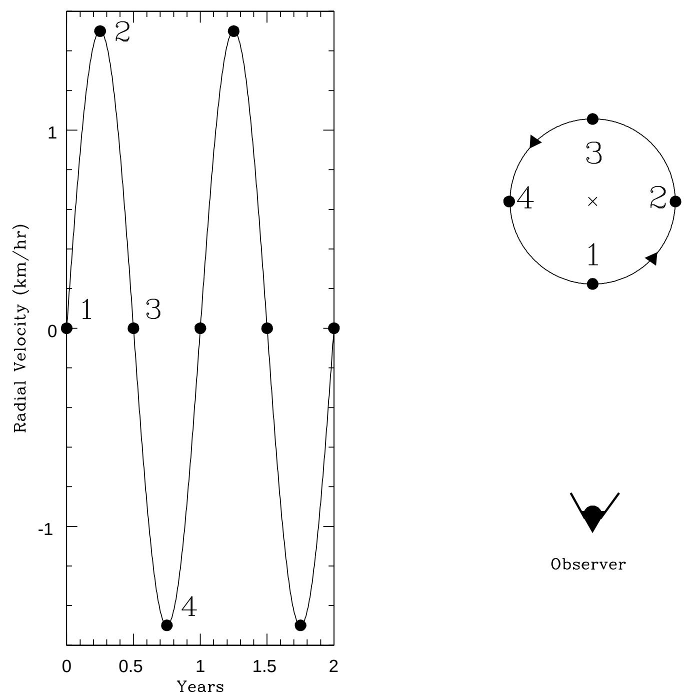


Figure 17.10: A radial velocity curve (left) for a planet with a one year orbit like Earth, but that imparts a reflex velocity of 1.5 km/hr on its host star. When the motion is directly away from us, #2, we have the maximum amount of positive radial velocity. When the motion of the object is directly towards us, #4, we have the maximum negative radial velocity. At points #1 and #3, the object is not coming towards us, or going away from us, thus its radial velocity is 0 km/hr. The orbit of the object around the center of mass ("X") is shown in the right hand panel, where the observer is at the bottom of the diagram. The numbered points represent the same places in the orbit in both panels.

Here is how it is done. To determine the mass of an exoplanet, we first must figure out the semi-major axis of its orbit (for the Earth, the semi-major axis = R = 1 AU). We return to Kepler's laws:

$$R^3 = \frac{GM_{star}}{4\pi^2}P^2 \qquad (Equation\ \#5)$$

In this equation, "G" is the gravitational constant. P is the orbital period. In physics equations like these, the *system* of units used must be the same for each parameter. Such as centimeter-gram-second, or meter-kilogram-second. We call these the "'cgs" and "mks" systems, respectively. You cannot mix and match. Thus, there have to be two flavors of G for this equation: $G_{cgs} = 6.67 \times 10^{-8}$, and $G_{mks} = 6.67 \times 10^{-11}$. The equation above is just Kepler's third law $P^2 \propto a^3$ you learned about at the beginning of the semester. What Isaac Newton did was figure out what is needed to change the "$\propto$" into the "=" sign. If we know "R" and the exoplanet host star mass (M_{star}) we can figure out the exoplanet's mass. So using equation #5 above, we find R. Since we know the orbital period (P), we can estimate the exoplanet's orbital velocity:

$$V_{pl} = \frac{2\pi R}{P} \qquad (Equation\ \#6)$$

The mass of the planet is simply:

$$M_{pl} = \frac{M_{star} V_{star}}{V_{pl}}$$

In this equation $\mathrm{V_{star}}$ is the host star reflex velocity like those we calculated above for the Earth-Sun, and Jupiter-Sun systems. The biggest unknown when making such mass measurements is estimating the host star mass. There are ways to do this, but they are beyond the scope of today's lab. We will use these equations in the take-home part of this lab, so make sure you understand what is going on here before leaving today.

Name:______________________________
Date:_______________________________

17.5.1 Take-Home Exercise (35 points total)

1) Discuss what you have learned about Exoplanets today. How hard are they to detect, and what are the main techniques astronomers use to find them? **(10 points)**

2) You have obtained a radial velocity curve for a transiting exoplanet that orbits the star 18 Scorpii, which is referred to as a "solar twin" (that is, identical in every way to the Sun). The planet has an orbital period of 400 days. The maximum reflex velocity of the star 18 Scorpii is 1 m/s. What is the mass of this exoplanet? You are going to need to use equations #5 and #6, and the mass (listed in Exercise #4) and radius (from Exercise #1) of the Sun. Remember that you must use a consistent set of units. In equation #5 "**G**" is listed in "mks". Thus, the period of the exoplanet must be converted from days to seconds, and the mass and radius of the Sun must be in kilograms and meters, respectively, to correctly use equations #5 and #6. Compare the mass of this exoplanet to the mass of the Earth (6.0×10^{24} kg). Show your work. **(10 points)**

3) As we noted, the exoplanet around 18 Scorpii is also a transiting system, and $\Delta F/F = 4.8 \times 10^{-4}$. Calculate the radius of this planet (like those in Exercise #3). Compare it to the radius of the Earth. What is the density of this planet in kg/m^3? [Hint: density = mass/volume. What is the volume of a sphere?] Compare this to the density of the Earth (5,511 kg/m^3), and Jupiter (1,326 kg/m^3). Is "18 Scorpii B" more like a Terrestrial planet, or a Jovian planet? Show your work. **(15 points)**

17.5.2 Possible Quiz Questions

1) What is an Exoplanet?
2) Name one of the techniques used to find Exoplanets
3) Why are Exoplanets so hard to discover?

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

Using the web, search for an article on an "Earth-like exoplanet" and write a one page discussion of this object, and what makes it "Earth-like". Note that there are quite a few such objects, just pick the one you find most interesting (and one that has sufficient discussion to allow you to write a short paper).

18 APPENDIX A: Fundamental Quantities

There are various ways to describe the world in which we live. Some are qualitative and others are quantitative. Qualitative descriptions describe aspects of objects or events such as texture, and use words like 'rough', 'smooth', 'flat' etc. Qualitative descriptions cannot be described numerically. One would not say that you looked tired with a value of 3.0 unless someone had first set up some kind of numerical scale to measure just how tired you were; tiredness is not something we measure quantitatively. On the other hand, length is a dimension that can be described either qualitatively or quantitatively; one can qualitatively describe an object as long, or one can quantitatively describe it as 10 feet in length.

All quantitative measurements are made in some kind of unit. Length, for example, can be measured in units of meters, feet, miles, etc. Other fundamental metric units are the kilogram (a measure of mass) and the second (a unit of time). Other units of measurement are combinations of these fundamental units. An example of a combination is velocity, expressed in units of meters per second (m/s) which measures how far something has moved in a given direction over a given period of time.

In astronomical studies, one sometimes uses units which express rather large values in the fundamental metric units. An example of this would be the Solar Mass unit (notated as $M\odot$). The mass of our Sun is, by definition, one Solar Mass or about 1,900,000,000,000,000,000,000,000,000,000 kilograms. A star with 10 times as much mass can be written as 10 $M\odot$; this is clearly more convenient to write than a number with all those zeros! Other units used in astronomy are the light year (ly), parsec (pc), and the astronomical unit (A.U.), all of which are units of distance. The unit you choose to use depends on the situation, and personal preferences. When describing distances in the solar system the astronomical unit is typically used since it is the average distance from the Sun to the Earth. In describing distances to stars the parsec or light year is usually used.

As described in the introductory lab, the metric system allows easy expression of large multiples of the fundamental units via prefixes. For example, 1,000 meters is called a kilometer and is usually written as 1km.

As described in section 1.4 scientists also use a notation system called scientific notation for representing very large or very small numbers without having to write lots of digits. As an example of how large numbers can get in science let's look at the mass of Mars. Using Kepler's laws of motion to study Mars' moons, astronomers have determined that Mars has a mass approximately equal to 640,000,000,000,000,000,000,000 kilograms. Now you can see that it is rather inconvenient to write down all those zeroes, and it is confusing to use the prefixes above. Imagine how much more mass there is in the Galaxy and you can see that we need an easy way to write very big (or very small) numbers. This leads us to the concept of Scientific Notation.

19 APPENDIX B: Accuracy and Significant Digits

The number of significant digits in a number is the number of non-zero digits in the number. For example, the number 12.735 has *five* significant digits; the number 100 has *1*. When computing numbers, people today often use calculators since they give us precise answers quickly. Unfortunately, many times they give us answers that are unnecessarily and sometimes unrealistically precise. In other words, they give us as many significant digits as can fit on the calculator screen. In most cases, you will not know the numbers you are plugging in to the calculator to this precise of a value, and therefore will get an answer that has too many significant digits to be correct. This will be the case for your astronomy labs this semester. In general, you should only report the accuracy of a calculation with the number of significant digits of the least certain (smallest number of significant digits) of any of the numbers which were the input into the calculation. For example, if you are dividing 13.2 by 6.8, although your calculator gives 1.94117647, you should only report two significant figures (i.e. 1.9), since that is the number of significant figures in the input number 6.8.

20 APPENDIX C: Unit Conversions

Very often, scientists convert numbers from one set of units to another. In fact, not only do scientists do this, but you do it as well! For example, if someone asks you how tall you are, you could tell them your height in feet or even in inches. If someone said they are 72 inches tall, and 12 inches equals 1 foot, then you know they are 6 feet tall! This is nothing more than a simple conversion from units of inches to units of feet. Another everyday unit conversion is from minutes to hours, and vice versa. If it takes you 30 minutes to drive from Las Cruces to Anthony, then it takes you 0.5 hours. We know this because 60 minutes are equal to 1 hour. However, how can we write these unit conversions, with all the steps, so that we are sure we are converting units correctly (especially when the units are foreign to us (i.e. parsecs, AU, etc.))?

Let us begin with our everyday conversion of inches to feet. Say a person informs you that they are 72 inches tall and you want to know how many feet tall they are. First, we need to know the unit conversion from inches to feet (12 inches = 1 foot). We then write the following equation:

$$72\ inches \times \frac{1\ foot}{12\ inches} = 6\ feet \tag{13}$$

Note how the inches units cancel (one in the numerator and one in the denominator) and the units which remain are feet. As for the mathematics, simply use normal rules of division (72/12 = 6) and you wind up with the correct result.

The second example, minutes to hours, can be performed using the method above, but what if someone asked you how many days there are in 30 minutes? You will need to use 2 unit conversions to do this (60 minutes = 1 hours, 24 hours = 1 day). Here is how you may perform the unit conversion:

$$30\ minutes \times \frac{1\ hour}{60\ minutes} \times \frac{1\ day}{24\ hours} \approx 0.0208\ days = 2.08 \times 10^{-2}\ days \tag{14}$$

Again, note that the minute units have cancelled as well as the hour units, leaving only days.

You have now seen how to perform single and multiple unit conversions. The key to performing these correctly is to 1) make sure you have all the conversion factors you need, 2) write out all of the steps and make sure the units cancel, and 3) think about your final result and ask whether the final result makes sense (is 30 minutes a small fraction of a day? Does 72 inches equal 6 feet?).

21 APPENDIX D: Uncertainties and Errors

A very important concept in science is the idea of uncertainties and errors. Whenever measurements are made, they are never made absolutely perfectly. For example, when you measure your height, you probably measure it only to roughly the nearest tenth of an inch or so. No one says they are exactly 71.56789123 inches tall, for example, because they don't make the measurement this accurately. Similarly, if someone says they are 71 inches tall, we don't really know that they are exactly 71 inches tall; they may, for example, be 71.002 inches tall, but their measurement wasn't accurate enough to draw this distinction.

In astronomy, since the objects we study are so far away, measurements can be very hard to make. As a result, the uncertainties of the measurements can be quite large. For example, astronomers are still trying to refine measurements of the distance to the nearest galaxy. At the current time, we think the distance is about 160,000 light years, but the uncertainty in this measurement is something like 20,000 light years, so the true distance may be as little as 140,000 light years or as much as 180,000 light years. When you do science, you have to always assess the errors on your measurements.

22 Observatory Worksheets

You *must* visit campus observatory twice this semester. You will need to take four of the observatory worksheets with you each time you go.

Campus Observatory Observation Sheet

Your Name: ____________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ______________

Type of Object: ________________ Object Name: __________

Object Description: ____

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Fact about this object (and the source of information):

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Campus Observatory Observation Sheet

Your Name: ____________________ T.A.: ____________________

Date & Time: __________________ Telescope: _____________

Type of Object: ________________ Object Name: __________

Object Description: ______________________________________

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Fact about this object (and the source of information):

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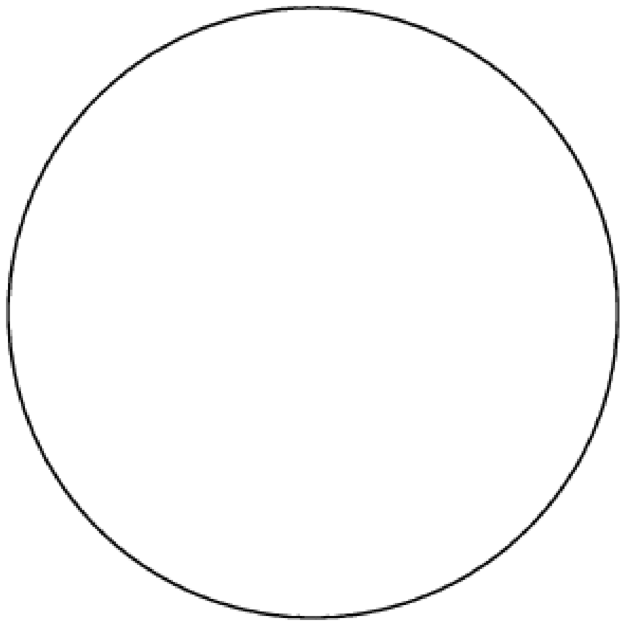
Campus Observatory Observation Sheet



Your Name: ____________________ T.A.: ____________________

Date & Time: ____________________ Telescope: ____________________

Type of Object: ____________________ Object Name: ____________________

Object Description: ____

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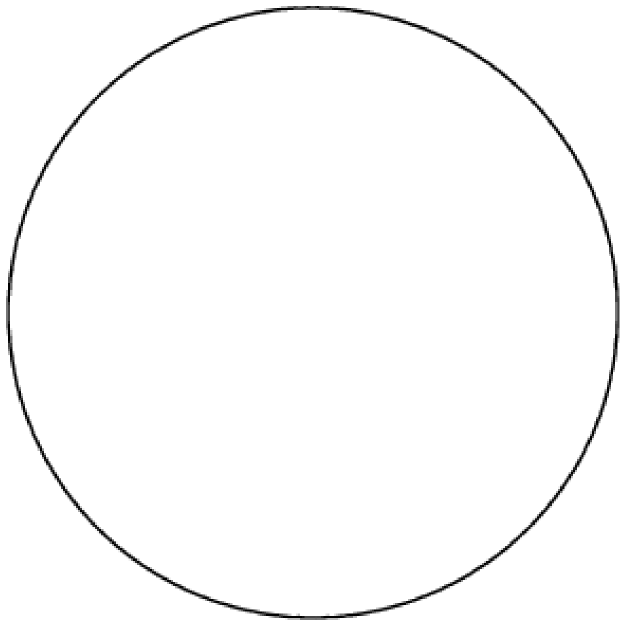
Campus Observatory Observation Sheet



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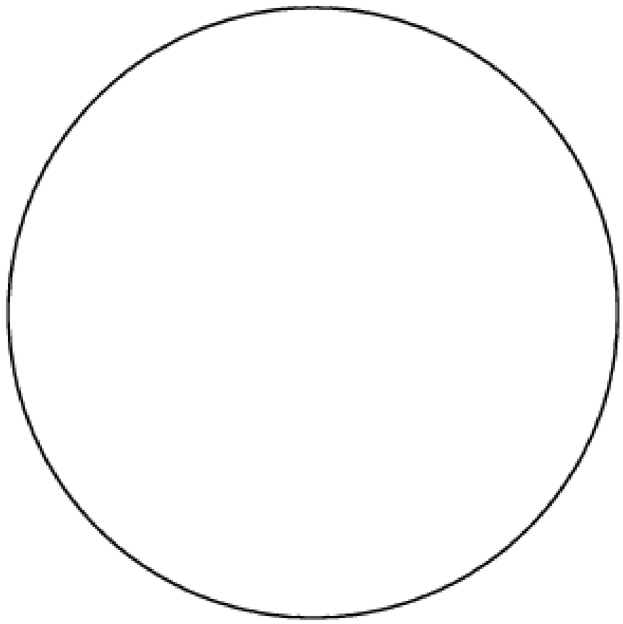
Campus Observatory Observation Sheet



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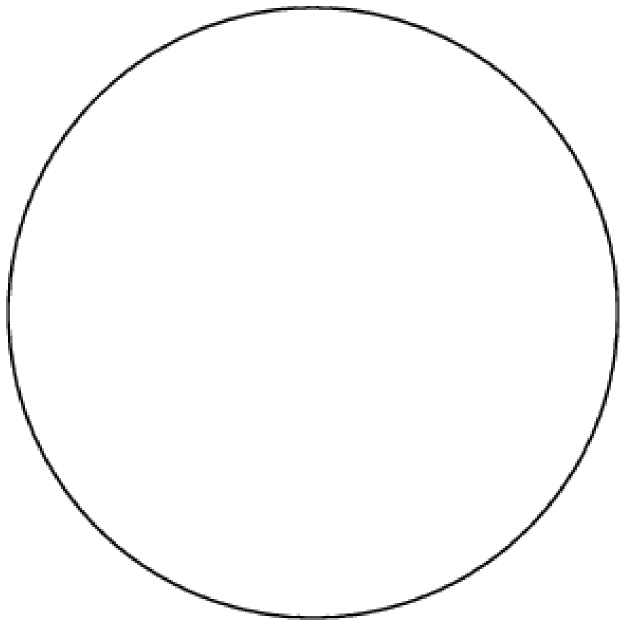
Campus Observatory Observation Sheet



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Date & Time: __________________ Telescope: ______________

Type of Object: ________________ Object Name: ___________

Object Description: ______________________________________

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Fact about this object (and the source of information):

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